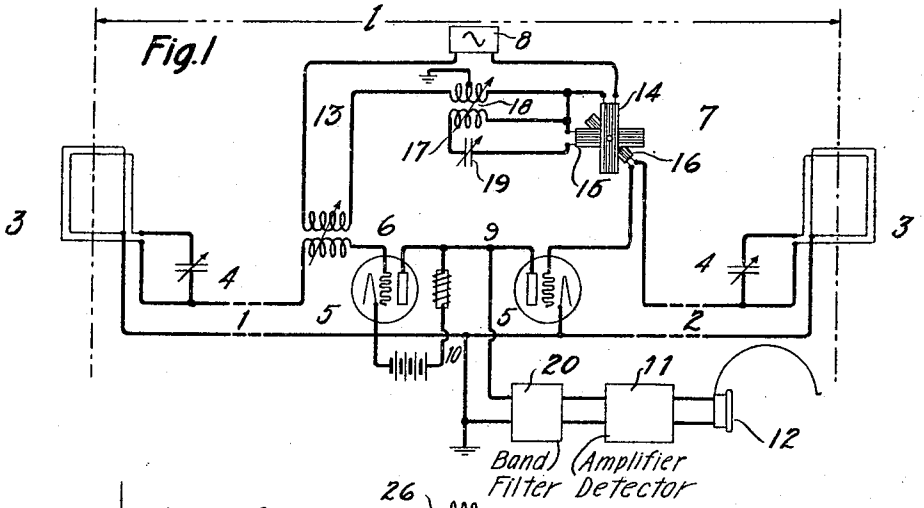
June 10, 1930. H. T. FRIIS 1,762,974

RADIO RECEIVING SYSTEM

Filed Oct. 30, 1924

Fig.1



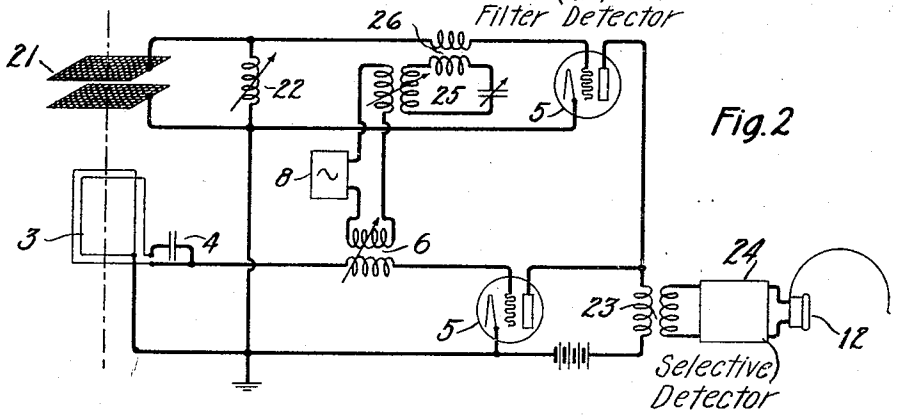


Fig.2

Fig.3

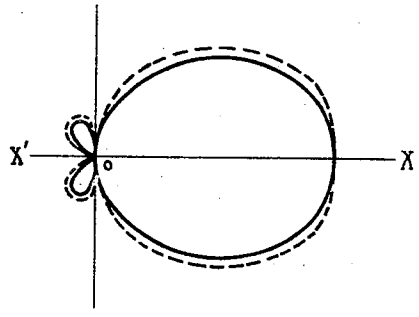
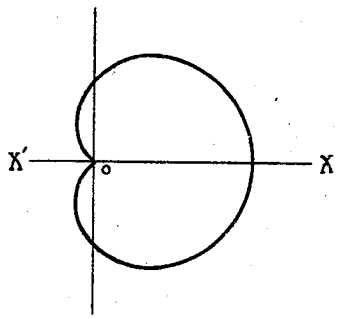


Fig.4



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Patented June 10, 1930 1,762,974

UNITED STATES PATENT OFFICE

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RADIO RECEIVING SYSTEM

Application filed October 30, 1924. Serial No. 746,753.

This invention relates to directional radio receiving systems, and more particularly to systems in which directional selectivity is obtained by combining the output voltages from a plurality of antennæ. It has for its principal object the provision of improved means for controlling the output voltages of the several antennæ of a directional system, so that they may be combined to neutralize each other or to reinforce each other according to the direction from which the received waves arrive.

It is a feature of the invention that the output voltages which are combined to produce the directional characteristics are the products of modulation of the waves received by the antennæ and an auxiliary wave locally generated, and also that the control of these output voltages is effected by operations performed upon the auxiliary wave.

