April 5, 1949. V. B. BAGNALL 2,466,354

DIRECTIONAL RADIO SYSTEM

Filed June 28, 1944

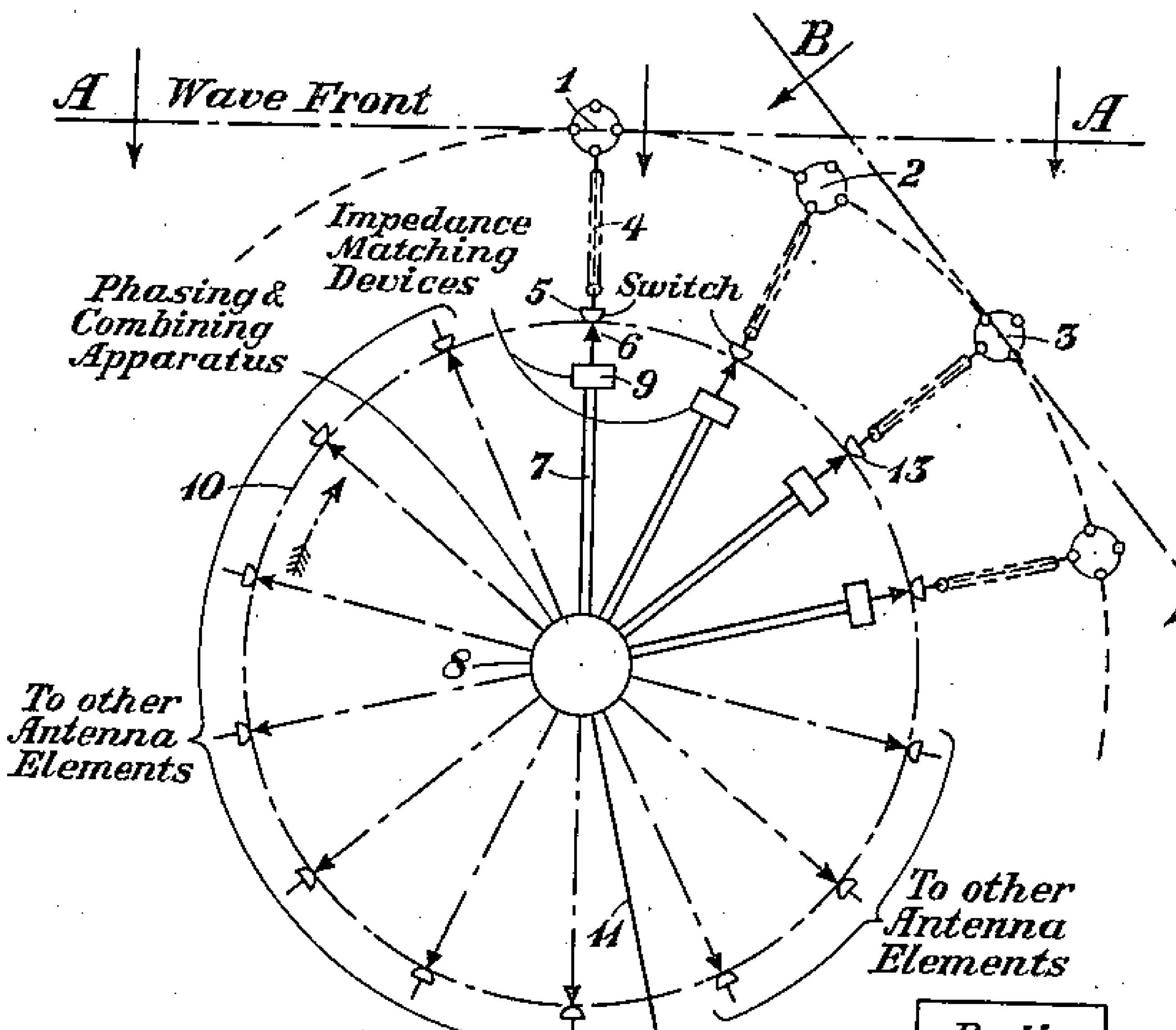

Fig. 1

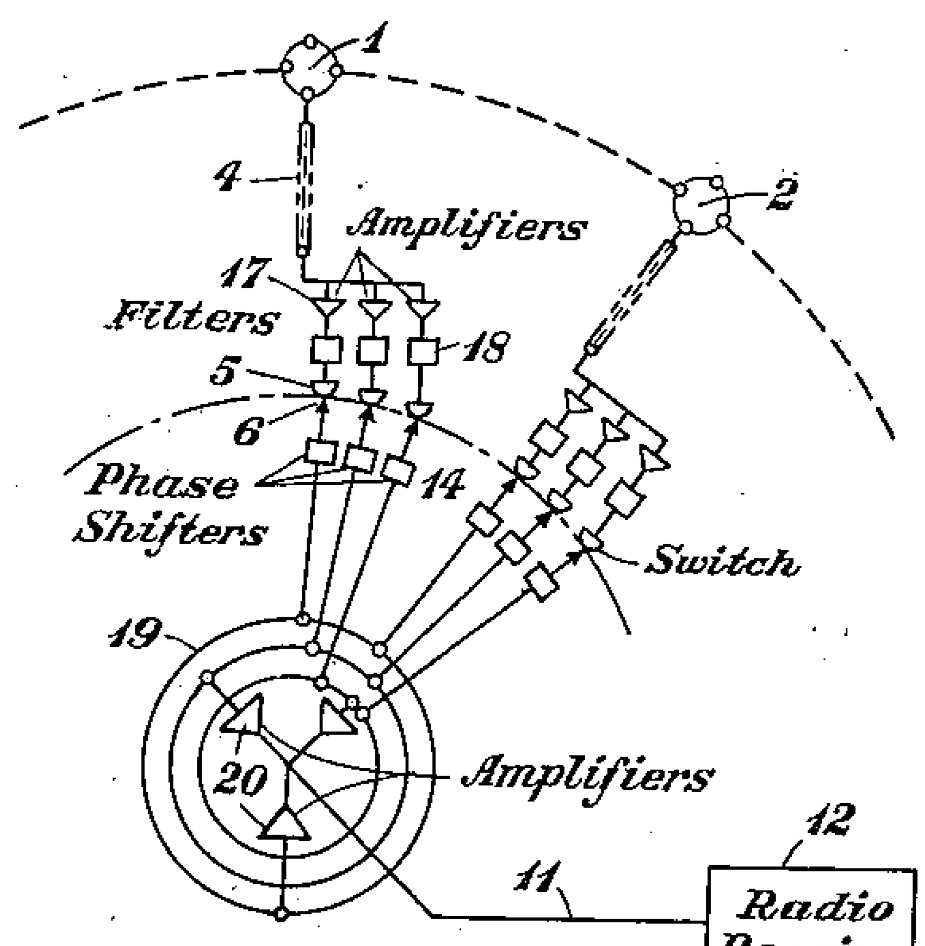

Fig. 4

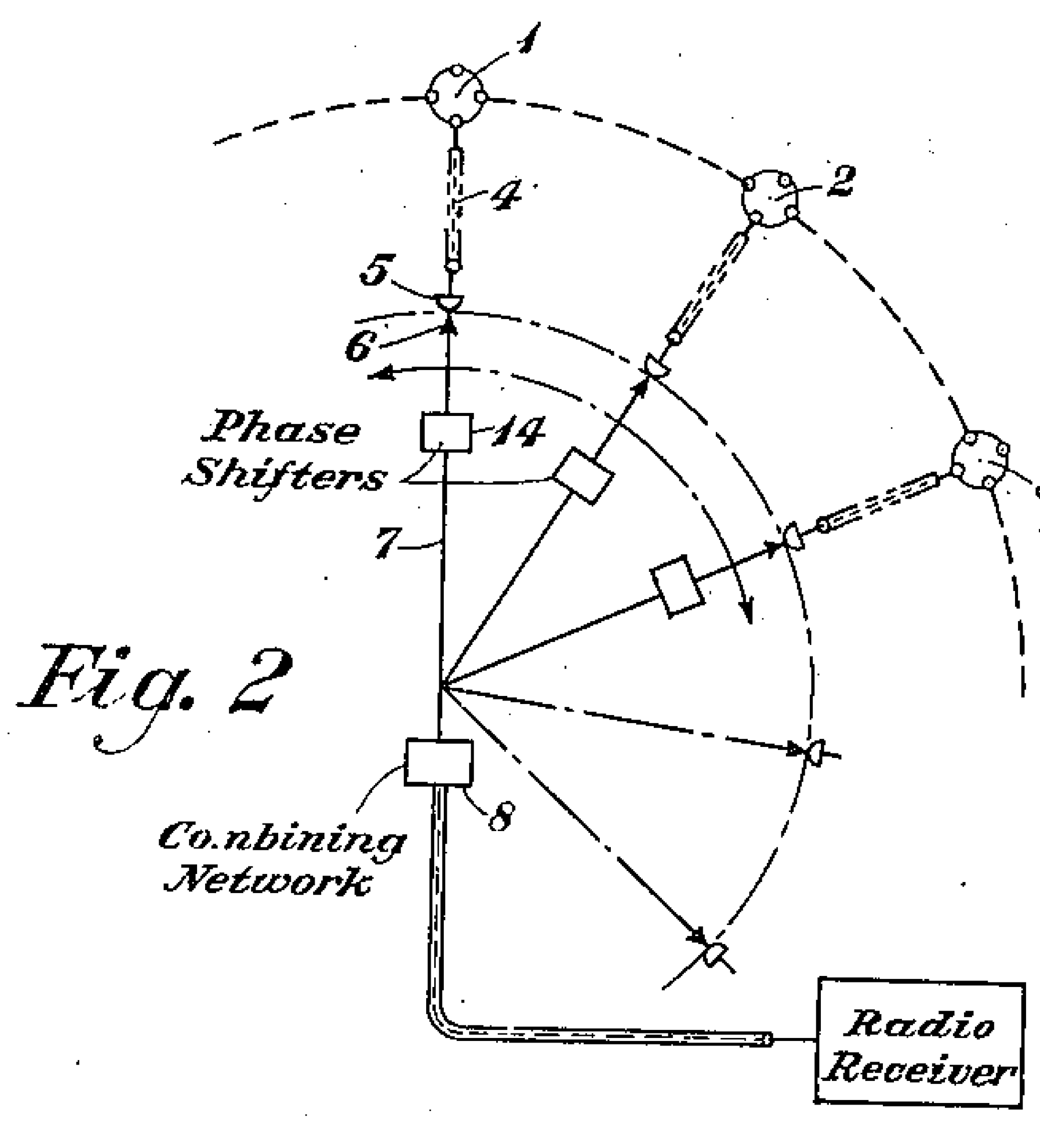

Fig. 2

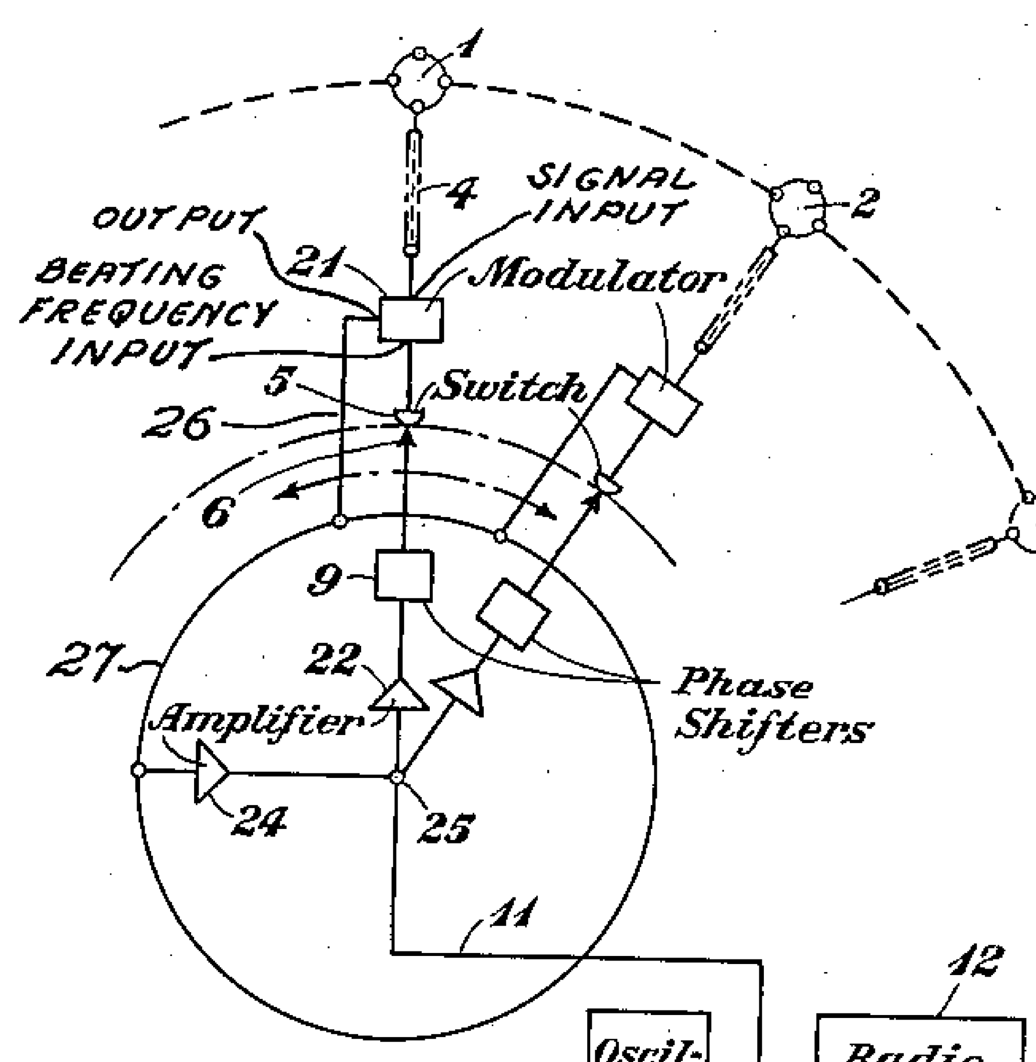

