

April 3, 1962

R. L. MATTINGLY

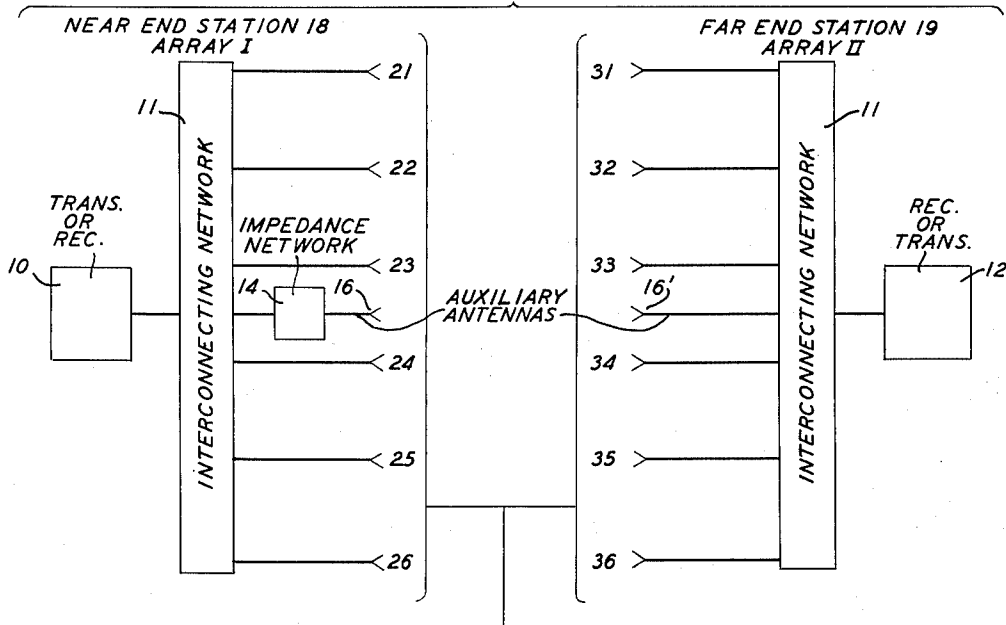
3,028,591

DIRECTIVE ANTENNA SYSTEMS

Filed Dec. 29, 1958

7 Sheets-Sheet 1

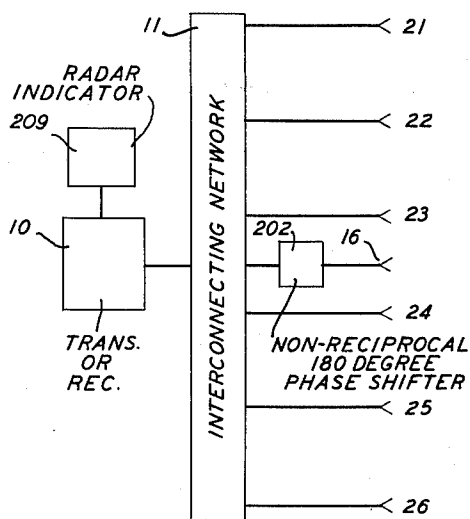
FIG. 1



DIRECTIONAL ANTENNA ARRAYS I & II
EACH COMPRISING SIX (21 THRU 26 AND 31 THRU 36) RESPECTIVELY,
OMNI-DIRECTIONAL EQUALLY SPACED ANTENNAS

FIG. 1A

NEAR END STATION



INVENTOR
R. L. MATTINGLY

BY *H. O. Wright*
ATTORNEY

April 3, 1962

R. L. MATTINGLY

3,028,591

DIRECTIVE ANTENNA SYSTEMS

Filed Dec. 29, 1958

7 Sheets-Sheet 2

FIG. 2

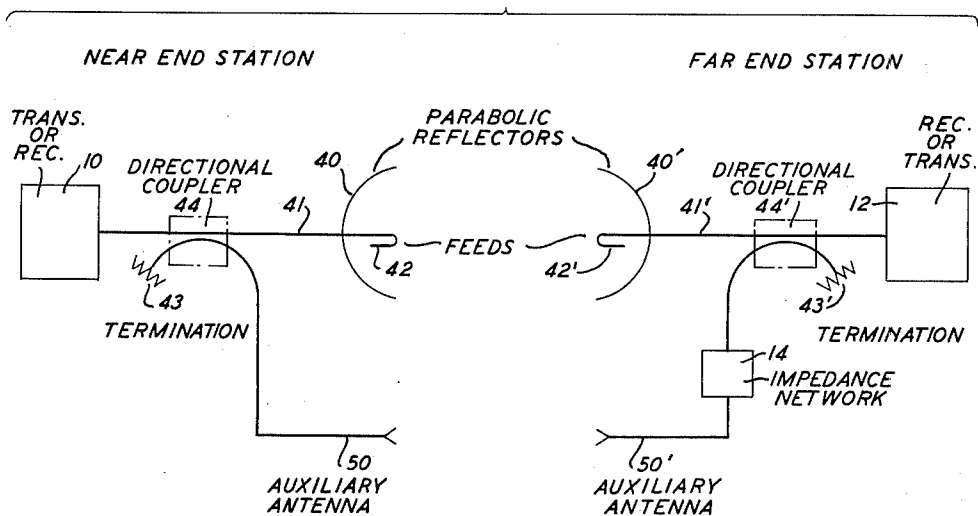
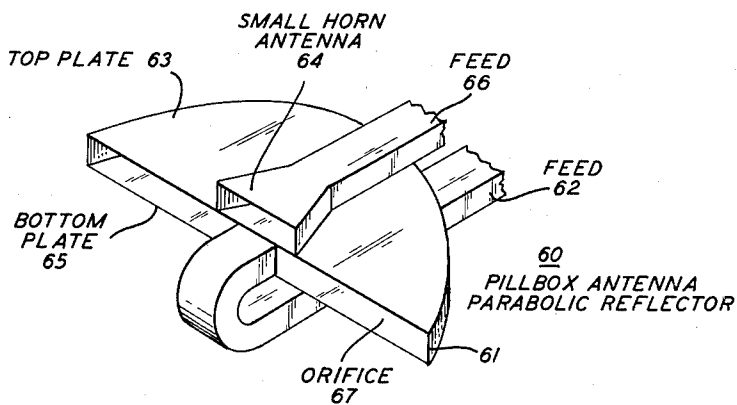


