

[54] **STEERABLE NULL ANTENNA ARRANGEMENT**

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[52] U.S. Cl. 343/844, 343/854

[51] Int. Cl. H01q 3/26

[58] Field of Search 343/853, 854, 844

[56] **References Cited**

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[57] **ABSTRACT**

A steerable null antenna arrangement capable of providing cardioid, figure-eight or multinull steerable patterns utilizing electrically optimized phase shifters or resolvers for the steering elements. Via a hybrid feed arrangement a first pattern excitation is developed from two orthogonally arranged pairs of omnidirectional radiators simultaneously with an omnidirectional omniphase reference pattern without the need for a separate sense antenna. The simultaneously generated patterns combine to form a resultant pattern having at least one null (cardioid) which is electrically steerable to any angle in azimuth. Provision is made for varying the azimuthal angular separation of the nulls produced in the resultant pattern.

27 Claims, 21 Drawing Figures

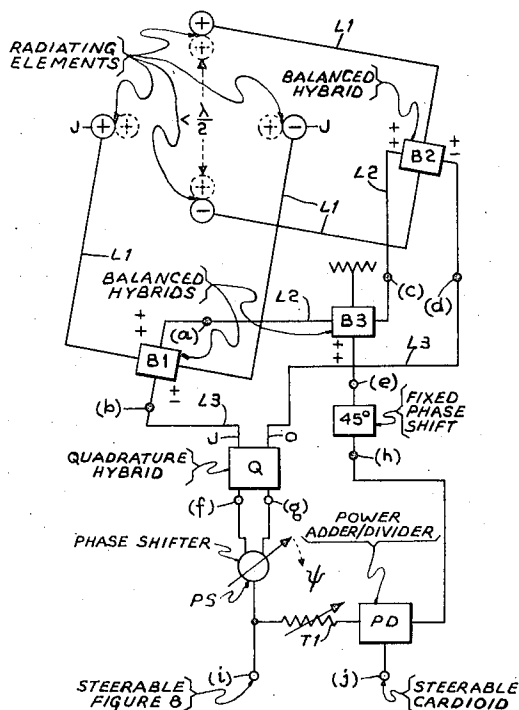
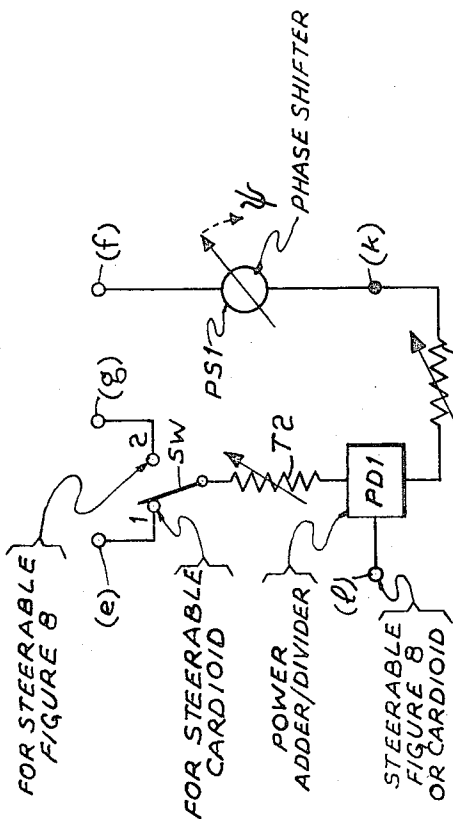
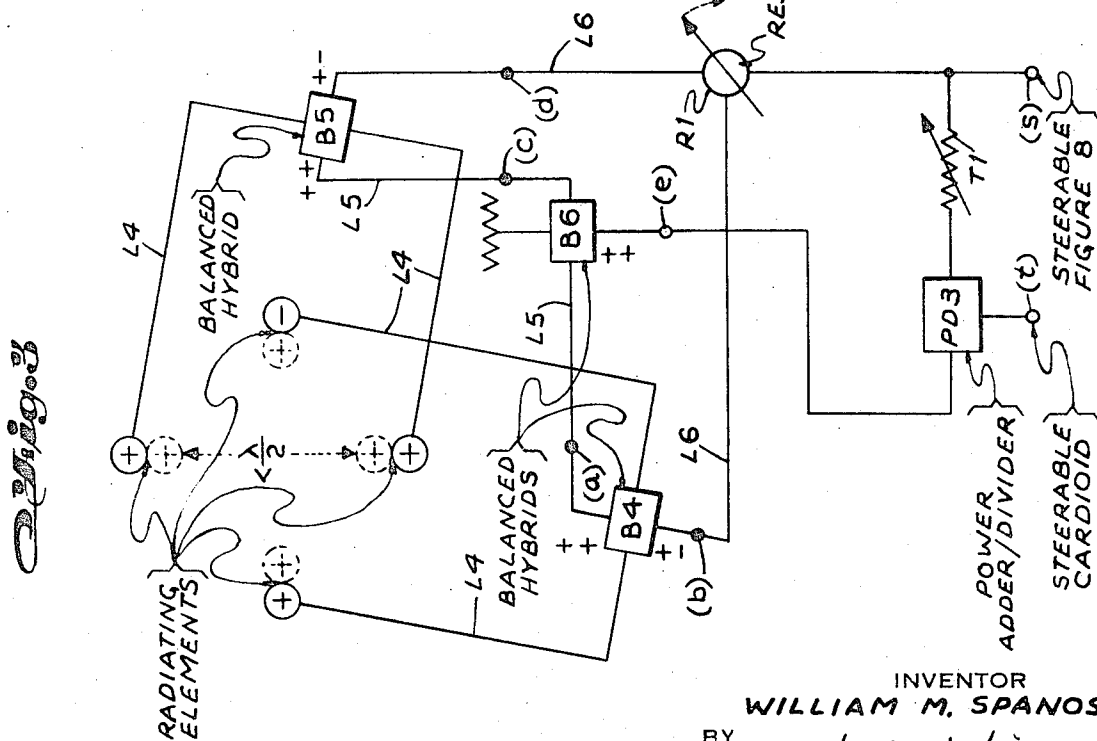
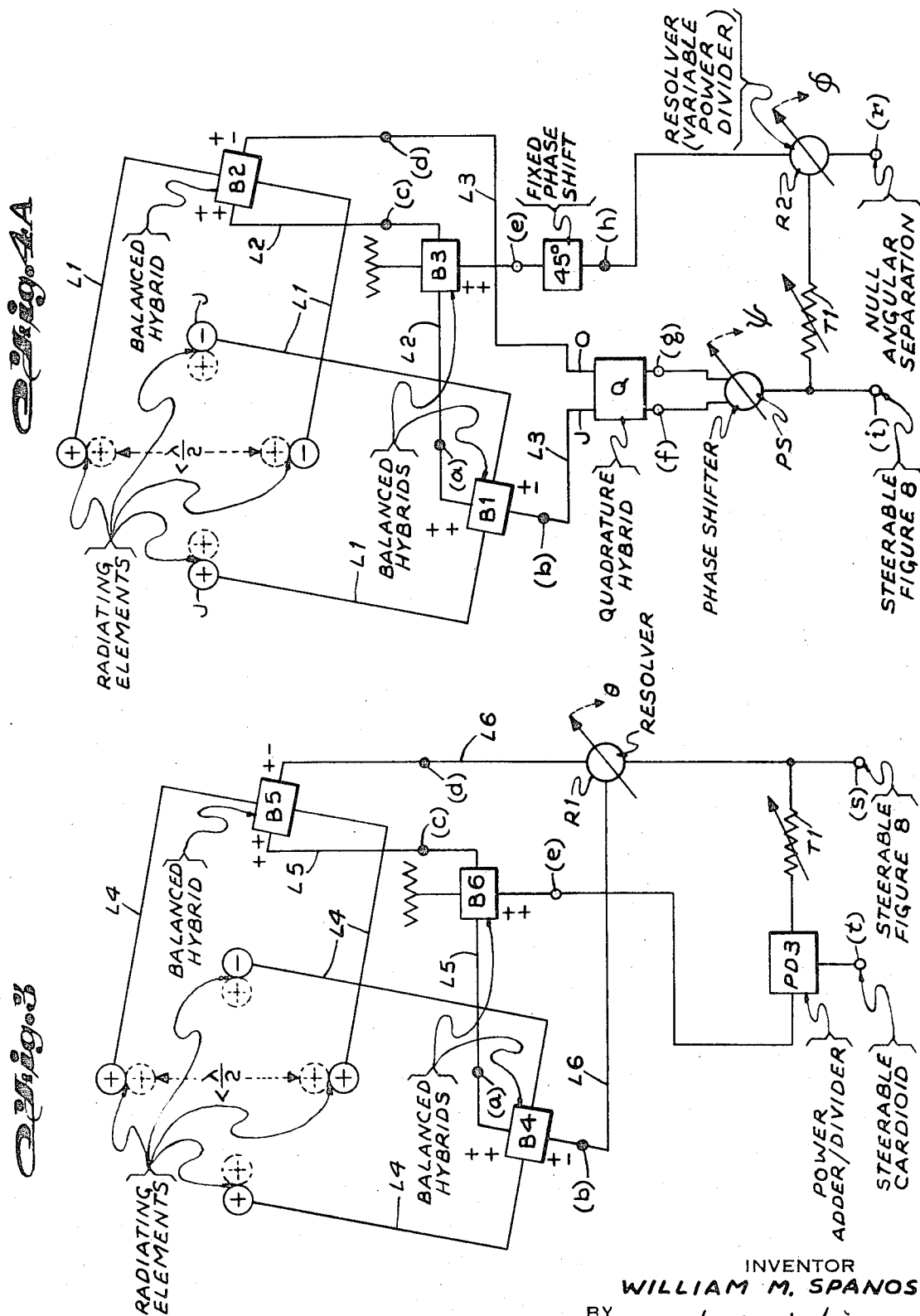