The principal advantage of such directional systems is the reduction of static interference. It is now well known that static disturbances have definite points of origin and that the waves or impulses which are detected at a receiving station have definite directions of propagation. A receiving system having no directional selectivity is therefore affected by static impulses from all directions, whereas a system which is so designed as to receive freely waves arriving from a limited range of directions is susceptible only to static disturbances propagated within that range.

The impulsive nature of most static makes it impossible to discriminate against it by frequency selective means, the effect of the impulses being to set up in the selective circuits free oscillations having a frequency and damping determined by the natural periods and the time-constants of the circuits. It follows, then, that static effects in a plurality of antennæ can be made to neutralize each other only if the natural periods and time constants of the antenna circuits are accurately alike, or, in more general terms, if the propagation, or complex damping, constants are equal.

In multi-antenna systems, it is necessary to control the phase and intensity of the currents delivered from each independent antenna circuit, in order that their mutual reinforcement or neutralization may be properly accomplished. Hitherto, this has been done by incorporating control apparatus directly in the antenna circuits, and the addition of such apparatus has made it extremely difficult to achieve the requisite equality of the propagation constants. For this reason, the use of directional receiving systems has been greatly limited and has been almost entirely restricted to long wave signaling systems. By placing the means for controlling the output voltages in a circuit that is substantially independent of the antenna circuits, these may be reduced to a simpler form and may readily be made accurately alike, thereby making it possible to receive waves of the highest radio frequencies with good directional selectivity.

The nature of the invention and its manner of operation will be more fully understood from the following detailed description taken in conjunction with the accompanying drawing, of which

Fig. 1 represents a receiving system embodying the invention;

Fig. 2 represents a receiving system embodying a modified form of the invention;

Fig. 3 illustrates diagrammatically the selective characteristic of the system of Fig. 1; and

Fig. 4 illustrates the selective characteristic of the system of Fig. 2.

The receiving system of Fig. 1 comprises two similar antenna circuits 1 and 2, the antennæ each of which is a loop 3, being so disposed as to produce in the two circuits E. M. F.'s which are, in general, different in phase. The circuit 1 includes, besides the loop antenna 3, a tuning condenser 4, a demodulator 5, and the secondary winding of a variable coupling transformer 6 by means of which an auxiliary wave from a source 8 is impressed upon the circuit. Circuit 2 includes similar elements, but is coupled to the wave source 8 through a phase shifting transformer 7. The loops 3 are arranged to have their planes substantially coincident and perpendicular both to the ground and to the plane

of the wave it is desired to receive. Their centers are spaced apart a distance l which should preferably be between one-twelfth and one quarter of the wave length it is desired to receive. The output circuits of the demodulators 5 are connected together at points 9 and 10, the output waves of the two antenna circuits being jointly transmitted through a band filter 20 and impressed upon a second demodulating and amplifying system, which is indicated conventionally by the rectangle 11.

The output waves of the demodulators 5 include components the frequency of which is equal to the difference between the frequency of the auxiliary wave and that of the oscillations set up in the antenna, and which bear whatever modulations, signal or interference, are present in the antenna oscillations. The band filter 20,which may be one of the well known types disclosed in U. S. Patent 1,227,-113, May 22, 1917, to G. A. Campbell, selects these components to the exclusion of the others, and the amplifier-detector 11 detects the signal modulations which are finally reproduced as audible signals by the telephone receiver 12. The functions of selection, detection, and reproduction performed in this channel are well known and understood, and as no novel feature of the invention is involved in this part of the system, no detailed description is necessary. The demodulators 5 are of the three-electrode space discharge type, this type being preferred on account of its relatively great input impedance.

The source 8 of the auxiliary waves may be of any form suitable for giving oscillations of steady amplitude and capable of adjustment as to frequency; the oscillator disclosed in U. S. Patent 1,356,763, October 26, 1920, to R. V. L. Hartley is well suited to this purpose. The output circuit 13 of the source 8 includes the primary windings of transformers 6 and 7 through which the auxiliary wave is supplied to the demodulators.

The phase shifting transformer 7 comprises two fixed coils 14 and 15 having their planes mutually perpendicular and their centers coincident, and a third coil 16 which occupies the space within the other two coils and is adapted to rotate about an axis substantially coincident with the line of intersection of the central planes of the two fixed coils. The fixed coil 14 is connected in series in the circuit 13 and is therefore traversed by the same current as flows in the primary winding of transformer 6. Coil 15 forms part of a resonant circuit 17 which is coupled to circuit 13 by variable coupling transformer 18 and tuned to resonance by condenser 19. The currents in coils 14 and 15 are thus in quadrature, thereby serving to produce in the space occupied by coil 16 a rotating magnetic fluid and to induce in that coil a synchronous E. M. F. whose phase is determined by its angular position relatively to the fixed coils. The coupling of transformer 18 is variable to permit the field intensities of the two coils to be adjusted to approximate equality; the midpoint of its primary winding is grounded and the windings of transformers 6 and 7 are arranged on opposite sides of the ground, thereby securing a symmetry that enables the slight electrostatic couplings in the transformers to be balanced.