FIG. 3



INVENTOR
R. L. MATTINGLY

BY *H. O. Wright*
ATTORNEY

April 3, 1962

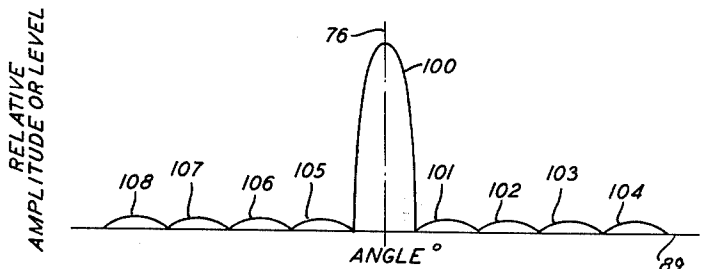
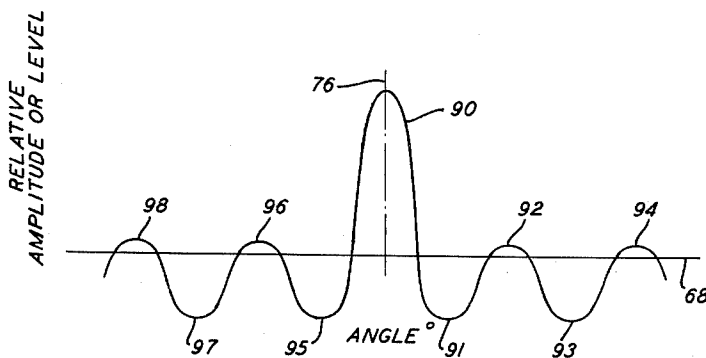
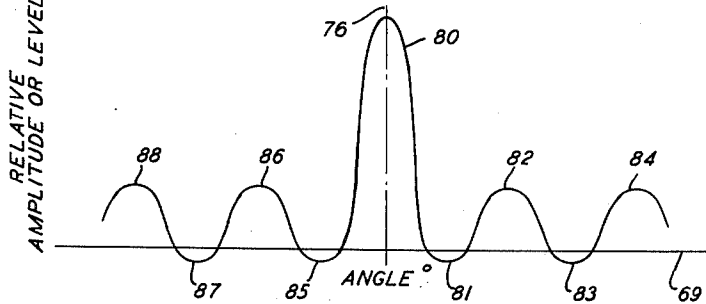
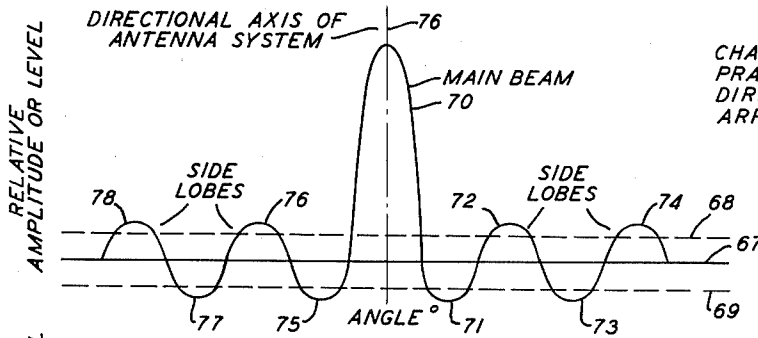
R. L. MATTINGLY

3,028,591

DIRECTIVE ANTENNA SYSTEMS

Filed Dec. 29, 1958

7 Sheets-Sheet 3



INVENTOR
R. L. MATTINGLY

BY *H. O. Wright*
ATTORNEY

April 3, 1962

R. L. MATTINGLY
DIRECTIVE ANTENNA SYSTEMS

3,028,591

Filed Dec. 29, 1958

7 Sheets-Sheet 4

RELATIVE
AMPLITUDE OR LEVEL

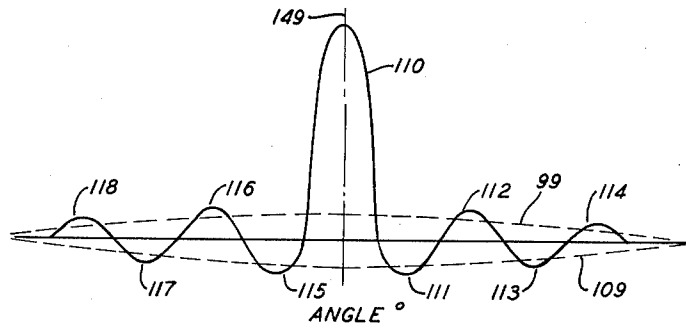


FIG. 5A

RELATIVE
AMPLITUDE OR LEVEL

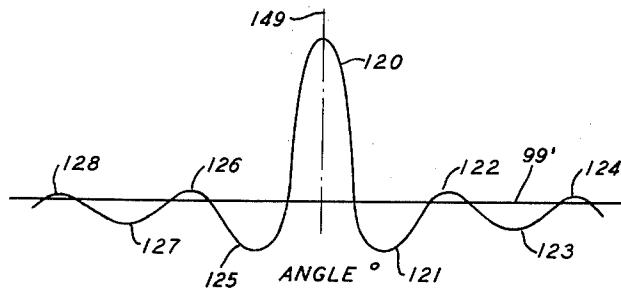


FIG. 5B

RELATIVE
AMPLITUDE OR LEVEL

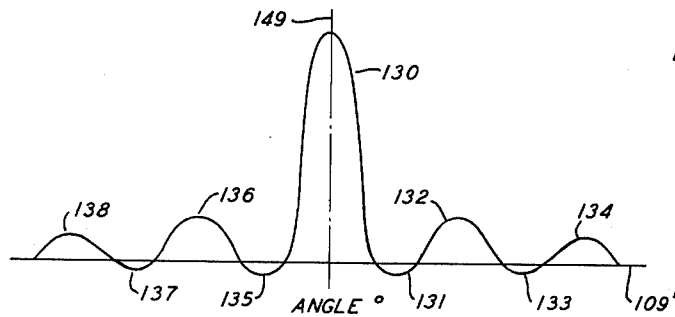


FIG. 5C

RELATIVE
AMPLITUDE OR LEVEL

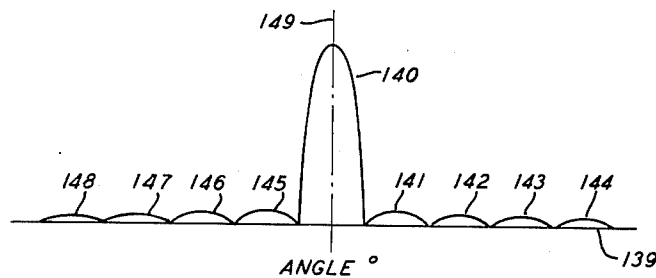


FIG. 5D

INVENTOR
R. L. MATTINGLY

BY *H. D. Wright*
ATTORNEY

April 3, 1962

R. L. MATTINGLY

3,028,591

DIRECTIVE ANTENNA SYSTEMS

Filed Dec. 29, 1958

7 Sheets-Sheet 5

FIG. 6

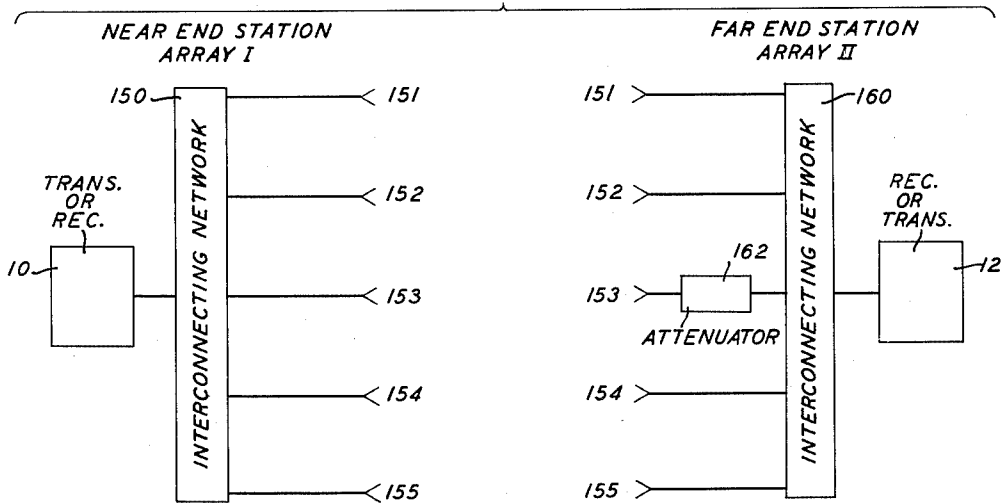
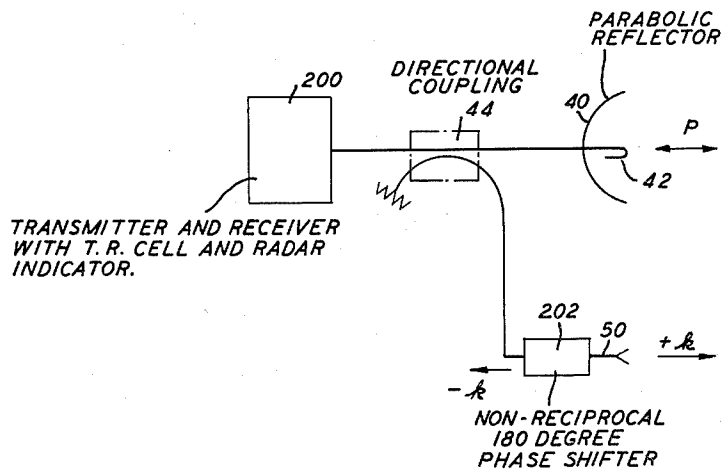