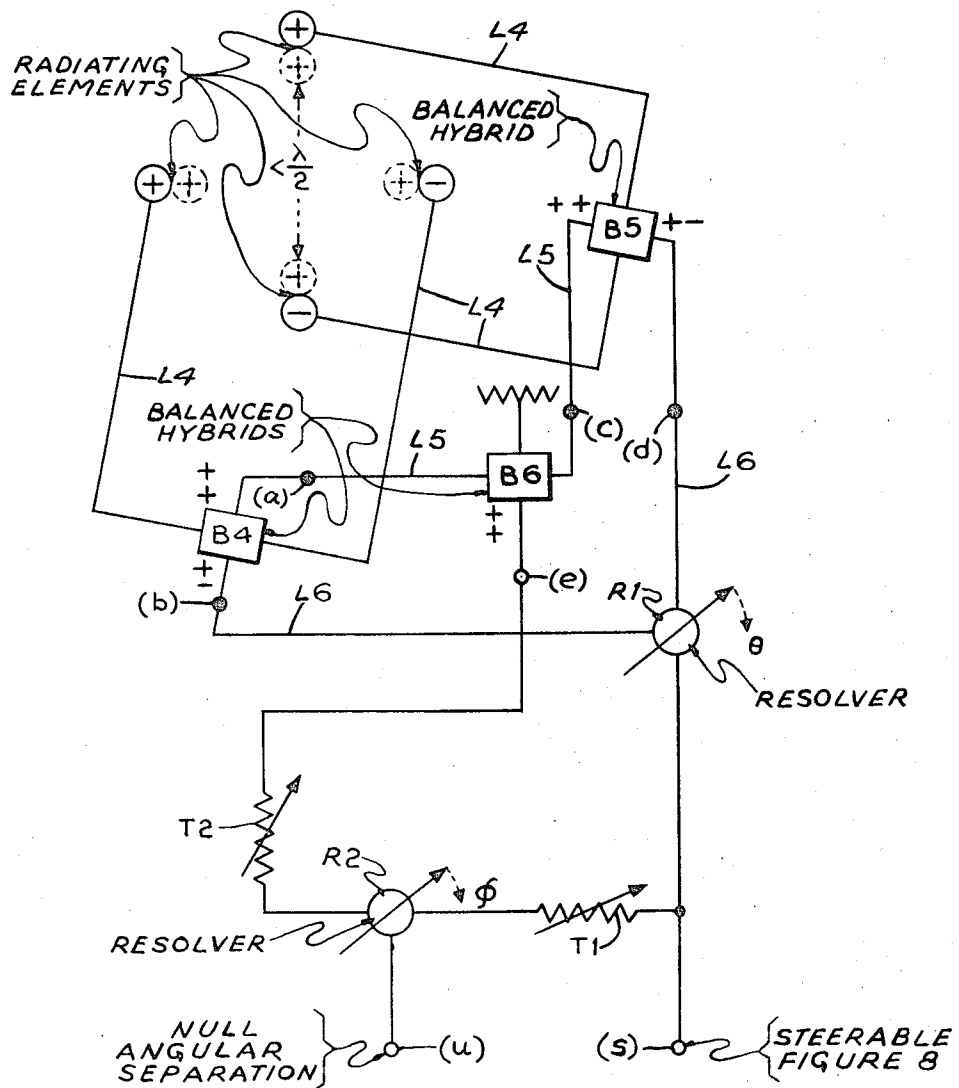
Fig. 2A





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Fig. 4B



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Fig. 5

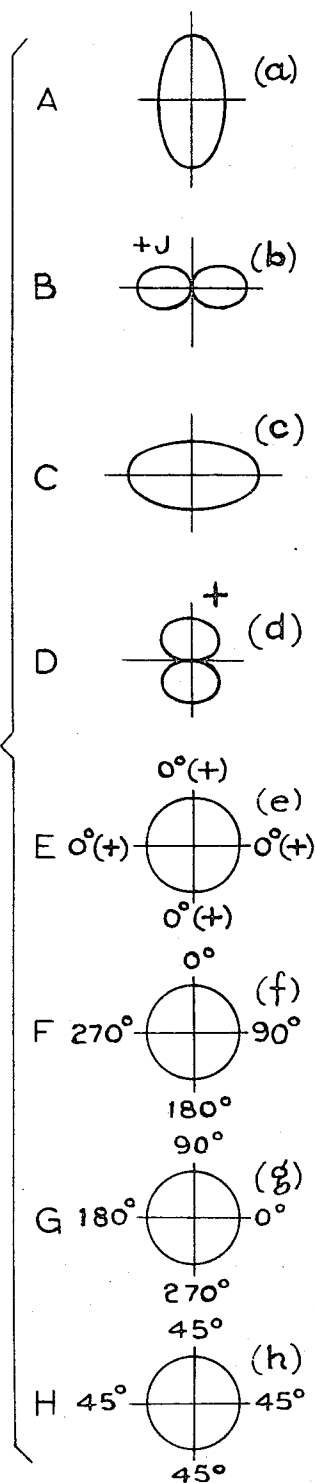


Fig. 6

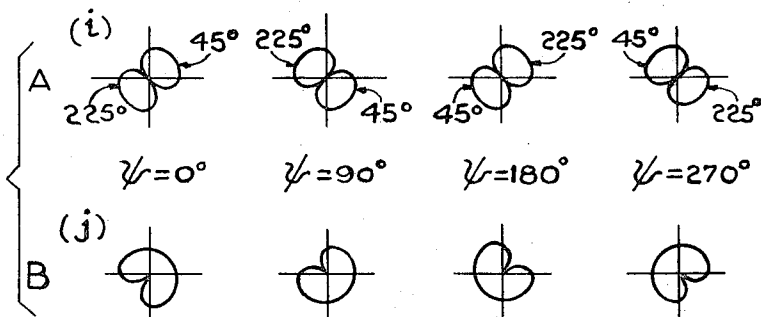
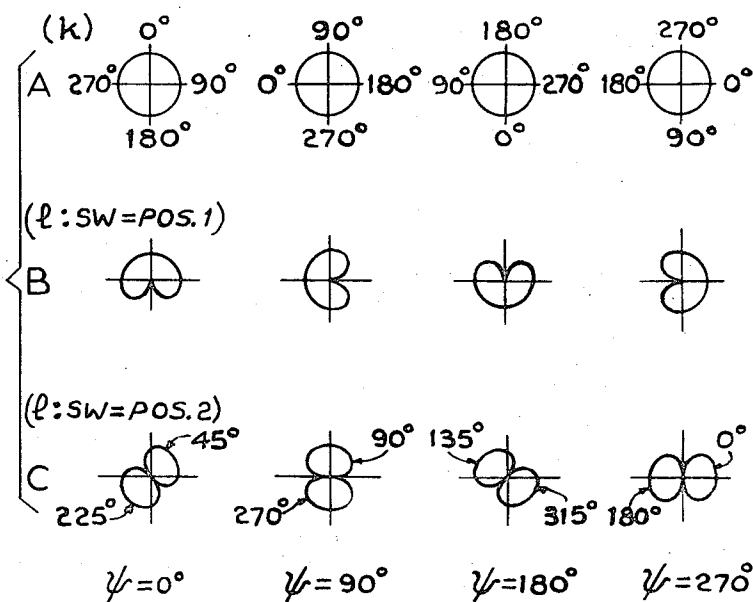