Fig. 5

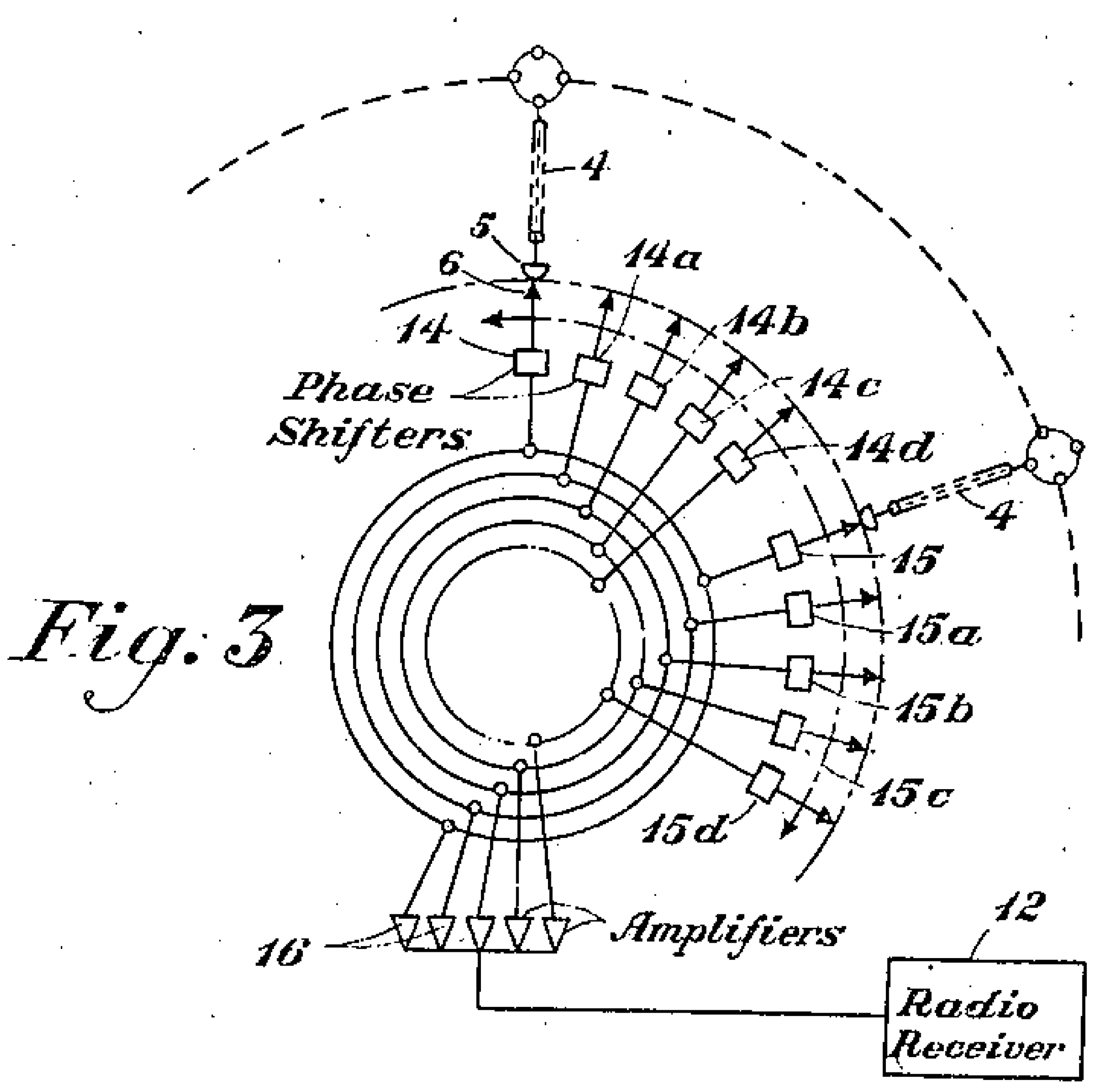

Fig. 3

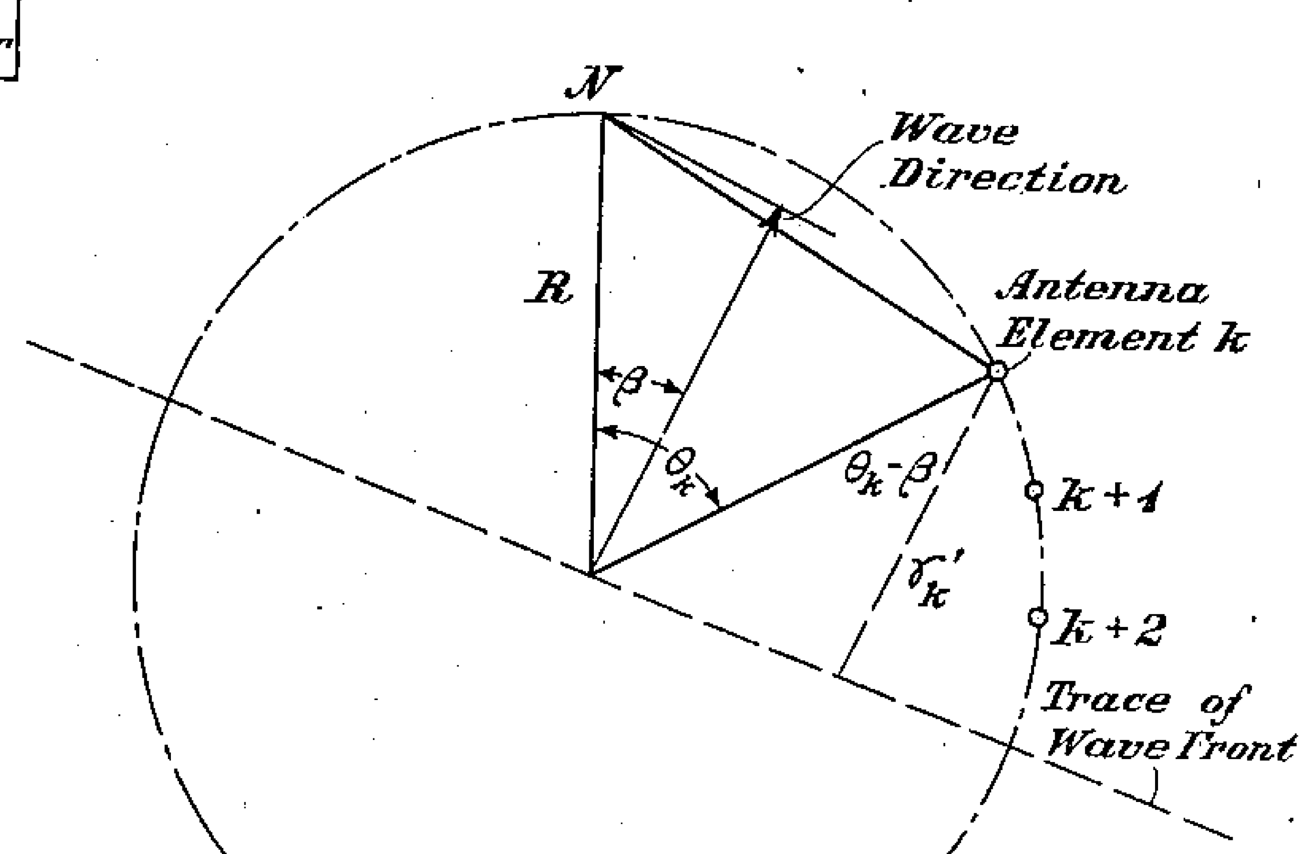

Fig. 6

INVENTOR

V. B. Bagnall

BY

John McGlone

ATTORNEY

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DIRECTIONAL RADIO SYSTEM

Vernon B. Bagnall, Arlington, Va., assignor to American Telephone and Telegraph Company, a corporation of New York

Application June 28, 1944, Serial No. 542,536

8 Claims. (Cl. 250—33.55)

This invention relates to a directional radio system for transmitting and receiving signals, and particularly to one in which a symmetrical antenna array may be steered effectively either in steps or continuously to obtain maximum directivity in any horizontal direction, and which is also capable of effecting an adjustment of the vertical directive pattern.