FIG. 7



INVENTOR
R. L. MATTINGLY

BY *H. O. Wright*
ATTORNEY

April 3, 1962

R. L. MATTINGLY
DIRECTIVE ANTENNA SYSTEMS

3,028,591

Filed Dec. 29, 1958

7 Sheets-Sheet 6

FIG. 8

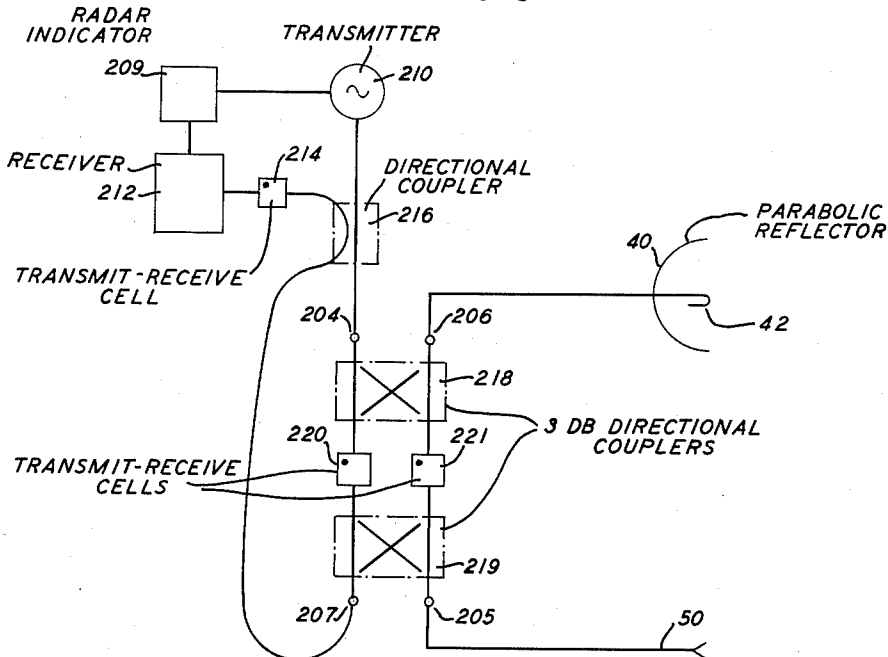
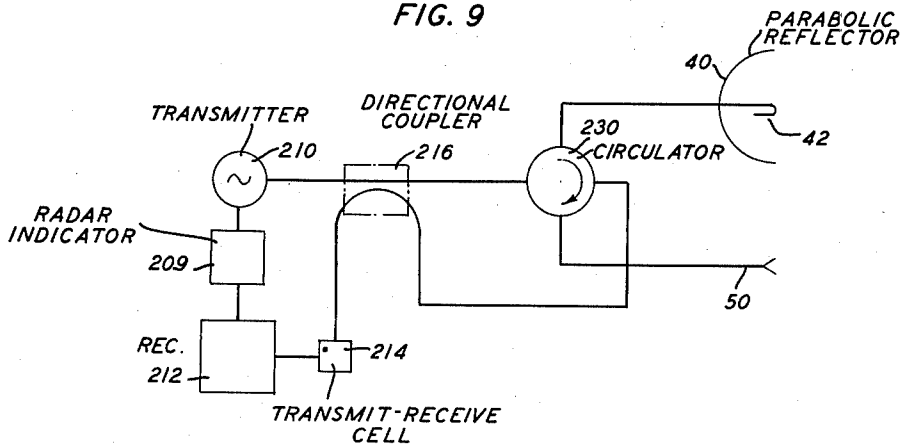


FIG. 9



INVENTOR
R. L. MATTINGLY

BY *H. D. Wright*
ATTORNEY

April 3, 1962

R. L. MATTINGLY

3,028,591

DIRECTIVE ANTENNA SYSTEMS

Filed Dec. 29, 1958

7 Sheets-Sheet 7

FIG. 10

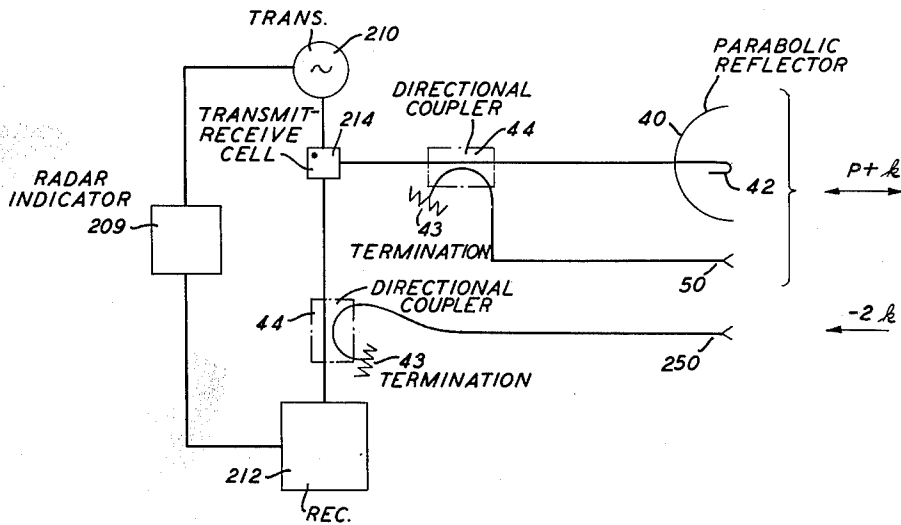
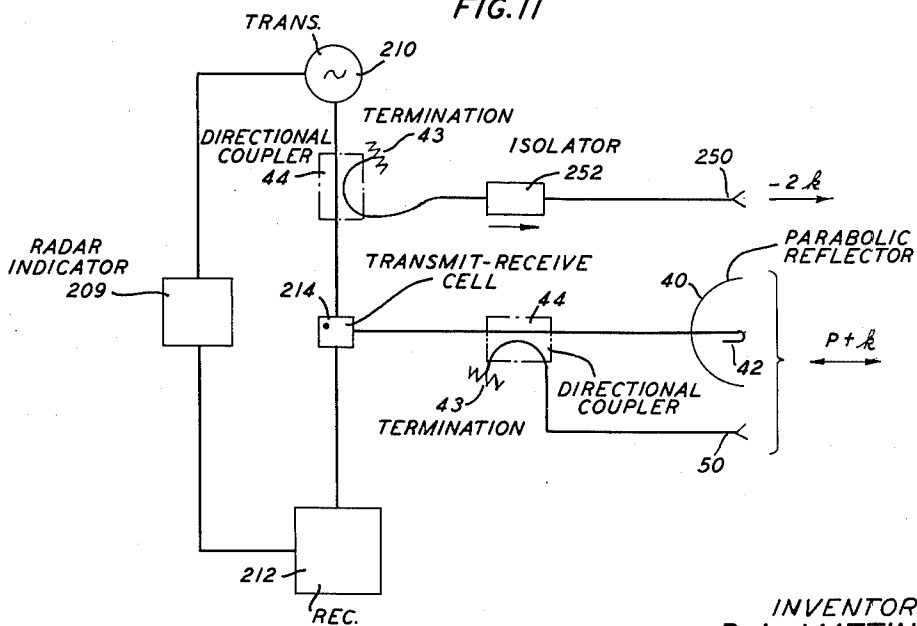


FIG. 11



INVENTOR
R. L. MATTINGLY

BY *H. O. Wright*
ATTORNEY

1

3,028,591

DIRECTIVE ANTENNA SYSTEMS

Robert L. Mattingly, Morristown, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York
Filed Dec. 29, 1958, Ser. No. 783,598
10 Claims. (Cl. 343-5)

This invention relates to directive systems for transmitting and receiving radiant energy. More particularly, it relates to highly directive antenna systems for use in systems of the above-mentioned types.