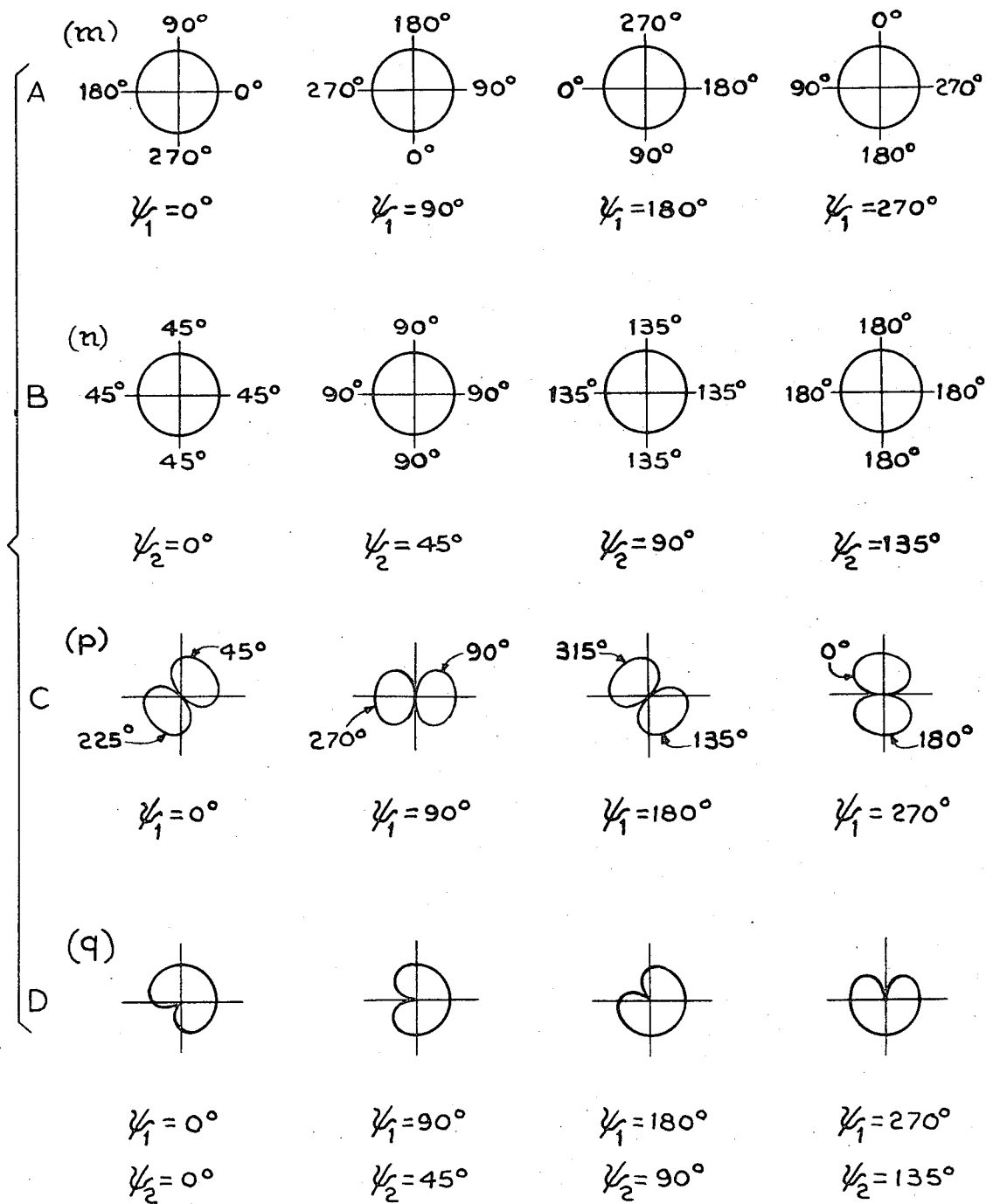


Fig. 7



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Fig. 8



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Fig. 9

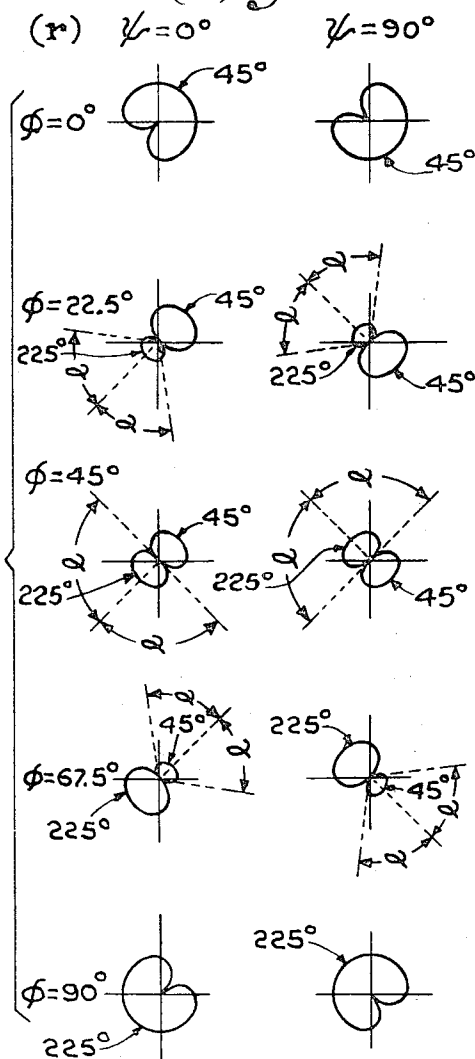


Fig. 11

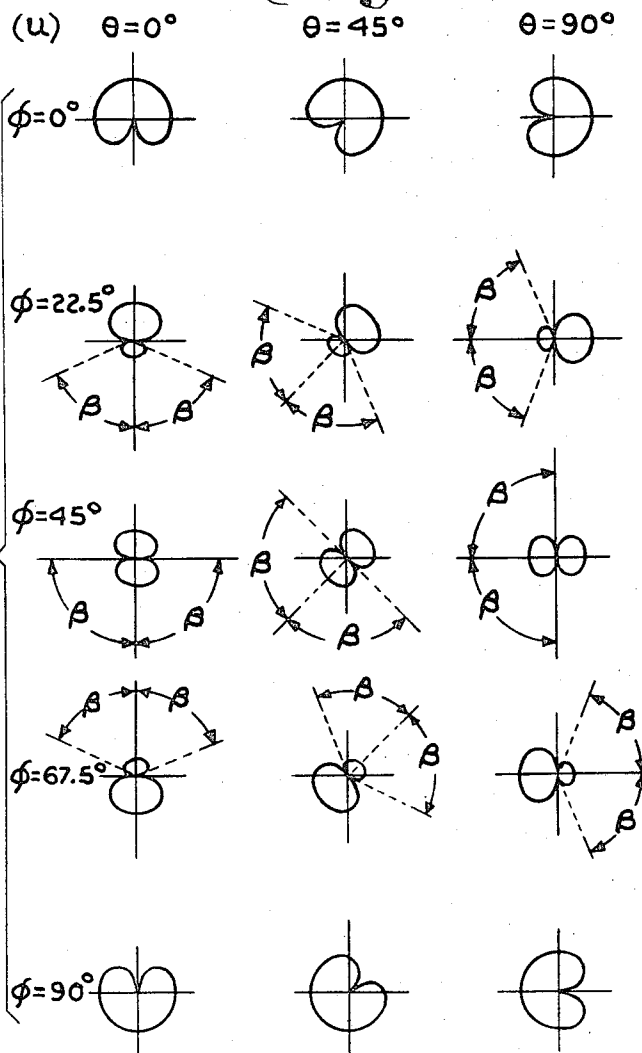
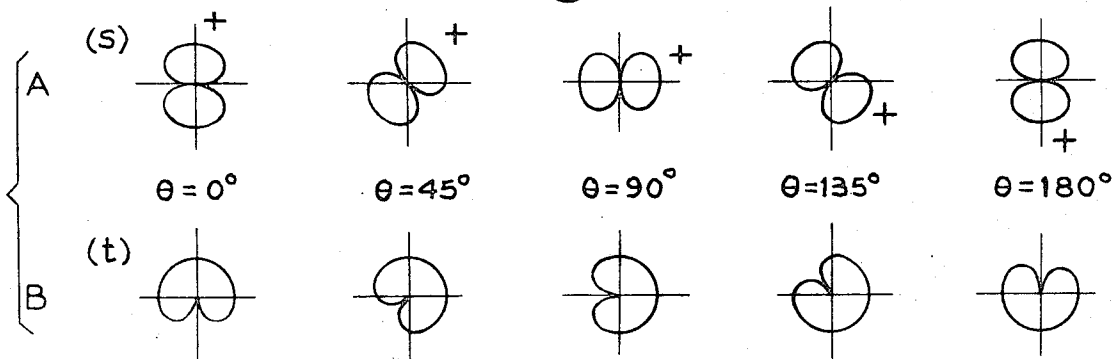