The operation of the system will now be described. It should first be observed that directional discrimination against continuous or signal modulated waves of frequencies different from that to which the antenna circuits are tuned is not necessary as the frequency selection effected by the high frequency and the intermediate frequency circuits is sufficient to suppress all interference from such waves.

Further, since the effect of static disturbances is in general to produce free oscillations in the antenna circuits at the frequency to which the circuits are tuned, it is evident that the directional discrimination against continuous waves of that frequency will be effective also against static impulses.

It will be assumed that the system is intended to receive waves of frequency designated by f propagated horizontally and in the direction from right to left in the diagram. The adjustments that should be given to the system and the proportions that should be adopted for the antenna spacing will be determined by considering the reception of horizontally propagated waves of the same frequency f arriving in a direction at any angle β to the direction of normal reception. As a measure of the directional effect, the intensity of the resultant intermediate frequency E. M. F. between the terminals 9 and 10 of the system will be taken. The manner in which this varies with the direction of propagation, assuming a constant field intensity, defines the directive selectivity.

Two factors enter into the variation of the E. M. F.'s produced in the circuits 1 and 2 by the waves intercepted by the antennæ. These are, first, the amplitude variation due to the directive properties of the individual loops, and second, the phase difference between the two E. M. F.'s which depends upon the effective separation of the loops in the direction of propagation. The amplitude of the E. M. F. induced in each loop is proportional to $\cos \beta$; the phase difference between the E. M. F.'s in the two loops is equal to

$$\frac{2\Pi l \cos \beta}{\lambda},$$

λ being the wave length corresponding to frequency f, and l, as indicated in the figure, denoting the actual distance between the centres of the two loops.

The instantaneous values of the two E. M.

F.'s impressed upon the demodulators 5 from the antennæ may be expressed by the equations—

$$\left.\begin{aligned} e_1 &= A \cos\beta \cos 2\,\Pi ft \\ e_2 &= A \cos\beta \cos (2\,\Pi ft + \Theta \cos\beta) \end{aligned}\right\} \quad (1)$$

in which A is the amplitude corresponding to zero value of the angle β, that is for the normal direction of propagation, and Θ is the angle

$$\frac{2\Pi l}{\lambda},$$

or the phase difference for the normal, or zero, direction. The subscripts 1 and 2 refer to the circuits 1 and 2, respectively.

From the source 8, there will also be impressed upon the demodulators E. M. F.'s of the auxiliary wave frequency and of relative phases and amplitudes determined by the adjustments of transformers 6 and 7. The instantaneous values of these E. M. F.'s may be expressed by the equations

$$\left.\begin{aligned} e_1' &= C \cos 2\,\Pi f_0 t \\ e_2' &= D \cos (2\,\Pi f_0 t + \phi) \end{aligned}\right\} \quad (2)$$

in which f_0 denotes the frequency of the auxiliary wave, ϕ the phase difference determined by the adjustment of the transformer 7, and C and D the amplitudes of the E. M. F.'s.

The important components of the demodulator outputs are those of the difference frequency $(f-f_0)$, the voltages of which, as measured between the terminals 9 and 10, may be determined in accordance with the principles set forth in U. S. Patent 1,448,702, patented March 13, 1923, to J. R. Carson. These voltages are given by the equations

$$\left.\begin{aligned} e_1'' &= K_1 CA \cos\beta . \cos 2\,\Pi(f-f_0)t \\ e_2'' &= K_2 DA \cos\beta . \cos (2\,\Pi(f-f_0)t + \theta\cos\beta\phi) \end{aligned}\right\} \quad (3)$$

the first of which represents the output of circuit 1 as the result of the intermodulation of the E. M. F.'s e_1 and e_1', and the second of which represents the output of circuit 2. The factors K_1 and K_2 involve the denodulating efficiencies of the demodulators and also the total impedances of their output circuits. They will, in general, be unequal but if the output circuits contain only pure resistance they will have simple numerical values and will not affect the relative phases of the E. M. F.'s e_1'' and e_2''. For frequencies within the transmission range of the band pass filter 20, this condition holds, it being a general property of such filters that their impedances within the range of frequencies transmitted are substantially non-reactive.