Much time, effort and treasure have been expended over a period of many decades in devising radiant energy emitting and receiving arrangements to the end that such arrangements shall have the greatest possible degree of directivity (i.e., they shall emit a main beam sharply defined within a narrow angle of radiation) and the least possible transmission by the inevitable "minor lobe" characteristics of the emitting and receiving "antenna" arrangements. These "minor lobes" or "side lobes" represent, as is well known to those skilled in the art, transmitting and receiving properties at reduced levels and at numerous angles other than that of the intended direction of transmission or reception. The latter direction should of course be coincident with the direction of the axis of the main beam of the directive antenna system.

In practice, a "practical optimum" design of any particular antenna system is usually selected which for a predetermined investment of material, labor and maintenance will provide the optimum in directivity with satisfactorily small minor lobe characteristics. In some cases, for example, somewhat less directivity may be deemed acceptable in order to make possible a further reduction of the level of the minor lobes, or vice versa.

The principal forms of radiant energy employed for such purposes are nonvisible electromagnetic wave energy commonly referred to as "radio wave" energy and acoustic or sound wave energy. Acoustic wave energy may be either audible (relatively low frequencies) or ultrasonic (relatively high or super-audible frequencies). Occasional systems have also been devised which employ visible electromagnetic wave energy (light) or infrared wave energy (heat) and possibly other types of radiant energy.

In general, it has heretofore been assumed that if both the transmitting and receiving antennas are made substantially identical and each is as highly directive and has as small "minor lobes" as the economic factors of the particular situation warrant, the "practical optimum" over-all antenna characteristic for the transmission system will be obtained.

The present invention proposes as its principal object the improvement from the standpoints of enhanced directivity and reduced minor or side lobe characteristics of the effective over-all antenna characteristic of a transmission system as compared with that obtainable by the use of identical transmitting and receiving antennas of the "practical optimum" type.

The arrangements of the present invention are based upon the fact well known to those skilled in the art that the over-all antenna characteristic of a radiant energy transmitting and receiving system is dependent upon the product of the transmitting and receiving antenna characteristics. Accordingly, by introducing predetermined complementary differences between the heretofore assumed "practical optimum" individual antenna characteristic and the individual transmitting and receiving antenna characteristics, respectively, of a system of the invention, applicant is able to realize a substantially improved over-all antenna characteristic for the system.

2

The above-mentioned complementary differences are, in accordance with some arrangements of the invention, readily introduced by combining a small, low-power, wide-angle, auxiliary antenna, which in general will have only moderate directivity or in some instances will be omnidirectional, with a prior art narrow-angle, sharp beam-type, "practical optimum" antenna to comprise the transmitting antenna and employing a similar combination for the receiving antenna of the system, the radiation of each auxiliary antenna being appropriately adjusted in phase and amplitude as will be described in detail hereinafter.

While the auxiliary antenna, in any specific case, causes the characteristic of the individual transmitting or receiving antenna with which it is employed to differ somewhat from the characteristic heretofore considered to be the "practical optimum" for that specific case, the product of the transmitting and receiving antenna characteristics is substantially improved from the standpoints of enhanced directivity and low minor or side lobe characteristics with respect to the product of the two unmodified identical prior art "practical optimum" antenna characteristics.

For reflection types of radar and sonar systems it is, of course, the usual practice to employ the same antenna for both transmitting the exploratory energy and for receiving reflections of the transmitted energy to determine the direction and distance of objects within the range of the system.

As will be described in more detail hereinafter, for such radar or sonar systems the principles of the invention can be applied in a number of ways. In one such arrangement, for example, a single, small, low-power, wide-angle, auxiliary antenna is employed in combination with a prior art, narrow-angle, sharp beam-type, "practical optimum" antenna. The auxiliary antenna is then interconnected with the principal antenna through a "nonreciprocal" circuit arrangement of such character that the appropriate complementary differences between the transmitting and receiving characteristics of the antenna combination are realized. The interconnecting circuit arrangement may be nonreciprocal with respect to the direction in which energy passes through it. By way of specific examples, it may be a "nonreciprocal phase shifter" or a "circulator." Alternatively, it may be nonreciprocal with respect to the amplitude level of the signal energy. For specific example, it may employ the well known "transmit-receive box" which may, for example, freely pass low level signals but effectively block high level signals.

Other and further features, objects and advantages of the invention will be more readily perceived from a perusal of the following detailed descriptions of specific illustrative embodiments of various and sundry principles of the invention and as well from the appended claims and the illustrative drawings accompanying this application.

In the drawings:

FIG. 1 illustrates in diagrammatic form a specific over-all transmitting and receiving system embodying the principles of the invention;

FIG. 1A illustrates a modification of an arrangement included in the system of FIG. 1;

FIG. 2 illustrates in diagrammatic form another specific over-all transmitting and receiving system embodying the principles of the invention;

FIG. 3 illustrates one specific combination of microwave antennas suitable for use in a system of the type illustrated in FIG. 2;

FIG. 4A is a curve illustrating the characteristic of one form of a "practical optimum" antenna array of the prior art;

FIG. 4B is a curve illustrating one modification of the characteristic illustrated in FIG. 4A suitable for use in systems of the invention;

FIG. 4C is a curve illustrating a second modification of the characteristic illustrated in FIG. 4A, suitable for use in systems of the invention to complement the modified characteristic illustrated in FIG. 4B;

FIG. 4D is a curve illustrating the over-all antenna characteristic of a complete system of the invention employing two antenna arrays (or two distinctive conditions of one array) having respectively the modified characteristic of FIG. 4B and the complementarily modified characteristic of FIG. 4C, one being employed to transmit while the other is employed to receive, and vice versa;

FIG. 5A is a curve illustrating the characteristic of a second form of a "practical optimum" antenna array of the prior art;

FIG. 5B is a curve illustrating one modification of the characteristic illustrated in FIG. 5A suitable for use in systems of the invention;

FIG. 5C is a curve illustrating a second modification of the characteristic illustrated in FIG. 5A, suitable for use in systems of the invention to complement the modified characteristic illustrated in FIG. 5B;

FIG. 5D is a curve illustrating the over-all antenna characteristic of a complete system of the invention employing two antenna systems (or two distinctive conditions of one system) having respectively the modified characteristic of FIG. 5B and the complementarily modified characteristic of FIG. 5C, one being employed to transmit while the other is employed to receive, and vice versa;

FIG. 6 illustrates in diagrammatic form a further specific over-all transmitting and receiving system employing antenna arrays and embodying certain principles of the invention;

FIG. 7 illustrates in diagrammatic form a still further specific system of the invention employing a nonreciprocal phase shifter;

FIG. 8 illustrates in diagrammatic form a system of the invention employing transmit-receive cells to obtain "nonreciprocal" effects;

FIG. 9 illustrates in diagrammatic form a system of the invention employing a circulator to obtain nonreciprocal effects;

FIG. 10 illustrates in diagrammatic form a system of the invention employing two auxiliary antennas to obtain nonreciprocal effects; and

FIG. 11 illustrates in diagrammatic form a second system of the general type illustrated in FIG. 10.

Throughout the various figures of the drawings the same designation number will be applied to a specific unit in every figure in which it is included.

In more detail, in FIG. 1 an over-all transmission system of the invention is diagrammatically illustrated. It comprises two stations separated by an appreciable distance and designated respectively, for convenient reference, as the "Near End Station" 18, comprising the apparatus within the dashline enclosure on the right of the figure and the "Far End Station" 19, comprising the apparatus within the dashline enclosure on the opposite side of the figure.

In general, the descriptions to be given throughout the application will be more directly applicable to radio transmission systems but it will be immediately apparent to those skilled in the art that corresponding systems employing sonic energy or heat energy or the like can be readily devised to embody the principles of the invention in substantially the same manner.