Fig. 10



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Fig. 12A

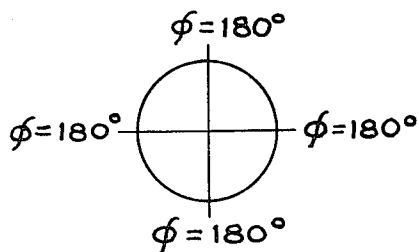


Fig. 12B

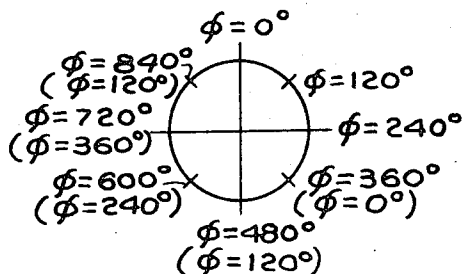


Fig. 12C

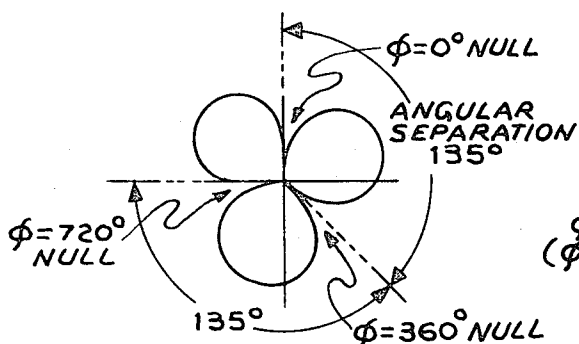


Fig. 13

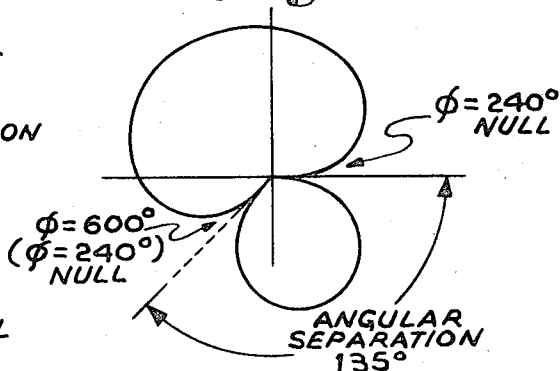


Fig. 14A

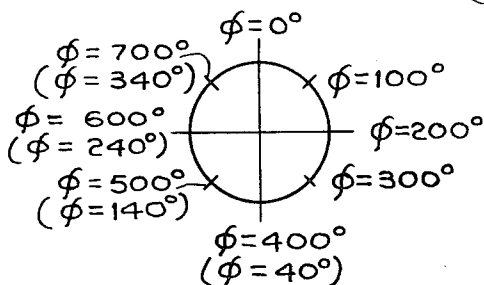


Fig. 14B

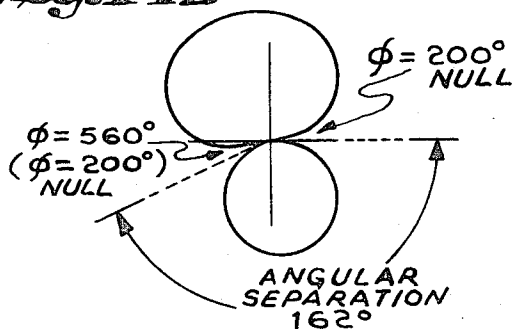


Fig. 15A

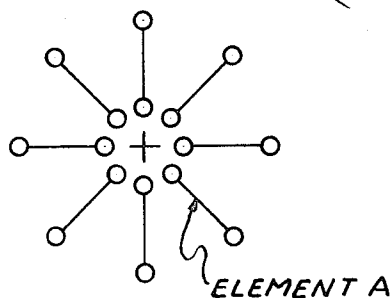
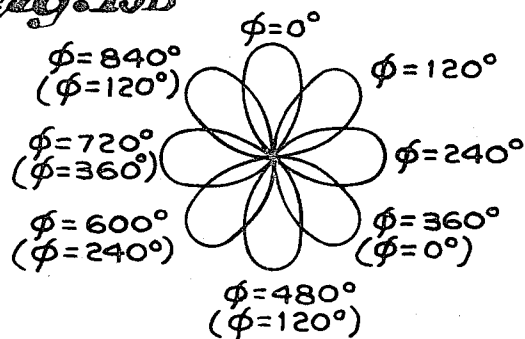


Fig. 15B



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STEERABLE NULL ANTENNA ARRANGEMENT

BACKGROUND OF THE INVENTION

This invention relates to steerable null antenna arrangements and more particularly to antenna arrangements providing phase shift or resolver steerable single, dual or multiple null excitation in azimuth with a capability of varying the azimuthal angular separation between nulls.

As a means of providing protection against localized interfering signals in the VHF and UHF frequency bands, it is desirable to have a steerable null capability in the antenna design. A steerable cardioid pattern for example may be obtained in several different ways. The simplest is an array of two dipoles (or monopoles) spaced by one-fourth wavelength and driven 90° out of phase. The complete array must be physically rotated however to position the radiated pattern in the desired direction.

Another arrangement for obtaining a steerable cardioid pattern employs two crossed Adcock arrays and a goniometer to give a rotatable figure-eight pattern which, when combined with the omnidirectional pattern from a separate sense antenna, produces a steerable cardioid pattern. While physical rotation of the array is not required for steering, this arrangement possesses several other drawbacks. A goniometer is not a matched device and is therefore undesirable for use in the VHF and UHF frequency ranges. Moreover, an additional antenna, i.e., the sense antenna, is required to achieve steering. Also, the element separation of the crossed Adcock arrays must be $\frac{1}{2}\lambda$, which at the lower frequencies necessarily effects adverse size considerations.

A third arrangement providing a non-physical steering of a cardioid pattern employs two crossed Adcock arrays driven in phase quadrature to give an omnidirectional field with phase dependent on the direction of arrival of the signal. By combining this signal with the signal from a separate omnidirectional sense antenna a cardioid pattern is produced. The direction of the cardioid pattern depends on the relative phase of the sense antenna signal. The cardioid pattern may be steered through 360° in azimuth by employing a variable phase shifter (0 to 360 electrical degrees) in the sense antenna line. This arrangement is superior to the last-mentioned examples in that the phase shifter device may be matched and suitable at VHF and UHF frequencies, such as that disclosed in my co-pending U.S. application Ser. No. 113,532, the disclosure of which is incorporated herein by reference. However, this arrangement also requires separation of the antenna elements by $\frac{1}{2}\lambda$ and a separate sense antenna.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to eliminate various drawbacks inherent in the arrangements above-described.

It is another object of the invention to provide non-physical phase shift or resolver steering of figure-eight or cardioid pattern excitation from the same radiators (i.e., no separate sense antenna) using matched steering devices.

It is a further object of this invention to provide, in addition to a null steering capability, variable angular null separation.

It is yet another object of the invention to provide a feed system using hybrids to enable the extraction of a sense or reference signal from the same radiators used to provide a steerable figure-eight or omnidirectional varying phase excitation.

It is still another object of the invention to provide an antenna array of four elements simultaneously excited in two radiation modes to permit a positioning of the pattern nulls to any azimuthal position and with any angular displacement.

It is yet a further object of the invention to eliminate undesirable antenna array size considerations by providing for a separation between radiators of considerably less than one-half wavelength, with radiator separation being minimally limited only by antenna efficiency.