The resultant effect in the signal reproducer is proportional to the sum of the two E. M. F.'s of Equation (3). Since it is required that the two E. M. F.'s neutralize each other for certain directions of propagation, it is obviously necessary that their amplitudes must be made equal. This may be done by varying the coupling of transformer 6, thereby changing the intensity of the auxiliary wave in circuit 1 and producing a proportionate change in the amplitude of the E. M. F. e_1''. To secure the neutralization of the signals from wave propagated in a specific direction, further adjustment of the phases of the two output waves is required in addition to the equalization of their amplitudes. The amplitude of the resultant E. M. F. from the addition of e_1'' and e_2'' after their amplitudes have been reduced to equality, is given by the equation

$$E_\beta = 2E \cos\beta . \cos\left(\frac{\phi - \theta\cos\beta}{2}\right) \quad (4)$$

in which E is the common amplitude of the two components and the subscript β denotes that the resultant E. M. F. is that for waves propagated at an angle β to the normal direction.

It is evident from Equation 4 that the resultant E. M. F. will be zero under two conditions; first, when β equals $\frac{\Pi}{2}$, that is when the wave is propagated at right angles to the common plane of the two loops, and second, when

$$\phi = \theta\cos\beta + \Pi \quad (5)$$

One of the most useful adjustments, although not necessarily the best under all circumstances, is that under which the signals from waves propagated in the opposite direction from the normal are neutralized. The particular value of the angle β for which the resultant E. M. F. is zero in this case is equal to Π and the requisite phase displacement ϕ of the two auxiliary waves is therefore equal to $(\Pi-\theta)$. The reception characteristic of a system having this adjustment is given by the equation—

$$E_\beta = 2E . \cos\beta . \sin\frac{\theta(1+\cos\beta)}{2} \quad (6)$$

which is derived directly from Equation 4. The signal producing E. M. F. which will be denoted by E_0, corresponding to waves received in the normal direction is the value of E_β for the special case of $\beta=0$, or,

$$E_0 = 2E \sin\theta \quad (7)$$

Equation 7 indicates that the phase difference θ between the waves induced in the antenna should not exceed $\frac{\Pi}{2}$, or, that the antennæ should not be spaced apart more than a quarter of the wave length. For quite small separations, the signal E. M. F. increases proportionally to the separation of

the antennæ and reaches half the maximum possible value when the separation is one-twelfth of the wave length. For separations greater than this, the gain increases more slowly than the separation.

The ratio of amplitude of the E. M. F. produced by a wave propagated in the direction β to that of the E. M. F. produced by a wave of equal intensity propagated in the normal direction, is expressed by the equation—

$$R = \cos\beta \times \frac{\sin\left(\frac{\theta}{2}(1+\cos\beta)\right)}{\sin\theta} \quad (8)$$

as the separation of the loops is reduced the ratio R approaches the limiting value

$$R_0 = \frac{\cos\beta}{2}(1+\cos\beta) \quad (9)$$

The ratios R and R_0 have maximum values for values of β equal to 0, 120° and 240° and have zero values at angles of 90°, 180°, and 270°. The ratios are naturally equal to unity when β is zero. The maxima occurring at 120° and 240° are relatively small, in the limiting case, for very small antenna separations, they are equal to $\frac{1}{8}$ and for an antenna separation of one-quarter wave length they have the value .1913.

The general form of the selective characteristic is shown in Figure 3, in which polar coordinates are used, the angles measured from the reference direction $o\,x$ representing the angles β, and the radii from the centre o representing the intensities of the signal E. M. F.'s The dotted figure represents the selectivity corresponding to an antenna separation of one-quarter wave length, and the full line that for the limiting condition which is closely approximated for all antenna spacings of less than one-twelfth wave length. It is evident that a distinct advantage in respect to the relative amounts of signal and interference received, is to be gained by reducing the antenna separation, and although this is accompanied by a reduction of the signal strength, that loss may easily be made up by additional amplification.

It has already been pointed out that neutralization of the interference may be secured in other directions than that considered in the foregoing analysis, and it may happen in practice that the most troublesome interference may be that arriving from some other general direction. The simplicity of the phase control arrangements and the fact that the control can be exerted without disturbing the equality of the propagation constants of the two circuits, make it a very simple matter to secure the most efficient suppression of interference under any circumstances. All that it is necessary to do is to adjust the position of the secondary coil 16 of transformer 7 until the signal is heard with the least amount of interference. If the interfering waves are attenuated in traversing the space between the antennæ, a slight adjustment of the coupling of transformer 6 may be found effectual in obtaining clearer signals.