In FIG. 1, block 10 is designated "Transmitter or Receiver" and block 12 is designated "Receiver or Transmitter." It is to be understood that, in accordance with conventional communication practice, when the near end station is transmitting the far end station is receiving and vice versa. Accordingly, blocks 10 and 12 may each preferably include both transmitting and receiving apparatus interconnected to their respective antenna arrays I and II

by appropriate switching arrangements such as "transmit-receive boxes" (or cells), numerous forms of which are so well known to and extensively used by those skilled in the art as to require no detailed description here. For the purposes of the present invention it is obviously sufficient to consider either direction of transmission since the antenna characteristic of the over-all system is the same for both directions.

At the near end station a so-called "broadside array antenna" designated array I and comprising six equally spaced, nondirectional radiating elements 21 through 26, inclusive, is connected to the unit 10 through a connecting network 11 of any of the numerous and varied types well known and extensively used by those skilled in the art to control the distribution of the energy to the several radiators and the phase of the energy at each radiator. The antenna array I may, by way of a specific example which lends itself readily to a lucid explanation of the principles of the invention, be designed and constructed as taught by C. L. Dolph, in an article entitled "A Current Distribution for Broadside Arrays Which Optimizes the Relationship Between Beam Width and Side-Lobe Level," published in the Proceedings of the Institute of Radio Engineers for June 1946, pages 335 through 344. Dolph's arrays will give for each individual antenna array minimum beam width (or beam angle) in the intended direction of transmission (i.e. maximum directivity) for minor or side lobes of an equal predetermined satisfactorily low level. The main-beam and side-lobe pattern for such an array, i.e. the individual antenna array characteristic, will be of the general type illustrated, by way of specific example, in FIG. 4A of the accompanying drawings. It comprises a main beam 70 with a plurality of side lobes on each side of the main beam represented in part by side lobes 71 through 74 on its right and side lobes 75 through 78 on its left, the side lobes all being of substantially the same level and being regularly distributed and alternately in phase and 180 degrees out of phase on each side of the main beam 70, as illustrated. The side lobes below axis 67 are out of phase and those above axis 67 are in phase with the main beam 70. Axis 67 is the median between the maxima of the in-phase and out-of-phase minor (or side) lobes.

Similarly, at the far end station 19, array II comprising the six radiators 31 through 36, inclusive, and interconnecting network 11 may be identical with array I of the near end station 18 as described in detail above.

Associated with each of the arrays I and II is an auxiliary antenna designated 16 for array I and 16' for array II. The auxiliary antennas are located at substantially the center point of their respective associated directive arrays. For a Dolph type array they are omnidirectional (frequently referred to as nondirectional), and are designed to radiate or receive at a level somewhat less than the level of the side lobes of their associated arrays, as will presently be explained in detail.

Each auxiliary antenna is connected to network 11 in such manner that its radiation (ignoring network 14 for the moment) is in phase with the radiation of its associated array.

One of the auxiliary antennas 16' is connected directly to its associated network 11. The other of the auxiliary antennas 16 is connected to its associated network 11 through an impedance network 14 as shown in FIG. 1. Impedance network 14, for reasons which will presently become apparent, may be a reciprocal phase shifting network introducing a phase shift of 180 degrees for both directions of transmission, with negligible attenuation. Alternatively, the interconnecting network 11 at the near end station can obviously be modified to introduce a phase shift of 180 degrees in the energy provided to auxiliary antenna 16, in which case the added network 14 should of course be omitted.

The effect of adding the nondirectional radiation characteristic (substantially constant in all directions) of ele-

5

ment 16' in phase with that of the Dolph type directional array II (beam 70 and lobes 71 to 78, inclusive) is, in effect, to lower the axis of the directional pattern of FIG. 4A, for example, to the dashline 69 of FIG. 4A. The combination then has the modified characteristic of FIG. 4B comprising main lobe 80, and side lobes 81 through 88, inclusive, the positive (or in-phase) even numbered side lobes now having a substantially increased amplitude or level and the negative odd numbered side lobes now having a substantially decreased amplitude or level.

Similarly, in adding the nondirectional radiation characteristic of element 16, rendered out of phase by the 180 degree phase shift of network 14, with respect to that of the directional array I, the effect is to raise the axis of the Dolph type directional pattern of FIG. 4A, for example, to the dashline 68. The combination then has the complementarily modified characteristic of FIG. 4C, comprising main lobe 90 and side lobes 91 through 98, inclusive, the negative odd numbered lobes being of increased and the even numbered lobes being of correspondingly decreased amplitude or level.

The over-all transmitting-receiving antenna characteristic for the system diagrammatically illustrated in FIG. 1 is then the product of the modified characteristic of FIG. 4B and the complementarily modified characteristic of FIG. 4C, this product being illustrated in FIG. 4D.

In FIG. 4D the main beam 100 will have a slightly lower level than main beam 70 of FIG. 4A and a somewhat reduced angular width (substantially equal to the angular width of lobe 90 of FIG. 4C at its axis 68). The side lobes of FIG. 4D, namely lobes 101 through 108, will be of substantially equal amplitude or level and will, for suitably proportioned auxiliary antenna versus main antenna characteristics, be of substantially reduced level with respect to the level of the side lobes of the product pattern of the two main antennas alone.

It can be shown mathematically, for example, that if the amplitude or level of the nondirectional radiation of each of the auxiliary antennas 16 and 16' of FIG. 1 is made .707 times the amplitude or level of the side lobes 71 through 78, inclusive, of FIG. 4A, the side lobes of the product pattern of FIG. 4D, namely lobes 101 through 108, inclusive, will be reduced to one-half the amplitude of the lobes of the product pattern of the two main antennas alone.

Accordingly, it is apparent that by the method described in detail above the angular width of the main lobe of the product pattern can be decreased (i.e. its directivity can be increased) and the amplitude of the side lobes of the product pattern can be cut to one-half that of the side lobes of a "practical optimum" directive antenna.

The mathematical basis for the principles of the invention can be demonstrated in very elementary form in the following way. If P represents a function of the angle of propagation, i.e. if it represents the "transmission pattern" of a "practical optimum" directional antenna (such, for example, as main beam 70 and side lobes 71 through 78 about axes 76 and 67 of FIG. 4A), a system using two identical antennas of this type, one for transmitting and the other for receiving, will have an over-all antenna characteristic P^2 . Now if like auxiliary nondirectional antennas having identical patterns k are added to each "practical optimum" antenna, one auxiliary antenna being in phase and the other out of phase with its associated "practical optimum" antenna (represented for example by dashlines 68 and 69, respectively of FIG. 4A), the combination patterns are $P+k$, and $P-k$, respectively (corresponding to those of FIGS. 4B and 4C, respectively). Then, the over-all antenna characteristic of the system employing one combination for transmitting and the other for receiving is the product of $(P+k)$ times $(P-k)$ which is (P^2-k^2) (corresponding to that of FIG. 4D).

Where k is made .707 (i.e. one-half the square root of two) times the amplitude (that is, one-half the power) of

6

the minor or side lobes of the "practical optimum" antenna, the net result is to slightly reduce the amplitude of the main beam, to decrease the angular width of the main beam (by from 10 to 15 degrees in a typical case, thus correspondingly increasing the directivity of the system) and to reduce the level of the side lobes of the product pattern to one-half that of the minor or side lobes of the product pattern of two "practical optimum" antennas.

Smaller values of k down to 0.5 or even less will produce an appreciable reduction in the over-all or product pattern minor lobes, with respect to those of the product pattern of two practical optimum antennas. Similarly, larger values of k up to 0.85 or larger will also produce an appreciable reduction in the level of the minor or side lobes of the product pattern.

In FIG. 1A a single station adapted for both transmitting and receiving is illustrated diagrammatically. It may be identical with the near end station of FIG. 1 as described in detail above except for the radar indicator 10' which has been added and except that the reciprocal impedance network 14 of FIG. 1 is replaced in FIG. 1A by a nonreciprocal 180 degree phase shifter 202. Phase shifter 202, as its name implies, products 180 degrees more phase shift for energy passing through it in one direction than for energy passing through it in the opposite direction.