In the operation of radio services, the use of directive antennas for transmitting and receiving is highly desirable not only because of the improvement in performance attainable, but also because of economy in the power required. In the mobile services, such as ship-to-shore and aircraft-to-ground services, it is ordinarily practicable to employ antennas of the directive type only at the fixed stations. Owing to the somewhat limited power available on mobile units, and also owing to the relatively high noise level on such units, it is desirable that the transmitting and receiving antennas at the fixed stations shall have relatively high gain and also noise discrimination to effect satisfactory transmission with such mobile units. Those requirements, and the further requirement of obtaining directivity in any selected direction in which a mobile unit may be operating with respect to the fixed station, necessitates either the provision of a large number of fixed directive antennas whose directional characteristics are such as to provide a reasonable coverage in the zones in which the mobile units are operating or, on the other hand, means for rotating the entire antenna, including its physical supporting structure in order to provide the directional characteristic necessary at a particular instant of time. Both of those methods are undesirable from the standpoint of cost and the operating complications that would ensue.

This invention resides in a directional radio system employing a single antenna array which is capable of being steered effectively, either in steps or continuously, so as to obtain maximum directivity in any horizontal direction and in which the vertical directive pattern may also be adjusted. This invention is not only applicable to fixed stations in the mobile radio services where the distance and direction of transmission vary over wide limits, but is also desirable for forked radio services where a single transmitter or receiver is employed to operate with a plurality of other fixed stations at various distances and in various directions from the first mentioned station, and likewise from each other. A further application of this steerable antenna arrangement is that of direction finding.

The invention is also applicable for use in connection with the operation of long-haul radio circuits on which the waves are subject to large angular deviation from a mean value, both in the horizontal and vertical planes. The antenna array employed in the aforementioned services, might be used alone or as an antenna element in a Musa array meaning a multiple unit steerable antenna system which is fully described in the Bell Laboratories Record, vol. XVI, No. 5 (January 1938), pages 148 to 156, and No. 6 (February 1938), pages 203 to 207.

This invention will be fully understood from the following description when read in connection with the attached drawing, of which Figure 1 shows schematically the embodiment of the invention in its most general form; Fig. 2 shows diagrammatically an arrangement of the phase shifting devices; Fig. 3 shows an arrangement in which the steering may be effected in smaller steps than in the arrangements previously shown; Fig. 4 shows the adaptation of the invention to a system employing a plurality of frequencies simultaneously; Fig. 5 shows means to enable the phase shifting to be done at a lower frequency by employing a modulator and an oscillator to beat down the received frequency; and Fig. 6 shows the method of proportioning a receiving or transmitting system in which this invention is embodied.

The antenna array of Fig. 1 comprises a plurality of identical antenna elements 1, 2, 3, etc. arranged in symmetrical form about a center as, for example, on the circumference of a circle and are equidistantly spaced thereon. The antenna element may be of any type having a circularly symmetric horizontal characteristic such as a simple vertical antenna, multi-element vertical antenna and vertical cage antenna. The antenna element 1 is connected by the transmission line 4 to the fixed contact point 5 of a switch and each of the other antenna elements 2, 3, etc. is similarly connected. The transmission lines are preferably, but not necessarily, of the coaxial type and should be of equal length; and each line terminates in a contact point, such as 5, which is intended to engage the other contact points, such as 6. The contact point 6 is connected by the transmission line 7 to a phasing and combining arrangement 8 at the center of the array, the connection including an impedance-matching device 9 to match the impedance of the circuits looking in both directions from the device 9. Each of the other contacts, similar to 6, is similarly connected to the phasing and combining apparatus 8, and each connection includes an impedance-matching device similar to 9. The circuits extending from the contacts such as 6 to the phasing and combining apparatus 8 are fixedly mounted upon a disk or turn-table represented symbolically by the dot and dash circle 10, and therefore are moved as a unit whenever the disk is rotated. In view of the unitary arrangement of the circuits upon the disk 10 it is obvious that if the disk is rotated so as to bring the movable contact point 6 into contact with a fixed contact point other than 5, the phasing networks, which form part of the phasing and combining apparatus 8 would be connected in the same relative manner to the antenna elements after rotation of the disk as they were prior to such rotation. This automatically ensures the proper phasing of the currents from the several antennas to produce an additive effect in the phasing and combining apparatus 8, whenever a change occurs in direction of the wave front of the received waves. The phasing and combining arrangement 8 is connected by the transmission line 11 to the radio receiver 12. The manner in which the arrangement shown in Fig. 1 functions in order to accomplish the purpose of the invention is as follows:

Let it be assumed that the position of the wave front of the approaching wave is as represented by the dot and dash line A—A and is moving in the direction indicated by the arrows. The voltages set up in the antenna elements 1, 2, 3, etc. which differ in phase will be transmitted to the phasing and combining apparatus 8 and the resultant voltage will be transmitted over the transmission line 11 to the receiver 12. In the arrangement shown, the distances from the center of the disk 10 to all of the antenna elements are equal, and, as hereinbefore stated, the impedance-matching devices 9 serve to match the impedance looking toward the antenna elements and the impedance looking toward the radio receiver. When the phasing has been once adjusted for a symmetrical antenna array for a particular direction of approach of the wave front, as represented by the line A—A, the system may be readily adjusted for maximum reception of waves coming from another direction, as represented by the line B—B by merely rotating the disk so as to bring the movable contact point 6 into contact with the fixed contact point 13, connected to the antenna element 3. By that operation, the phasing network forming a part of the phasing and combining apparatus 8, which formerly was connected by the transmission line 7 to the antenna element 1, is, after rotation of the disk, connected by the same transmission line to the antenna element 3 which has the same angular position with respect to the wave front B—B as antenna element 1 had with respect to the wave front A—A. In like manner the phasing networks which, prior to rotation of the disk were connected to other antenna elements symmetrically arranged with respect to element 1, will, after rotation of the disk, be connected to other antenna elements which have the same relative positions with respect to element 3. This means that, after rotation of the disk, the phasing networks will be connected to antenna elements that have the same (or substantially the same) angular position with respect to the latter wave front B—B as they had, prior to rotation, with respect to the former wave front A—A. Then the voltage waves set up in the various antenna elements by the waves whose front is represented by B—B will produce the same additive effect in phasing and combining arrangement 8 as when the wave front had the position represented by the line A—A.

Figs. 2 to 6 illustrate various ways in which the phase adjustments may be made and the outputs combined. In Fig. 2, in which the same numerals have been used to represent parts similar to those shown in Fig. 1, the movable contact point 6 is connected to a combining network 8 by the conductor 7, the connection including a phase shifter 14. Similar phase shifters are inserted in the connections between the other movable contact points and the combining network. Each phase shifter has the characteristic necessary to make the total phase delay from each antenna element equal for a wave arriving in the desired horizontal and vertical directions. The phase shifters may consist of suitable electrical networks, or they may be transmission lines having the required lengths to effect the necessary phase delay for the voltage wave of the antenna with which they may be connected, as described in my copending application, Serial No. 542,537, filed June 28, 1944, which issued as Patent No. 2,432,134. The use of an actual transmission line as the phase-adjusting device is desirable not only because of simplicity, but also because it possesses the desirable characteristic that the required line length for phase adjustment is independent of the operating frequency, so that, when adjusted for any frequency the phase compensation will be correct for any other frequency. With the arrangement of Fig. 2, steering in the horizontal direction may be accomplished in angular steps by mechanically rotating the fixed phase adjusters as a unit with respect to the antenna elements. The directive pattern of the array may be steered horizontally in steps corresponding to the angular separation between the antenna elements through a complete circle of 360 degrees.

The sharpness of the major lobe of the directive characteristic of an antenna of the type contemplated increases as the ratio of the array radius to the operating wave-length increases, and also as the number of antenna elements is increased. Thus, for a given number of antenna elements the angular width of the major lobe of the directive pattern decreases as the size of the array is increased. If a high degree of directivity is required in the major lobe and is obtained by increasing the size of the array in proportion to the wave-length without increasing the number of elements a point may be reached where the antenna directivity is too great for the angular steps in which the array is steered thus resulting in substantial decrease in effectiveness of the array at intermediate angles between the angular steps to which the array can be steered. To compensate for this variation in effective gain versus angle between steps, intermediate phase-adjusting networks 14*a*—14*d* may be used as indicated in Fig. 3. In this manner and by proper choice of array size and number of elements any required degree of uniformity in gain over a required angular range can be obtained for arrays having any required maximum directivity. With the arrangement shown in Fig. 3 the outputs from each group of phase shifters are combined through amplifiers 16 as indicated, thus isolating each group of phase shifters.

In the aforedescribed arrangement the vertical plane characteristic of the directive pattern of the array is fixed with reference to the horizontal plane characteristic by the design and adjustment of the phasing arrangement therein shown. However, in the manner similar to that shown in Fig. 3 intermediate or auxiliary phase-adjusting networks may be provided to steer the directive characteristics in the vertical plane in steps as desired. In that manner the array may be controllably steered in finite steps over the full range of horizontal and vertical angles of 360 degrees and 90 degrees, respectively.

Fig. 4 shows in simplified form an arrangement by which the directional characteristics may be adjusted for each of a plurality of frequencies. In this arrangement the transmission line 4 is connected to a plurality of amplifiers 17, the output of each of which is connected to a filter such as 18. The filters are in turn connected to a fixed contact point 5 of switching contacts. The movable contact points 6 are connected through the phase shifters 14 to the bus-bars 19, which bus-bars are connected through the amplifiers 20 to the line 11 leading to the radio receiver 12. The phased outputs of the phase shifters 14 are combined after passing through the amplifiers 20 and the combined results are impressed upon the radio receiver.