According to the broader aspects of the invention, there is provided an antenna array of four omnidirectional radiators separated by 90° in azimuth and arranged in two orthogonal pairs (crossed) with a separation between paired radiators being less than $\frac{1}{2}\lambda$ (wavelength), a hybrid feed arrangement including first means providing first antenna pattern signal energy in the form of a figure-8 or an omnidirectional varying phase excitation and second means providing sense or reference antenna pattern signal energy in the form of an omnidirectional phase excitation, and means in the form of a matched phase shift or resolver device for varying the signal energy of the first antenna pattern relative to the reference pattern signal energy to provide a combined steerable antenna pattern signal energy having at least one null. Means are included in the form of a matched resolving device for providing variable angular separation of pattern nulls to any separation angle.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-mentioned and other objects and features of this invention and the manner of obtaining them will become more apparent and the invention itself will be best understood by reference to the following description when taken in conjunction with the accompanying drawings comprising FIGS. 1-11, in which:

FIG. 1 schematically illustrates an antenna array and feed arrangement providing cardioid and figure-8 pattern excitation and employing a phase shifter for null steering, according to the invention;

FIGS. 2A and 2B are schematic illustrations of alternative embodiments of the phase shift steerable arrangement of FIG. 1, as taken along the terminal points (e), (f) and (g);

FIG. 3 schematically illustrates an antenna array and feed arrangement providing cardioid and figure-8 pattern excitation and employing a resolver for null steering, according to the invention;

FIGS. 4A and 4B schematically illustrate the arrangements of FIGS. 1 and 3 respectively in a modified form which provides for varying the null angular separation;

FIG. 5 shows basic pattern excitations occurring upon signal energy being present respectively at points (a)-(h) in FIGS. 1-4;

FIG. 6 shows the pattern excitations which occur upon signal energy being present respectively at points (i) and (j) in FIG. 1;

FIG. 7 shows the pattern excitations corresponding to signal energy being present at points (k) and (l) of FIG. 2A;

FIG. 8 shows pattern excitations occurring upon signal energy being present respectively at points (m), (n), (p) and (q) of FIG. 2b;

FIG. 9 shows some of the various patterns achievable upon signal energy being present at point (r) of FIG. 4A;

FIG. 10 shows pattern excitations occurring upon signal energy being present respectively at points (s) and (t) of FIG. 3;

FIG. 11 shows some of the patterns obtainable at point (u) of FIG. 4B, depending on the settings of resolvers R_1 and R_2 ;

FIGS. 12A-12C illustrate respectively an omnidirectional reference pattern excitation, an omnidirectional multiphase pattern excitation, and the multinull pattern resulting from combining the reference and multiphase excitations via a multinull steerable antenna array according to the invention;

FIG. 13 represents a new resultant pattern derived from combining the multiphase pattern excitation with an omnidirectional reference excitation differing in phase from that shown in FIG. 12A;

FIGS. 14A and 14B illustrate respectively an alternative omnidirectional multiphase excitation and the resultant combination thereof with an omnidirectional reference pattern excitation having a phase of 20° ;

FIGS. 15A and 15B illustrate respectively an antenna arrangement capable of generating a multiphase pattern according to the invention and an example multiphase pattern derived therefrom.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Each of the embodiments described hereinafter with reference to FIGS. 1-4 is intended as a reciprocal arrangement, i.e., it may be utilized in either a transmitting or receiving function; however, the description regarding these figures will be largely from a transmit point of view. The inventive arrangements disclosed with reference to FIGS. 1-4 are passive in nature; utilization, for example, of the front end of a receiver to reduce the frequency to be operated on by the arrangement is not intended, such as would for instance be found in active interference elimination arrangements involving mobile communications. The invention provides for either resolver steering as illustrated in FIG. 3 and 4B or phase shift steering as indicated in the remaining embodiments. It is deemed preferable to employ the phase shifter/resolver of the type disclosed in the referenced application wherever a phase shifting or resolving device is called for in this invention, in order to enable an optimization of the electrical and pattern characteristics and minimize losses.

Referring to FIG. 1, there is illustrated therein a non-physical type phase shift steerable cardioid antenna arrangement involving low-loss passive circuitry according to the invention, having provision also for a steerable figure-8 pattern. Four omnidirectional type radiators (e.g. monopoles) are arranged in orthogonal crossed pairs, wherein separation between the elements of each pair is less than one-half the wavelength of the operating frequency. The connecting lines L1 running

between the radiators and the feed arrangement are of the same electrical length for achieving optimized characteristics, i.e., no inherent feed line phase variations, in order to accurately obtain the desired azimuthal null setting and the greatest possible null depth.

The antenna elements, in conjunction with the illustrated feed arrangement, provide via the crossed element pairs on the one hand orthogonal figure-eight's in the azimuthal plane, and on the other hand omnidirectional reference excitation in azimuth having omniphase, i.e., the same phase at every angle in azimuth, generated from all four radiators fed essentially in an in-phase relationship. The former are indicated at the radiating elements by +, - and +J, -J respectively, and the latter by the +'s inscribed within the dashed circles representing the same four elements.

In the steerable cardioid mode (see FIG. 6B), signal energy is applied by way of terminal (j) to power divider (power adder in a receive operation) PD. By way of the power divider PD, the signal energy is split into two essentially equal outputs, one of which leads to phase shifter PS through trimmer T1 and the other to point (h) and a fixed phase shift means. In the preferred example the intended fixed phase shift employed is 45° , and may be introduced into the system at this point by any suitable conventional means.

As indicated in FIG. 5H, signal energy present at point (h) would provide an omnidirectional omniphase (45°) pattern excitation from the four radiators, which in the example represents the reference pattern excitation, as indicated by the $\oplus$ element symbols in FIG. 1. From the 45° fixed phase shift the reference signal energy is fed to a first balanced hybrid B3 via terminal (e), which as indicated in FIG. 5E results in an omnidirectional excitation with an omniphase of 0° in azimuth.

It is to be noted in the remainder of this disclosure that the waveforms illustrated in FIGS. 5-11 represent the patterns which are generated by signal energy being present at the correspondingly labeled points in the various feed arrangements of FIGS. 1-4. Thus in the above instance, energy present at terminal point (e) of FIG. 1 (and also FIGS. 2-4) results in the pattern as shown in FIG. 5E. Moreover, each of the balanced hybrids in the feed arrangements of FIGS. 1-4 have first and second ports, an in-phase port (designated ++ in the figures) and a balanced port (designated +- in the figures).

The signal energy from terminal (e) is received by balanced hybrid B3, at its in-phase port, which in turn is simultaneously fed from the first and second ports of hybrid B3 in a substantially equal power split to the in-phase ports of balanced hybrids B1 and B2 via points (a) and (c) respectively. In this case the balanced port of hybrid B3 has been terminated. The resultant patterns developed by the signal energy present at the in-phase ports of B1 and B2 are shown respectively in FIGS. 5A and 5C. Again, in the largely symmetrical arrangement of FIG. 1, the lines L2 including the points (a) and (c) are intended to be of the same electrical length in order to achieve the best possible pattern response. Via hybrid B1 the signal energy at point (a) is fed from its first and second ports to the radiators with the J designations. Similarly, the signal energy at point

(c) is fed via the first and second ports of hybrid B2 to the radiators of the orthogonally arranged antenna element pair. The combined excitation of all four elements in the in-phase relationship results in the omnidirectional omniphase reference pattern illustrated for instance in FIG. 5E, which ideally would be a perfect circular pattern in azimuth but which in practice may be somewhat squared as shown in FIG. 5E. Of course, the closer the reference signal pattern to perfect circularity in azimuth, the greater the null depth obtainable in the steerable cardioid pattern.

Reverting to power divider PD in FIG. 1, the other output thereof is received by a balanced dual-channel phase shifter PS capable of providing 360° of continuous phase shift. By "dual-channel" phase shift is meant that two outputs are provided for a single input in which to the one output the desired amount of phase is added while the equivalent amount of phase is simultaneously subtracted from the other output. In the preferred arrangement it is intended that the phase shifter disclosed in the referenced application would be used in its dual channel phase shifting capacity. Thus, with signal energy being present at the input of phase shifter PS, due to which a figure-eight pattern is correspondingly generated as illustrated in FIG. 6A, dual outputs, one of increasing phase and the other of decreasing phase, are provided which in turn are fed to first and second ports respectively of quadrature hybrid Q. The respective inputs to hybrid Q are shown in FIGS. 5F and 5G which illustrate that, with 0° phase shift introduced by phase shifter PS, signal energy at terminals (f) and (g) would cause to be generated respectively right-hand and left-hand single phase omnidirectional patterns in azimuth. By "single phase" is meant 1° of phase difference in azimuth for each degree of rotation. As indicated in FIG. 6A, the lobes of the figure-eight at point (i) retain the same value of phase regardless of the setting of the phase shifter PS.