Numerous varieties of such nonreciprocal phase shifters are well known and extensively used by those skilled in the art. Reference may be had, for example, to C. L. Hogan's article on "The Ferromagnetic Faraday Effect at Microwave Frequencies and Its Applications—The Microwave Gyrator," published in the Bell System Technical Journal, volume 31, No. 1, for January 1952, pages 1 through 31, inclusive, and to numerous other well known articles and patents, such as, for example, Patent 2,760,166 granted August 21, 1956, to A. G. Fox.

Phase shifter 202 is adjusted so that for one direction of the energy passing through it, as for example, when energy is transmitted from unit 10 to the antenna radiators 21 through 26, inclusive, and to auxiliary radiator 16, the phase of the energy emitted by auxiliary radiator 16 will be the same as that of the main beam of the array comprising radiators 21 through 26, inclusive. In the opposite direction (i.e. when receiving energy) then, the energy reaching the receiver of unit 10 from radiator 16 will, by virtue of the nonreciprocal phase shift property of element 202, be 180 degrees out of phase with that reaching the receiver from the arrays 21 through 26, inclusive. It is, accordingly, apparent that for the case assumed above, the antenna system of FIG. 1A comprising the combined antennas (i.e. arrays 21 through 26, inclusive, and radiator 16) will have the characteristic illustrated in FIG. 4C for transmitting energy and the characteristic illustrated in FIG. 4B for receiving energy. When used as a reflection type radar system the over-all antenna characteristic is therefore obviously that of FIG. 4D.

If a second station identical in every respect to that of FIG. 1A (but both stations omitting the radar indicator 10') is employed as a distant station oriented to receive from and transmit to the first station in accordance with FIG. 1A, the over-all antenna characteristic of the two stations for each direction of transmission will also be that of FIG. 4D. When two or more stations of the type illustrated in FIG. 1A are employed, as described immediately above, for conventional communication purposes it is obvious that the radar indicator 10' should, as suggested above, be omitted from all of the stations.

When it is desired to employ a single station as illustrated in FIG. 1A as a radar system, then a radar indicator 10' of any of the numerous and varied types well known and extensively used in the art should of course be interconnected in conventional manner with the transmitter and receiver unit 10 to provide radar indications of the desired type. The over-all transmitting-receiving antenna characteristic of a station, as illustrated in FIG. 1A,

adapted to function as a radar system will, as stated above, be substantially as illustrated in FIG. 4D.

For conventional communication purposes, the use of two or more stations such as that illustrated in FIG. 1A, but omitting radar indicator 10', has the advantage over systems of the type illustrated in FIG. 1 that all of the stations can be identical, whereas in the system of FIG. 1 the impedance network 14 is employed by only one of each two stations between which communication is to be established, thus limiting the combinations of two stations which can intercommunicate with the benefits of the enhanced directional properties and reduced minor lobes of the present invention.

Considering now the system of the invention illustrated diagrammatically in FIG. 2, the apparatus to the left side of the figure represents one station, designated for convenience the "near end station" and the apparatus to the right side of the figure represents a second station designated the "far end station," the two stations representing a system for transmitting intelligence between two points separated by an appreciable distance. Units 10 and 12 can be as described above for the correspondingly numbered units of FIG. 1.

The main, highly directive, narrow-angle, beam-type antennas 40, 40' of FIG. 2 may be of any of the numerous well known reflector types having associated feeds 42 and 42', respectively, which may be also of conventional type.

The auxiliary antennas 50 and 50' are smaller antennas having only slightly directive (i.e., "wide-angle") characteristics as will be explained in more detail presently.

Feed 42 is connected to unit 10 via line 41 including therein a path through the directional coupler 44, one terminal of which is connected to termination 43.

Similarly, feed 42' is connected to unit 12 via line 41' including therein a path through the directional coupler 44', one terminal of which is connected to termination 43'.

Auxiliary antenna 50 is connected through directional coupler 44 to unit 10 and auxiliary antenna 50' is connected through impedance network 14 and directional coupler 44' to unit 12. Network 14 may be as described above in connection with FIG. 1.

Physically, auxiliary antennas 50 and 50' should be located at or as near as practicable to the center of the main directive antennas with which they are associated, respectively. They are shown to one side in the diagrammatic illustration of FIG. 2 solely to avoid a confusing intermingling of their circuits with those of their associated main antennas. One appropriate specific physical arrangement for the combination of an auxiliary antenna and a main antenna suitable for use in the system of FIG. 2 is shown, by way of example, in FIG. 3 and will be described in detail hereinafter.

The "directional couplers" 44 and 44' and their respective associated terminations 43 and 43' are employed in the system of FIG. 2 primarily as "power dividers" to appropriately limit the amount of power directed to the auxiliary antenna when transmitting and the amount of power reaching the receiver from the auxiliary antenna when the station is receiving.

The antenna characteristics pertinent to the operation of the system of FIG. 2 are exemplified by the curves of FIGS. 5A through 5D inclusive.

Assume, for purposes of illustration, that the main antennas 40, 40', of FIG. 2 each have characteristics of the general type illustrated in FIG. 5A comprising the narrow-angle, main beam 110 and minor or side lobes 111 through 118, inclusive. This characteristic obviously differs from that of FIG. 4A for a "Dolph type" antenna array in that the level of the side lobes decreases appreciably with angular deviation from the axis 149 of the main beam.

However, a curved dashline 99 can be drawn in FIG. 5A so as to pass through each in-phase or positive minor

lobe at a level, for example, of .707 times its maximum level. Similarly, a second curved dashline 109 can be drawn through each out-of-phase or negative minor lobe at a level of .707 times its maximum level.

Curved line 99 then represents the radiation pattern which should be contributed by the wide-angle, auxiliary antenna 50' which contributes out-of-phase radiation or reception with respect to its associated main antenna. Similarly, curved line 109 represents the radiation pattern which should be contributed by the wide-angle, auxiliary antenna 50 and is in phase with its associated main antenna. The auxiliary antennas 50 and 50', then, should have low level slightly directive (wide-angle) radiation patterns, the curvatures of their radiation characteristics being tailored to fit the progressively decreasing levels of the minor or side lobe patterns of their respective main antennas as indicated above.

If line 99 is conceived of as being straightened out carrying the main beam and minor or side lobe patterns of FIG. 5A with it, the result is line 99' of FIG. 5B and main beam 120 with minor or side lobes 121 through 128, inclusive.

Similarly, if curved line 109 of FIG. 5A is conceived of as being straightened out carrying the main beam and side lobes with it, the result is line 109' of FIG. 5C and main beam 130 with side lobes 131 through 138, inclusive.

FIG. 5B then represents the characteristic of main antenna 40' combined with auxiliary antenna 50' and, similarly, FIG. 5C represents the characteristic of main antenna 40 combined with auxiliary antenna 50.

Finally, the product of the characteristics of FIGS. 5B and 5C is the over-all transmitting-receiving antenna characteristic of the system of FIG. 2 and is shown in FIG. 5D. This over-all characteristic of FIG. 5D comprises main beam 140 and minor or side lobes 141 through 148, inclusive. Side lobes 141 through 148 will be of half the amplitude or level of the corresponding lobes of the product pattern of the main antennas only.

In FIG. 3, one specific form of a combination of a main antenna and an auxiliary antenna suitable for use at each of the near end and far end stations of FIG. 2 is illustrated.

The combination of FIG. 3 comprises a main antenna 60 which may be of the well known and extensively used "pill-box" type comprising a parabolically curved reflecting metallic member 61 with upper and lower plane metallic members 63, 65, defining a rectangular radiating orifice 67. Energy is fed to or collected from the "pill-box" antenna just described by wave guide feed 62 which passes under the antenna and has an end curving up and back to face into the pill-box from a central position with respect to orifice 67, as shown.