Fig. 5 shows a form of invention in which the received frequency is beaten down to a lower frequency before being impressed upon the phase shifting network. In that figure the antenna element 1, one of a plurality of similar elements, is connected by the transmission line 4 to the input side of the modulator 21. The beating frequency is supplied to the modulator 21 by the oscillator 25 over a circuit that includes conductor 11, amplifier 22, phase shifter 9, terminals 5 and 6 of the switch and the modulator 21. The lower frequency, resulting from the beating operation, passes to the output of the modulator 21 which is connected by conductors 26 and 27 to the amplifier 24, which is in turn connected to the line 11 extending to the radio receiver 12. Other antenna elements would be connected to the junction point 25 by a circuit similar to that by which the antenna element 1 is so connected. The voltage wave, set up in the antenna elements such as 1, would be impressed upon the modulator 21 upon which are also impressed oscillations of the beating frequency transmitted from the oscillator 23 over the line 11 and through the amplifier 22, the phase shifter 9 and the terminals 5 and 6 of the switching contact. The resultant intermediate frequency will be impressed upon the input side of the amplifier 24, together with the currents of the same intermediate frequency from other modulators connected to other antenna elements similar to 1. The combined currents, as amplified by 24, would then be transmitted over the line 11 to the radio receiver 12 wherein they would be detected by oscillations of the frequency of the oscillator 23. In the arrangement shown in Fig. 5, the phase shifter 9 acts upon the beating frequency of the oscillator 23, and thus controls the phase relationship of the output currents of the plurality of modulators, each of which is individual to an antenna element. By reversing the terminals of the amplifiers 22 and 24, and likewise reversing the connection of those amplifiers to the input and the output terminals of the modulator 11, the beating frequency would then be conveyed from the oscillator 23 over a path that includes the line 11, amplifier 24, the input terminals of the modulator 21, and the output of that modulator would be transmitted to the radio receiver 12 over a path that includes the phase shifter 9, the amplifier 22 and the line 11. In the latter arrangement the shift of phase is made upon the modulated output current instead of upon the current of the beating frequency, from the oscillator 23, as occurs with the amplifiers arranged as shown in Fig. 5.

The directional characteristic of an array, the magnitude of the output current and the necessary phase adjustment may be determined in the following manner:

In Fig. 6 one form of antenna array of the type contemplated having symmetry about a central point is shown diagrammatically. In this array N antenna elements are arranged with equal spacing on the circumference of a circle having a radius R. If the center of the array is considered as the reference point for phases and the outputs from the separate antenna elements are combined in parallel after transmission through lines of equal length R or equal phase shift the output current at the angular frequency ω corresponding to the wave-length λ can be represented by the expression

$$I=K\sin\omega t\left|\sum_{k=1}^{N}A_k e^{-j\frac{2\pi}{\lambda}(R-r_k)}\right| \qquad (1)$$

for an impressed plane wave as indicated in Fig. 6. The notation in the above and following equations is as follows:

N=number of equally spaced elements comprising array.
R=radius of array circle.
k=element of array $k=1 \ldots N$.
β=horizontal wave angle measured clockwise from radius vector through N.
δ=vertical wave length measured from plane of array.
θ_k=horizontal angle subtended by element k.
rk'=distance in plane of array from element k to plane of wave front.
r_k=perpendicular projection of element k on plane of wave.
A_k=amplitude factor of element k.
B=horizontal wave angle at which maximum is desired.
Δ=vertical wave angle at which maximum is desired.
K=proportionality factor.

From the geometry of Fig. 6 the following relation holds:

$$r_k=R\cos(\theta_k-\beta)\cos\delta \qquad (2)$$

where

$$\theta_k=\frac{2\pi k}{N} \qquad (3)$$

Using this relation and Equation 1 the combined output current of the array is

$$I=K\sin\omega t\left|\sum_{k=1}^{N}A_k e^{-j\frac{2\pi R}{\lambda}[1-\cos(\theta_k-\beta)\cos\delta]}\right| \qquad (4)$$

To make all elements add in phase for

$$\beta=\mathrm{B} \text{ and } \delta=\Delta$$

artificial phase shift may be added to each branch in the amount

$$\phi_k=\frac{2\pi R}{\lambda}[1+\cos(\theta_k-\mathrm{B})\cos\Delta] \qquad (5)$$

or the phase shift may be added by providing additional transmission line of the appropriate length in each branch of the array at a point ahead of the combining junction. The required line length is given by

$$L_k'=R[1+\cos(\theta_k-B)\cos\Delta]\frac{V}{V_0} \qquad (6)$$

where V/V_0 is the ratio of phase velocity in the transmission line to the velocity of light. It should be noted that the length of line required in each branch is independent of the frequency.

With these phase adjustments the output current may be represented by

$$I=K\sin\omega t\left|\sum_{k=1}^{N}A_k e^{+ju_k}\right| \qquad (7)$$

where

$$u_k=\frac{-2\pi R}{\lambda}[\cos(\theta_k-B)\cos\Delta-\cos(\theta_k-\beta)\cos\delta] \qquad (8)$$

Equation 7 can be reduced to the form

$$I=K\sin\omega t\left|\sqrt{\left(\sum_{k=1}^{N}A_k\cos u_k\right)^2+\left(\sum_{k=1}^{N}A_k\sin u_k\right)^2}\right| \qquad (9)$$

for computational purposes.

Equation 9, together with Equation 8 gives the complete directional characteristic of a circular array consisting of any number antenna elements phased to obtain maximum directivity in the direction $\beta=B$ and $\delta=\Delta$.