The quadrature hybrid Q in both FIGS. 1 and 4A is a four-port device having first and second ports, a 0° phase port relative to the first port (a 90° phase port relative to the second port), and a 90° phase port relative to the first port (a 0° phase port relative to the second port). Signal energy present for example at its first port would result in essentially equal power division thereof at the relative 0° and 90° phase ports, thus automatically providing two outputs with a 90° phase difference from a single input.

Looking then to the signal energy present at the first port, i.e., that associated with point (g), signal energy is derived from the port designated O of hybrid Q, which energy has 0° phase relative to the energy at terminal (g); also energy appears at port O resulting from energy present at the second port, i.e., terminal (f). The signal energy at port O is fed to the balanced port of hybrid B2 via line L3 and point (d), and effects thereby a figure-8 pattern excitation having an orientation as illustrated in FIG. 5D.

Similarly, at the J port of hybrid Q signal energy is derived from that appearing at the respective first and second ports, which energy is fed also by a line L3 to the balanced port of hybrid B1. As shown in FIG. 5B, signal energy present at point (b) will cause to be generated a figure-8 pattern having the indicated orientation. The feed lines L3 running from hybrid Q to the

balanced ports of hybrids B1 and B2 are also of the same electrical length. Hybrids B1 and B2 feed the crossed antenna element pairs with the signal energy derived from the J and O ports of hybrid Q to provide the two figure-8 excitations in orthogonal relationship. In a combined consideration there results a single figure-eight excitation as indicated in FIG. 6A, which is steerable in accordance with the angular ψ setting of the phase shifter PS. Any suitable conventional quadrature and balanced hybrids may be used in the feed arrangements disclosed herein.

As a matter of course, power adjustments are required for the combined figure-eight and "omni" reference patterns, in order that the greatest possible null depth in the resultant cardioid pattern be achieved. The power adjustment is provided by trimmer T1, which may take any suitable conventional form. According to the invention the simultaneous generation of a steerable figure-8 pattern and an omnidirectional omniphase reference pattern will result in a combined cardioid pattern if first of all the phase of the reference pattern is the same as one or the other lobes of the figure-eight pattern, and secondly if the relative strengths of the two patterns are substantially equal. As the signal strength differential increases between the patterns, the cardioid null depth suffers correspondingly. Particularly, if the reference pattern has a signal strength greater than the figure-8 pattern, no null is achievable theoretically.

Thus, in order to ensure that the optimum theoretical condition of equal signal energy strengths in the figure-eight and reference patterns is obtained, trimmer T1 has been added to the figure-eight leg between phase shifter PS and power divider PD. Also, the phase of the "omni" reference pattern is maintained the same as the phase of the one or the other of the lobes of the combined figure-eight pattern (compare FIGS. 5H and 6A). In the illustrated example the matching phase is 45°. It could just as easily have been 225°, in which case the fixed phase added between points (e) and (h) in FIG. 1 would be 225° instead of 45°. Therefore, it is completely within the spirit of this invention to provide between points (e) and (h) a switching capability for manually or automatically switching-in different fixed phase shifts to correspond to the phase of either lobe of the combined figure-8 excitation.

The resultant cardioid becomes steerable, i.e., the null directed to any point in azimuth, by the inclusion of the phase shifter PS in the antenna feed arrangement. As indicated in FIG. 6B, there is a cardioid pattern azimuthal orientation for every position ψ of the phase shifter PS, though only four specific examples are given.

If instead of a cardioid, occasions arise wherein pattern generation involving dual opposing nulls is needed (e.g. a figure-eight) it would be advantageous to provide for this alternative mode of operation. In the preferred case according to the invention, a figure-eight capability is already inherent within the arrangements, as illustrated in FIGS. 1-4. All that is required (though not shown) is to have switching means added to the illustrated system, for example in FIG. 1 between terminals (i) and (j), to provide for the immediate selection between these two modes. As already demonstrated in FIGS. 6A and 6B, points (i) and (j) respec-

tively provide, in response to signal energy being present thereat, figure-eight and cardioid pattern excitations.

As demonstrated above for FIG. 1, and which is equally true for the arrangements in FIGS. 2-4, the use of RF hybrids permits signals of different phase to be obtained from the same antenna arrangement; thereby it is possible to achieve the reception of sense signals from the four radiators without the need for a separate and additional sense antenna.

Referring to FIG. 2A, there is illustrated therein an alternative embodiment of FIG. 1 taken along the terminals (e), (f) and (g), the remainder of the antenna arrangements of FIGS. 1 and 2A being the same.

As shown in FIG. 2A switch means for switching between the figure-eight and cardioid modes of operation has been incorporated in the form of a simple two-position switch SW. With switch SW in position 1, i.e., the cardioid mode, it is immediately apparent that this arrangement presents a significant difference from the FIG. 1 arrangement in that both the reference and the other main pattern, which when combined form a resultant cardioid, are in this case both omnidirectional omniphase patterns.

FIG. 7 illustrates the various excitations resulting from signal energy being present at points (k) and (l) (depending on the position of switch SW) in dependence on the setting of phase shifter PS1. In the embodiment of FIG. 2A signal energy is introduced to power divider PD1 (which in each of the embodiments in FIGS. 1-4 may be a balanced hybrid operated as a simple power splitting device) via terminal (l). On the one hand the split power is fed through an adjustable trimmer attenuator T_2 to switch SW, and thereby to terminals (e) or (g) depending on the switch position, and the further circuitry associated therewith as particularly illustrated in FIG. 1. It is to be noted that the pattern excitations associated with this leg of the feed arrangement are, in either switch position, omnidirectional in azimuth. However, in the cardioid mode, i.e., switch position 1 and terminal (e), signal energy passing through trimmer T_2 will result in an omniphase (45°) omnidirectional reference excitation, whereas there will result with switch position 2 an omnidirectional pattern having a left-hand single phase orientation. In the other leg of the feed arrangement, the divided signal energy is fed via a trimmer attenuator T_1 and point (k) to a single-channel variable phase shifter PS1, and on to terminal (f) and the remainder of the feed arrangement. Though the phase shifter is shown in FIG. 2A to be placed in the feed line running between power divider PD1 and terminal (f), it just as easily could be placed in the feed line running between the power divider PD1 and switch SW. In either event, the generated pattern resulting from signal energy being present in the terminal (f) leg is omnidirectional in azimuth, and having right-hand single phase orientation, as indicated in FIG. 5F, in which 0° of phase have been introduced by phase shifter PS1.

In this embodiment a resultant cardioid is obtained by the simultaneous generation of the omnidirectional omniphase reference pattern and the single phase omnidirectional excitation. However, in theory for a complete null to occur in a cardioid pattern, the signal energy strength of the two omnidirectional patterns

must be equal. Therefore trimmers T_1 and T_2 have been included in the respective legs of the feed arrangement to provide in practice the greatest possible null depth. With the phase shifter PS1 present in one leg thereof, each change in phase results in a corresponding change of phase in each lobe of the figure-eight pattern as shown in FIG. 7C. With the switch SW in position 2, the two terminals (f) and (g) of quadrature hybrid Q are coupled together via power divider PD1.

From the illustrations in FIGS. 7A and B and FIG. 5F it is evident that the cardioid null appears in the azimuthal direction in which the two omnidirectional patterns appear to be 180° out of phase. The trimmers are needed particularly in view of the fact that in practice the two omnidirectional excitations to be combined to form a cardioid pattern are not perfectly omnidirectional in azimuth, and tend instead to take on a slightly squared shape as demonstrated in FIG. 5E.

Referring now to FIG. 2B, there is illustrated therein another alternative embodiment of the arrangement in FIG. 1, in which the two basic patterns to be combined in order to obtain a cardioid pattern are, as was the case in FIG. 1, a figure-eight and an omniphase omnidirectional reference pattern. As in the above examples of embodiment, the steering capability for either the cardioid or figure-eight modes of operation is provided by a variable phase shifter. However, in the embodiment of FIG. 2B, two single-channel phase shifters PS1 and PS2 are employed, wherein the shafts thereof are in a ganged relationship in which for every degree of phase added by phase shifter PS1 by a corresponding rotation ψ_1 of its shaft there are two degrees of phase shift added by phase shifter PS2 in a corresponding rotation ψ_2 of its shaft. In this example, phase shifter PS2 is placed in the reference pattern leg of the antenna feed arrangement, whereas phase shifter PS1 is placed in the figure-eight leg.