The auxiliary antenna comprises a small horn antenna 64 fed by a wave guide 66, the small horn 64 being supported on the upper plate 63 of the pill-box antenna 60 and aligned with the center line of plate 63. Its orifice is centered with and in the same plane as orifice 67. An antenna combination of the type just described has been constructed and found to possess a characteristic closely resembling that of FIG. 5B, when the horn and pill-box were energized out of phase, and that of FIG. 5C, when the horn and pill-box were energized in phase, thus indicating that the auxiliary horn 64 introduced substantially the compensating characteristics represented by curves 99 and 109, respectively, of FIG. 5A and that horn 64 was sufficiently close to the actual center point of the orifice 67 of the main antenna 60 to provide and over-all antenna characteristic (transmitting and receiving) substantially as illustrated in FIG. 5D.

It is apparent from the above detailed description of the system represented diagrammatically in FIG. 2 that the principles of the invention are readily applicable to effect the described improvements of the over-all antenna characteristic of a transmitting-receiving system in which the minor or side lobes of the main, highly directive an-

tennas vary in substantially any regular manner about the axis of the main beam.

In FIG. 6 a system similar to that illustrated in FIG. 1 is shown in diagrammatic form but differs from that of FIG. 1 in that each antenna array (near end and far end) consists of an odd number of individual antennas 151 through 155, inclusive, with one individual antenna 153 being centrally located in its associated array. In such a case, assuming by way of specific example that a "Dolph type" array (see hereinabove) is being employed and that therefore antenna characteristics of the type illustrated by FIGS. 4A through 4D are applicable, to obtain the additional nondirectional radiation from the center of the array as required to obtain the characteristic of FIG. 4B, it is only necessary to appropriately increase the radiation or reception from the centrally located individual radiator 153 (near end station).

This can be readily effected by designing network 150 to direct an appropriately increased amount of energy to the radiator from unit 10 and from radiator 153 to unit 10. Similarly, at the far end station, to appropriately decrease the radiation or reception from the centrally located radiator 153, it is only necessary to insert an attenuator 162 as shown in FIG. 6. Alternatively, interconnecting network 160 can be modified to effect the appropriate reduction in the energy received from or radiated by the central radiator 153 at the far end station.

In FIG. 6, therefore, the fact that the antenna arrays each have a centrally located radiator can be taken advantage of by appropriately adjusting the relative level of the energy radiated by or received from the centrally located radiator to obtain virtually the same effects as are obtained by the auxiliary antennas and their associated circuits in the system illustrated in FIG. 1.

In FIG. 7 a further form of system of the invention, the antenna system of which obviously closely resembles that of the near end station of FIG. 2 except for the addition of the nonreciprocal 180 degree phase shifter 202 in the electrical circuit interconnecting the auxiliary antenna 50 and the directional coupler 44, is shown.

The system of FIG. 7 of course bears the same relation to the near end station of FIG. 2 as the system of FIG. 1A has to the near end station of FIG. 1. The system of FIG. 7 differs from that of FIG. 1A only in the forms of main and auxiliary antennas employed.

In transmitting, directional coupler 44 directs the appropriate amount of the transmitted energy to auxiliary antenna 50 through nonreciprocal phase shifter 202, the over-all circuit arrangements being proportioned so that the radiated energy contributed by antenna 50 is in phase with the energy radiated by the main antenna 40.

In receiving, nonreciprocal phase shifter 202 reverses the phase of the energy received by antenna 50. The over-all effect is that in transmitting the over-all characteristic of the two antennas is $P+k$ and in receiving it is $P-k$, P being the characteristic of antenna 40 and k being the characteristic of antenna 50, the complementary and over-all characteristics of the antenna system being substantially as illustrated in FIGS. 5B, 5C, and 5D, respectively.

Obviously, as for the system of FIG. 1A, the system of FIG. 7 can be used as a radar provided unit 200 includes a radar indicator appropriately associated with the transmitting and receiving equipment in unit 200 in accordance with conventional radar practice well known and extensively used in the art.

Alternatively, the system of FIG. 7 can function as a complete station of a transmission system comprising a plurality of identical other stations precisely as described above for the system of FIG. 1A.

In FIG. 8 a somewhat more complex transmitting-receiving system is illustrated diagrammatically which employs transmit-receive boxes (or cells) 220, 221 to effect the required reversal of phase between antennas

40, 42 and 50 for the transmitting and receiving conditions.

So-called "3DB directional couplers" 218 and 219, well known to those skilled in the art, are electrically connected on opposite sides of the transmit-receive cells 220, 221 as shown.

In transmitting, directional coupler 216 directs an appropriate amount of energy from transmitter 210 to terminal 207 (for antenna 50). Transmit-receive cell 214 breaks down protecting receiver 212 from the high level energy. Transmit-receive cells 220, 221 break down reflecting high level energy from transmitter 210 to terminal 206 and thus to the main antenna 40. In like manner the energy directed to terminal 207 is reflected by cells 220, 221 to terminal 205 and thus to auxiliary antenna 50. Assume that the circuit parameters are such that the energy radiated by the two antennas is in phase, then the transmitting characteristic of the two antennas is $P+k$.

In receiving, transmit-receive cells 220, 221 and 214 become conductive at the low energy levels of the received signals. The combination of the 3DB directional couplers then, as is well known and understood by those skilled in the art, interconnects terminals 204 and 205 and likewise interconnects terminals 206 and 207, thus reversing the phase relation between the energy received by main antenna 40 and that received by auxiliary antenna 50 as compared with their phase relation in transmitting. The effective receiving pattern of the combined antennas is accordingly $P-k$ and the over-all transmitting-receiving pattern of the system is again P^2-k^2 . Radar indicator 209, electrically interconnected with transmitter 210 and receiver 212, may then provide any of the conventional radar target displays if the system is employed as a radar system. Alternatively, the radar indicator can be omitted and the system can be employed with a plurality of identical systems for intercommunication as described above for the system of FIG. 1A.

A further alternative system of the invention is illustrated diagrammatically in FIG. 9 and employs circulator 230 to realize the effective reversal of phase between the antennas 40 and 50 with respect to transmission and reception. A common prior art form of circulator suitable for use in the system of FIG. 9 is disclosed and described in the above-mentioned paper by C. L. Hogan.

In transmitting, energy from transmitter 210 goes through the upper left quadrant of circulator 230 to the main antenna 40. An appropriately lesser amount of energy from transmitter 210 passes through directional coupler 216 and the lower right quadrant of circulator 230 to auxiliary antenna 50. Transmit-receive cell 214 protects receiver 212 from the high level transmitted energy. It will be assumed that the circuit parameters have been so chosen that these transmitting components of energy emerge from their respective antennas in phase whereby the combined characteristic of the two antennas is $P+k$.

In receiving, low level energy from antenna 50 passes through the lower left quadrant of circulator 230, directional coupler 216 and transmit-receive cell 214 to receiver 212. Energy from antenna 40 passes through the upper right quadrant of circulator 230, directional coupler 216 (lower path) and transmit-receive cell 214 to receiver 212 arriving in phase opposition to that from antenna 50. Accordingly, again the receiving characteristic of the two antennas is $P-k$ and the over-all antenna characteristic for both transmitting and receiving is P^2-k^2 . It is apparent that radar indicator 209 may be employed to provide any conventional type of radar indication desired, or that indicator 209 may be omitted and the system employed for communication purposes as described above for the system of FIG. 1A.

In FIGS. 10 and 11, circuit arrangements including two auxiliary antennas are employed, one of these auxiliary antennas being utilized both in transmitting and

receiving and the other being utilized for either receiving or transmitting only.

Except for isolator 252, all apparatus units in FIGS. 10 and 11 have been shown in one or more of the previously described circuit arrangements and may be identical with the correspondingly numbered units of those arrangements. Isolator 252 is, as its name implies, a device which will pass energy in the direction indicated by the arrow beneath it but will not pass energy in the opposite direction. It may take any of the numerous forms well known to those skilled in the art. Specific forms by way of example are shown in FIG. 8 of Patent 2,748,353 granted May 29, 1956, to C. L. Hogan and in Patent 2,802,184 granted August 6, 1957, to A. G. Fox.