In the foregoing description it has been assumed that signal waves arrive from a fixed direction. In order to adapt the system to a condition of ready adjustability for reception of waves arriving from any point of the compass it has been found convenient to mount the loops 3 on a structure similar to a turn-table which is capable of 360° of rotation in a horizontal plane. The loops are preferably mounted equidistantly from the center of the turn-table. The plane of each loop is made parallel to a line joining the center of the loop and the central pivot of the turn-table. Inasmuch as the distance between loops needs to be in some instances no more than one-twelfth wave length, the turn-table, although somewhat large, may be of entirely practicable dimensions, for example 30 metres length in the case of a 360 metre wave.

In the system of Figure 2, the two antennæ are placed in the same vertical centre line, one being a simple loop 3, and the other a condenser antenna 21 which is tuned to resonance by a variable inductance 22. The antenna circuit E. M. F.'s, as in the system of Figure 1, are impressed upon demodulators 5, the outputs of which are delivered through transformer 23 to the selecting and detecting system 24 and finally to the telephone receiver 12. The system 24 performs the same functions as the circuit elements 20 and 11 of Figure 1, and comprises essentially similar apparatus. The auxiliary wave from the source 8 is delivered to the loop antenna circuit through variable coupling transformer 6 and to the condenser antenna circuit through a coupled intermediate tuned circuit 25 and a transformer 26. This simple arrangement is possible since the E. M. F.'s induced in the two antennæ are always in quadrature, and therefore require that the two auxiliary waves should also be in quadrature. The interposition of the tuned circuit 25 between the output circuit of source 8 and the antenna circuit produces the required phase difference.

The directional selectivity of this system may be determined by a similar procedure to that used in the analysis of the system of Figure 1; the difference between the two characteristics is due to the fact that the condenser aerial possesses no selectivity between horizontally propagated waves. The characteristic is represented by the polar diagram of Figure 4. The maximum signal is produced by waves propagated in the plane of the loop and the discrimination as to the sense

of this direction may be reversed by simply reversing the loop. Discrimination against interference from a specific direction may be secured by directing the plane of the loop towards the interfering source, the polarity of the loop being such that signals of that sense are suppressed. For complete suppression, the coupling of transformer 6 must also be varied so that the output E. M. F.'s of the demodulators are equalized.

The invention is not limited in its application to the specific systems illustrated but may be applied in a variety of ways limited only by the appended claims.

What is claimed is:

1. In a directive radio receiving system of the type in which electro-motive forces of different phases are produced in a plurality of receiving circuits from a space propagated wave and combined in a common signal circuit after separate demodulation with a common heterodyne wave, the combination with a plurality of wave receiving circuits of a source of heterodyne waves, a metallic circuit coupling said source to said circuits, and means included in said metallic circuit for independently adjusting the phase of the heterodyne waves in at least one of said wave circuits.

2. In a directive radio receiving system of the type in which electro-motive forces of different phases are produced in a plurality of receiving circuits from a space propagated wave and combined in a common signal circuit after separate demodulation with a common heterodyne wave, the combination with a plurality of spaced receiving circuits having equal damping and resonance, of a source of heterodyne waves, a metallic circuit coupling said source to said circuits, and means included in said metallic circuit for independently adjusting the phase of the heterodyne wave in at least one of said circuits.

3. In a directive radio receiving system of the type in which electro-motive forces of different phases are produced in a plurality of receiving circuits from a space propagated wave and combined in a common signal circuit after separate demodulation with a common heterodyne wave, the combination with a pair of tuned loop receiving circuits separated in space, of separate space discharge detectors operatively associated therewith, a heterodyne oscillator, a metallic circuit coupling said oscillator and said detectors, and means included in said coupling circuit for controlling the relative phases of the oscillations supplied to said detectors, said metallic circuit being coupled to said detectors in a high impedance circuit branch external to said tuned loops whereby the constants of said coupling circuit are ineffective to modify the damping of said loops.

4. In combination in a directive radio receiving system a plurality of wave receiving circuits adapted to produce from a space propagated wave electro-motive forces differing in phase, detecting devices individual to said circuits, a signal circuit connected in common to the output terminals of said detecting devices, a local heterodyne oscillator, a metallic circuit coupling said oscillator with said receiving circuits, and phase controlling means included in said metallic circuit to vary the phase of the heterodyne wave in one of said wave receiving circuits whereby the resultant beat current in said signal circuit produced from received waves is reduced to zero for waves propagated in at least one direction in space.

In witness whereof, I hereunto subscribe my name this 27th day of October, A. D. 1924.

HARALD TRAP FRIIS.