In the embodiment of FIG. 2B signal energy for exciting a cardioid pattern is fed via terminal (q) to power divider PD1. Substantially one-half of the signal energy is in turn fed via trimmer attenuator T_1 to a second power divider PD2, which may be a balanced hybrid as shown in the figure receiving the signal energy at its in-phase port. Half this signal energy is then applied to terminal (f) and on to the first port of hybrid Q as in FIG. 1. The other half of the signal energy from power divider PD2 is coupled to terminal (g) and the second port of hybrid Q via the phase shifter PS1 and point (m). Signal energy at the in-phase port of power divider PD2 and at point (m) provides the excitations given respectively in FIGS. 8A and 8C, in dependence upon the setting of PS1. As was the case with the steerable figure-eight mode of the arrangement of FIG. 2A, in the patterns at terminal (P) (FIG. 8C) the phase of each lobe changes with a corresponding change in phase as provided by phase shifter PS1. Once again, the excitations responsive to signal energy at points (f) and (g) are in the form of omnidirectional single phase patterns having respectively right and left-hand orientation.

From power divider PD1, the remaining signal energy is fed to phase shifter PS2 in the reference pattern leg of FIG. 2B. This energy then passes via a fixed phase shift means (a fixed phase shift of 45° in this example) to the terminal (e) and on to the antenna array

as outlined above for FIG. 1. FIGS. 8B, 5H, and 5E demonstrate the respective patterns associated with signal energy being present at points (n), (h) and (e), and in dependence of phase shifter PS2. As illustrated in FIG. 8B, when compared with FIG. 8C, the phase of the omnidirectional reference pattern as developed by signal energy at point (n) changes correspondingly with one of the lobes of the steerable FIG. 8 associated with signal energy at point (p), for each setting of the ganged phase shifters. FIG. 8D demonstrates the relationship of the ganged phase shifters in their capacity of enabling a phase shift steerable cardioid excitation.

As is the case in each of FIGS. 5-11, while specific settings of the steerable elements are illustrated, it is to be understood that in each embodiment of the invention 360° of continuous steering are available to enable the null in the cardioid mode (dual coincident nulls) or the dual opposing nulls in the figure-eight mode to be directed to any point in azimuth. Once again, in the embodiment of FIG. 2B, a trimmer attenuator T₁ has been included in one leg in order to improve the null depth.

Referring now to FIG. 3, a steerable cardioid antenna arrangement is provided in which the steering member is a resolver, preferably of the type disclosed in the above-referenced application. In the arrangement of FIG. 3 the feed circuitry from points (a)-(d) and including the arrangement of the orthogonal crossed pairs of antenna elements is the same as that provided with reference to FIG. 1, and will therefore not be discussed again in detail. It is to be particularly noted, however, that the resolver-steerable embodiment of FIG. 3, in distinction to the arrangement of FIG. 1 in which the hybrids B1 and B2 feed respective signal energies to the corresponding orthogonal radiator pairs with a relative phase difference of 90°, provides for hybrids B4 and B5 to feed the crossed element pairs with respective signal energies having no relative phase difference. The respective excitations resulting therefrom, however, remain orthogonal by virtue of the arrangement of the antenna element pairs. Additionally, although the arrangement of FIG. 3 (and FIG. 1) shows a third balanced hybrid B6 (B3 in FIG. 1) included in the arrangement, it is to be understood that this hybrid may in both FIGS. 1 and 3 be replaced with a simple power divider (power adder). A balanced hybrid at B6 would be operated as a mere power splitter, with the balanced port appropriately terminated.

In FIG. 3 signal energy is applied to the steerable cardioid terminal (t), which in turn is power divided and on the one hand fed to hybrid B6 via terminal (e) and on the other hand fed to variable resolver R1 via trimmer attenuator T1 and terminal point (s). FIGS. 10A and 10B illustrate the pattern excitations corresponding to signal energy present at points (s) and (t) respectively while FIG. 5E shows the resulting excitation corresponding to the signal energy present at terminal (e). As was the case in FIG. 1, the feed lines L4 connected to the radiators are of the same electrical length in order to optimize pattern characteristics, in particular null depth. Similarly, the member lines of pairs L5 and L6 are respectively also of equal electrical lengths.

In this arrangement the four antenna elements arranged in crossed pairs are connected through a

resolver feed arrangement to give a steerable figure-eight pattern, as provided by the one leg of the arrangement which includes resolver R1. Via the hybrid feeding arrangement there is also simultaneously provided omnidirectional type excitation using the same antenna elements and via the leg of the arrangement which includes hybrid B6. The combination of the omnidirectional excitation with the figure-eight excitation from the resolving arrangement will provide a resultant cardioid steerable-null (dual coincident nulls) pattern.

Trimmer T1 has been added as before to ensure optimum pattern characteristics through relative control of the energies in the principle (figure-eight) and reference legs. Once again, it is intended to ensure via trimmer T1 that the energy in each leg is such that the maximum amplitudes of the respective excitations are substantially equal.

Again, the use of RF hybrids in the feed arrangement permits signals of different excitation to be obtained from the same antenna, thus allowing the reception (derivation) of sense signals from the four radiators employed without the need for a separate sense antenna.

The flexibility of the arrangement is demonstrated by its ability to provide both steerable cardioid and figure-8 excitations, which permits expanded effectiveness in combating interference, as for example broad side interference with the figure-eight pattern and rearward interference with the cardioid pattern. For selection between the two modes of operation, a selection switch may be provided between terminals (s) and (t). In either case the variable angular position of the excited pattern in azimuth at any given time is derived from the resolver setting Θ . The ability of this arrangement to provide steering in both modes is demonstrated in FIGS. 10A and 10B. The resolver in this arrangement essentially provides a transformation of axes function resulting in the orthogonal figure-8 patterns shown in FIGS. 5B and 5D responsive to signal energy being present at points (b) and (d), as applied to resolver R1 at its input(s).

Referring now to FIG. 4A, there is illustrated the steerable cardioid antenna arrangement of FIG. 1 in a modified form providing a variable angular null separation capability. The power divider (power adder) PD of FIG. 1 has been replaced by a resolver R2 having optimized electrical characteristics which functions as a variable power divider. The immediate effect of this upon the arrangement in the cardioid mode of operation (a cardioid may be considered theoretically as having dual coincident nulls) is to vary the relative power in the two previously "equal-power" main feed legs in a manner to be described. It is to be assumed that when ϕ , i.e., the angular setting of the shaft of resolver R2, is equal to zero the power in the principle (figure-eight) and reference (omnidirectional) feed legs is such that the amplitudes of the respective excitations are substantially equal. At this resolver setting the resultant excitation will of course be a cardioid, regardless of the ψ setting of phase shifter PS. Thus, in effect the cardioid pattern is a special case, i.e., equal power in both legs of the feed arrangement, of a more general consideration involving pattern variations resulting from any relative power variations in the two legs. It is to be remembered, as mentioned previously, that if the am-

plitude of the omnidirectional reference pattern exceeded that of the figure-eight pattern there could be no null generation theoretically. Therefore, since this invention is directed to steerable null arrangements, the operational range of resolver R2 is intended to include those settings wherein the power in the figure-eight relative to the reference leg is such that the amplitude of the omni reference pattern does not exceed that of the figure-eight excitation.

In its function as a variable power divider, resolver R2 provides unequal maximum amplitudes for any setting other than $\phi=0^\circ$ in the intended operating range. The effect of same is illustrated in FIG. 9, which shows four specific example settings for the continuous variable resolver R2. As illustrated for $\phi=22.5^\circ$ and $\phi=67.5^\circ$, the combination of the principle or figure-8 excitation with the lesser-amplitude omni reference excitation causes to be generated a two-lobed resultant pattern, wherein the dual coincident nulls of the cardioid pattern have in effect been separated by an angle equal to 2α . In this excitation there is provided a major lobe and a minor lobe which results from phase as well as amplitude considerations in combining the principle and reference excitations.

As ϕ increases from 0° to 45° the minor lobe continues to grow, and hence the null angular separation increases until a point is reached whereby the two lobes are of equal size and the two nulls are 180° apart. But, this is the criteria for a figure-eight pattern. Thus, at the special setting $\phi=45^\circ$ a figure-eight will be the resultant excitation in the arrangement of FIG. 4A. A further increase of ϕ will have a similar effect on the other lobe, though in reverse, with the angle of separation of the nulls becoming greater than the 180° and approaching 360° as the other lobe continues to decrease in amplitude (see FIG. 9 for $\phi=67.5^\circ$). At $\phi=90^\circ$ the point is reached in which the other lobe ceases to exist and the two separated nulls once more become the theoretical dual coincident nulls in forming a cardioid pattern which is oriented 180° with respect to the pattern associated with the resolver setting $\phi=0^\circ$. Of course at $\phi=90^\circ$ the relative power in the two legs of the feed arrangement is once again such that the maximum amplitudes of the figure-8 and omni reference patterns are substantially equal.