More specifically, in the system of FIG. 10 the two antennas 40 and 50 are employed in both transmitting and receiving and their combined characteristics can be, by way of example, $P+k$ in which case the single or second auxiliary antenna employed only in receiving is designed to have the characteristic $-2k$. This results in a transmitting characteristic of $P+k$ and a receiving characteristic of $P-k$. The over-all antenna characteristic of the system for both transmitting and receiving is therefore again P^2-k^2 . When provided with radar indicator 209 the system of FIG. 10 can function as a radar system. Alternatively, unit 209 can be omitted and the system of FIG. 10 may be employed with a plurality of identical systems for communication purposes.

Similarly, in FIG. 11 the two antennas 40 and 50 have the combined characteristic $P+k$ and the second auxiliary antenna 250 employed only in transmitting may have the characteristic $-2k$. Accordingly, in transmission the combined characteristic of the three antennas is $P-k$. Again, the over-all transmitting and receiving antenna characteristic is P^2-k^2 and the system of FIG. 11 can be employed in the same manner as for that of FIG. 10. Obviously, in both of the systems of FIGS. 10 and 11 the signs (or phases) of the two auxiliary antennas can be interchanged without affecting the over-all characteristic P^2-k^2 of the system. Structurally, the second auxiliary antenna 250 can be, by way of specific example, a second small horn antenna superimposed upon the horn antenna 64 of FIG. 3 and may be substantially identical to it, but it should obviously be coupled with the transmitter or receiver (FIG. 11 or FIG. 10, respectively) so that twice as much energy passes through it as for the auxiliary antenna 50.

Numerous, sundry and varied other arrangements embodying principles of the invention of which the above described limited number of arrangements are illustrative will readily occur to those skilled in the art. No attempt to exhaustively illustrate all possible such arrangements has been made.

What is claimed is:

1. A radiant energy transmission system for transmitting intelligence between near end and far end stations, each station including an antenna system, each antenna system comprising a first highly directive antenna and a second substantially nondirective antenna, the radiation of the second antenna being of a level of substantially .707 times the maximum level of each of the side lobes of one polarity of the pattern of the first antenna for one station and of the opposite polarity for the other station, and means at each station electrically interconnecting the first and second antennas, the radiation of the second antenna being in phase with that of the first antenna at one of said stations and 180 degrees out of phase at the other of said stations.

2. A transmission system which includes a transmitting station and a receiving station, each station having a directional antenna system comprising in combination a first highly directional antenna, a second substantially omnidirectional antenna substantially centered with re-

spect to the first antenna, and circuit means for controlling the amplitude and phase of the energy contributed by the second antenna with respect to the amplitude and phase of the energy contributed by the first antenna, the phase relation between the highly directional antenna and the omnidirectional antenna of the transmitting station differing by 180 degrees from that between the highly directional antenna and the omnidirectional antenna of the receiving station.

3. The transmission system of claim 2 in which the amplitude of the energy contributed by the omnidirectional antenna is substantially .707 times the maximum amplitude of the side lobes of the highly directional antenna at both the transmitting and the receiving stations.

4. A directional antenna system comprising in combination a first highly directional antenna, a second substantially omnidirectional antenna substantially centered with respect to the first antenna, and circuit means for controlling the amplitude and phase of the energy contributed by the second antenna with respect to the amplitude and phase of the energy contributed by the first antenna, the circuit means including in the path of the substantially omnidirectional antenna a nonreciprocal phase device having 180 degrees more phase shift for energy passing through it in one direction than in the other.

5. A transmission system which includes in combination a first means for transmitting energy in a highly directional pattern, a second means for transmitting from substantially the center of radiation of the first means a greatly reduced level of energy in a substantially omnidirectional pattern, means for controlling the phase and amplitude of the energy transmitted by the second means with respect to the energy transmitted by the first means, and means connecting the second transmitting means to the controlling means, the connecting means including a nonreciprocal phase changing device, said device introducing a phase difference of 180 degrees between energy passing through it in one direction and energy passing through it in the opposite direction.

6. A directional antenna system comprising in combination a first highly directive antenna having side lobes of a predetermined amplitude, a second substantially omnidirectional antenna centrally positioned with respect to the first antenna, means comprising an interconnecting circuit for the first and second antennas, the interconnecting circuit proportioning the amplitude of the energy of the second antenna to be between 0.5 and 0.85 times the predetermined amplitude of the side lobes of the first antenna, and nonreciprocal means interposed between one of the antennas and the interconnecting circuit, the nonreciprocal means introducing 180 degrees more phase shift to energy passing in one direction than to energy passing in the other direction.

7. A highly directive antenna system for radiant energy comprising a first, narrow-angle, beam antenna; a second, wide-angle antenna positioned to radiate from substantially the center point of radiation from the first antenna and symmetrically about the beam axis of the first antenna, means for controlling the amplitude of radiation of the second antenna to substantially .707 times the amplitude of the minor lobes of the first antenna, means for controlling the phase of the second antenna relative to the phase of the first antenna, and means for changing the phase relation between said first and second antennas by 180 degrees when the direction of energy through the antennas is reversed.

8. A radar system comprising a first antenna having a highly directive, narrow-angle, radiation beam characteristic P ; a second antenna having a broad angle radiation characteristic k and being located to radiate from substantially the center of radiation of the first antenna symmetrically about the axis of the beam of the first antenna, a nonreciprocal 180 degree phase changing means included in the feed line connecting to one of the antennas,

13

a transmitter, a receiver, a transmit-receive cell and a radar indicator, the transmitter and the receiver being connected to the antennas through the transmit-receive cell, the indicator being connected between the transmitter and receiver, whereby the over-all combined characteristic of the antennas for transmitting and receiving is $P^2 - k^2$.

9. An antenna system for use in a highly directive transmission system comprising a highly directive, narrow-angle, beam-type antenna having a propagation characteristic P and auxiliary antenna means having a beam width sufficient to include the radiation arc of all minor lobe radiation of the highly directive antenna and an aggregate propagation characteristic k , where k is substantially .707 times the amplitude of the minor lobes of the highly directive antenna, and means interconnecting the main antenna and auxiliary antenna means to provide a propagation constant of $P+k$ for one direction of energy transmission through the antenna system and a propagation constant of $P-k$ for the other direction of energy transmission through the antenna system, whereby the over-all transmitting-receiving propagation characteristic of the antenna system is $P^2 - k^2$.

10. A system for directionally transmitting and receiving radiated energy comprising a source of energy to be radiated, a first high-gain, highly directive, narrow beam, radiating means and a second low-gain, broad-beam energy radiating means, the beams of the first and the second radiating means being directed along a common longitudinal axis, means for directing a major portion of

14

the energy to be radiated to the first energy radiating means, means for directing a minor portion of the energy to be radiated to the second energy radiating means, means for adjusting the energies radiated by the radiating means to a predetermined phase relation, energy receiving means comprising a receiver, a first high-gain, highly directive, narrow beam, radiant energy receiving means and a second low-gain, broad-beam, radiant energy receiving means, the first and second radiant energy receiving means having their beams aligned along a common longitudinal axis, means for connecting the first and the second radiant energy receiving means to the receiver, the last-mentioned connecting means including means for introducing a phase reversal of the predetermined phase relation between the energy passing from the second radiant energy receiving means and the energy passing from the first radiant energy receiving means to the receiver, and means controlling the amplitude of the energy reaching the receiver from the second radiant energy receiving means, whereby the effective combined transmitting-receiving directivity of the system is increased and the effect of energy transmission by minor lobes of the radiating means is reduced.

References Cited in the file of this patent

UNITED STATES PATENTS

2,885,677	Zaleski	May 5, 1959
2,898,593	Ruse	Aug. 4, 1959