If the array consists of an even number of elements such that $N=2M$ and if the elements are considered as doublets with paired elements K and $K+M$, and if the following relations are satisfied

$$A_{k+m}=A_k$$
$$\theta_{k+M}=\theta_k+\pi$$
$$u_k=-u_{k+M}$$

Then for this special case Equation 9 reduces to

$$I=K\sin\omega t\left|\sum_{k=1}^{M}2A_k\cos u_k\right| \qquad (10)$$

Equation 10, together with Equation 8 gives the complete directional characteristics of a circular array consisting of M doublets phased to obtain maximum directivity in the direction

$$\beta=B \text{ and } \delta=\Delta$$

Although this invention has been described in connection with its function to receive radio waves for subsequent impression upon a radio receiver, it is to be understood that such description is purely illustrative of the structure and the mode of functioning of the invention, but does not constitute a limitation upon it since it is equally applicable for use in connection with a radio transmitter. The sole change necessary to effect such a difference in functioning would be merely an interchange of the connections of the apparatus to provide for the difference in direction of flow of the currents between the elements of the antenna array and the translating device, that is, a radio receiver or radio transmitter.

While this invention has been disclosed as embodied in particular forms and arrangements of parts, it is not so limited since it is capable of embodiment in other and different forms without departing from the spirit and scope of the appended claims.

What is claimed is:

1. In a directional radio system, the combination with a plurality of antennas spaced equidistantly apart upon the circumference of a circle, of a translating device intended for simultaneous connection to all of the said antennas, means to connect the said device to all of the said antennas, the said connecting means including phase-shifting means adjusted to bring into phase the currents from all antennas, and means operable at will, to simultaneously rotate all of the said connecting means and establish a connection between said translating device and the antennas of the said array to automatically adjust the said system for optimum reception for different angles of approach of the wave front.

2. In a directional radio system, the combination with an antenna array comprising a plurality of antennas spaced equidistantly apart upon the circumference of a circle, of a radio transmitter or receiver intended for connection to all of the said antennas and means to connect the said transmitter or receiver to the said antennas, the said connecting means comprising a plurality of branches each being designed to automatically effect the necessary phase adjustment of the voltage waves set up in its branch to ensure the optimum transmission or reception of the radio waves transmitted or received by the said antenna array.

3. In a directional radio system, the combination with an antenna array comprising a plurality of antennas spaced equidistantly apart upon the circumference of a circule, of a radio translating device and a plurality of means to simultaneously couple the said device to all antennas of the said antenna array, each of said coupling means being designed and proportioned to effect such phase adjustment of the voltage wave being conducted thereover, that the combined effect upon the said translating device of all such voltage waves from all of the said antennas shall be a maximum for radio waves impressed upon the said array from any given direction, and means to simultaneously rotate all of said coupling means whenever the wave front of the radio waves approaches the array from a different direction whereby each of said means will connect said device with another of said antennas, thereby automatically adjusting the said system for maximum effect regardless of the direction of approach of the said radio waves.

4. In a directional radio system, the combination with a plurality of antennas spaced equidistantly apart upon the circumference of a circle, a translating device intended for simultaneous connection to all of the said antennas, means comprising a plurality of branches to connect the said device to all of the said antennas for the transmission of radio waves therefrom, each branch of the said connecting means including phase-shifting means to adjust the phase of the currents set up in the antennas so that the radiations therefrom will produce a cumulative effect in a given direction, and means to simultaneously rotate all of the branches of the said connecting means and establish a different connection between said translating device and the antennas of the said array in order to automatically adjust the said system for optimum reception or transmission for different angles of approach of the wave front.

5. In a directional radio system, the combination with an antenna array comprising a plurality of antennas spaced equidistantly apart upon the circumference of a circle, of a radio transmitting device and a plurality of means to couple the said device to the said antenna array, each of said coupling means being designed

and proportioned to effect such phase adjustment of the voltage wave being conducted thereover, that the effect of all such voltage waves upon their respective antennas shall be such as to produce maximum radiation in any given direction, and means to simultaneously rotate all of said coupling means and to connect each of them to another of said antennas without changing the sequence of the said connections, thereby automatically adjusting the said system for maximum effect regardless of the direction of transmission of the said radio waves.

6. In a directional radio system, the combination with an antenna array comprising a plurality of antennas of a radio receiver, means to couple the said receiver to the said array, the said coupling means comprising a combining network and a plurality of phase controlling circuits each extending from the said network to one of said antennas, each of said circuits having a switching contact to effect connection to an antenna and also means to adjust the phase of the voltage wave set up in each circuit by the antenna to which the said circuit may then be connected so that the voltage waves in all of said circuits will produce the maximum effect in the combining network when the wave-front of the radio waves makes a given angle with a given axis of the antenna array, and means to simultaneously rotate all of the said phase controlling circuits so as to connect each such circuit to another antenna to automatically produce maximum reception for a different angle of wave-front of the radio waves.

7. In a directional radio system, the combination with a circular antenna array comprising a plurality of antennas of a radio receiver, means to couple the said receiver to each of said antennas, the said coupling means comprising a combining network and a plurality of phase controlling circuits each connecting the said network to one of said antennas, the said circuits

being so adjusted as to produce the maximum effect in the combining network for a radio wave approaching the said array from a given direction, and means to simultaneously rotate all of the said phase controlling circuits and to connect each to another antenna without altering the sequence of the said phase controlling circuits, thereby ensuring maximum receptivity for a radio wave approaching the said array from another direction.

8. In a directional radio system the combination with an antenna array comprising a plurality of pairs of antennas arranged oppositely and symmetrically about a central point, means to apply current to all of the pairs of the said antennas, the said means being adapted to control the phase and amplitude of the currents in the several antennas whereby the directional characteristic may be controlled, and means to alter at will the said characteristic by simultaneously changing the connections of the said means to the said antennas, in accordance with a fixed plan.

VERNON B. BAGNALL.

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