It is to be noted also that the arrangement of FIG. 2B could also have been modified to the extent of replacing power divider PD1 with a continuous variable resolver, in order to achieve the same operation depicted in FIG. 9. Once the desired angular separation between nulls is selected, the azimuthal orientation of the entire pattern may be set by phase shifter PS.

Referring to FIG. 4B there is illustrated the resolver-steerable equivalent arrangement to the phase shift-steerable arrangement of FIG. 4A. The arrangement of FIG. 4B provides for continuous variable dual null angular separation and in this capacity constitutes a modified arrangement of FIG. 3, in a similar manner to that relationship which exists between FIGS. 1 and 4A. In particular, the power divider PD3 of FIG. 3 has been replaced with a continuous variable resolver R2 having optimized electrical characteristics, and which functions in the feed arrangement of FIG. 4B as a variable power divider. Inasmuch as the remainder of the circuitry of FIG. 4B functions in the manner already

described with reference to FIG. 3, it will not be further discussed in detail. Also, it is to be noted that resolver R2 in both FIGS. 4A and 4B has the same function, which leads to the same resultant patterns. The limits on the operating range of resolver R2 in FIG. 4B, with regard to the relative energies in the principle (figure-eight) and reference (omni) legs of the feed arrangement, are the same as given for the resolver R2 in FIG. 4A.

The resultant pattern excitations of the arrangement of FIG. 4B in relation to signal energy being present at terminal point (u) are given in FIG. 11, in which is demonstrated the variable dual null angular separation in accordance with specific example settings of resolver R2. As was the case in FIG. 4A, given a ϕ setting of resolvers R2 in which the relative maximum amplitudes of the figure-8 and omni reference excitations are unequal, with the former greater than the latter as discussed previously, a resultant pattern having dual nulls separated by an angle 2β is derived, wherein a major and a minor lobe are derived. As the ϕ setting of resolver R2 increases, the amplitude of the minor lobe increases until a figure-eight pattern is eventually realized, and so on in a manner quite identical in nature to the pattern generation corresponding to FIG. 4A under the control of its resolver R2. A cardioid pattern having, theoretically, dual coincident nulls is achieved whenever the relative maximum amplitudes of the figure-eight and reference excitations are substantially equal. As was the case with the arrangement of FIG. 3, no phase considerations are present with regard to the arrangement of FIG. 4B. It is to be noted also that both FIGS. 4A and 4B retain the steerable figure-eight mode, although it is not subject to the dual null angular separation provisions as described above. Provision may be made in the form of any suitable conventional switching means to enable the operator to select between the two possible modes of operation, i.e., the steerable figure-8 and the dual null variable angular separation with pattern steering.

While it is advantageous to minimize interference from localized noise sources which tend to "jam" a received signal, in many instances more than one independently steerable null is desired. To achieve more than one independently steerable null it is proposed to add to (combine with) a reference omnidirectional omniphase antenna pattern (FIG. 12A) an omnidirectional multiphase antenna pattern such as given in FIG. 12B. In the particular multiphase pattern shown, the rate of change of phase is 240° per 90° of azimuth angle. As illustrated in FIG. 12C, simultaneous nulls appear where the multiphase pattern has a phase of $\phi=0^\circ$, $\phi=360^\circ$, or $\phi=720^\circ$, i.e., wherever matching points in azimuth between the reference and multiphase patterns are 180° out of phase for the reference phase (FIG. 12A) of 180° .

The separation between nulls is dependent on the rate of change of phase with azimuth angle. The location of the first reference null depends on the relative phase of the reference pattern compared to the multiphase pattern. FIG. 13 shows the null positions for a reference phase of 60° when combined with the multiphase pattern of FIG. 12B; the first null would be located at the $\phi=240^\circ$ phase point on the multiphase pattern as the two patterns would there be at 180° in

opposition and the other null located at $\phi=600^\circ$ ($\phi=240^\circ+360^\circ$). It is thus demonstrated that the selection or change in the reference phase is a determining factor in the number of nulls to be generated. This example arrangement, therefore, can produce a minimum of two nulls separated by spatial angle of 135° which can be oriented to any spatial angle from 0° to 360° in azimuth by means of a phase shifter.

As already mentioned, to change the angular separation between nulls, the rate of change of phase in the multiphase pattern must be varied. FIG. 14A shows a multiphase example pattern having a rate of change of phase of 200° per 90° of azimuth angle. FIG. 14B illustrates the resultant null pattern derived from combining the multiphase pattern of FIG. 14A with a reference pattern having a phase of 20° , which resultant can of course be rotated in azimuth by a phase shifter. It is to be noted that the angular separation derived in this example is 162° in azimuth.

The multiphase pattern itself may be established by arranging antenna arrays to cover the spatial region with appropriate crossover levels (amplitude) and the selected phase relationships as shown in FIG. 15A and 15B, in which FIG. 15A is a top view of an arrangement of vertical dipoles capable of generating the pattern of FIG. 15B via a corresponding proper feed arrangement. The total field pattern is formed by groups of subarrays which yield directive beams to restrict coverage. The individual elements are fed in an "end fire" mode in order to achieve the total field pattern.

One possible arrangement having provision for varying the phase of the reference pattern and also the rate of change of phase per 90° of azimuth angle in the multiphase pattern, is one which requires a phase shifter for the group plus one phase shifter for each of N elements (such as element A in FIG. 15A), i.e., N phase shifters ganged together, for a total of N+1 phase shifters.

While the principles of the invention have been described above in connection with specific apparatus, it is to be understood that this description is made only by way of example and not as a limitation to the scope of the invention as set forth in the objects and features thereof and in the accompanying claims.

What is claimed is:

1. An electronically steerable antenna arrangement capable of having patterns with a plurality of steerable nulls comprising:

- a. a plurality of omnidirectional antenna elements arranged to provide at least two orthogonal element pairs;
- b. first means coupled to said plurality of antenna elements for providing first antenna pattern signal energy;
- c. second means coupled to said plurality of antenna elements for providing reference antenna pattern signal energy; and
- d. means for continuously electronically varying the signal energy of said first means relative to said second means to provide a combined antenna pattern signal energy having a plurality of steerable nulls.

2. The arrangement according to claim 1 wherein said plurality of omnidirectional antenna elements include two orthogonally arranged pairs of om-

nidirectional elements, with the element separation of each pair being equal and less than $\frac{1}{2}\lambda$.

3. The arrangement according to claim 2 wherein said first means include a first balanced hybrid having a balanced port, an in-phase port, a first port coupled via a first line to one element of one of said antenna element pairs, and a second port coupled via a second line to the other element of said one antenna element pair, said first port being responsive to first energy and said second port being responsive to said first energy having a 180° phase relationship with said first energy at said first port, said first and second ports simultaneously being responsive to in-phase second energy.

4. The arrangement according to claim 3 wherein said second means include a second balanced hybrid having a balanced port, an in-phase port, a first port coupled via a third line to the one element of the other of said antenna element pairs, and a second port coupled via a fourth line to the other element of said other antenna element pair, the first port of said second balanced hybrid being responsive to said first energy having a $+90^\circ$ phase relationship with said first energy at the first port of said first balanced hybrid and the second port of said second balanced hybrid being responsive to said first energy having a -90° phase relationship with said first energy at the first port of said first balanced hybrid, the first and second ports of said second balanced hybrid simultaneously being responsive to said in-phase second energy.

5. The arrangement according to claim 4 wherein said first, second, third and fourth lines are electrically the same length.

6. The arrangement according to claim 5 wherein a steerable cardioid pattern is provided and wherein said means for varying the signal energy of said first means relative to said second means comprise phase shifting means.

7. The arrangement according to claim 5 wherein a steerable cardioid pattern is provided and wherein said means for varying the signal energy of said first means relative to said second means comprise signal energy resolving means.

8. The arrangement according to claim 6 wherein said first means further include a quadrature hybrid having a first port, a second port, 0° phase port coupled via a fifth line to the balanced port of said first balanced hybrid and a 90° phase port coupled via a sixth line to the balanced port of said second balanced hybrid, said fifth and sixth lines having the same electrical lengths.

9. The arrangement according to claim 8 wherein said second means further include a first power adder/divider having an in-phase port and first and second ports coupled via seventh and eighth lines respectively to the in-phase port of said first and second balanced hybrids, said seventh and eighth lines being of the same electrical length.

10. The arrangement according to claim 9 wherein said phase shifting means includes a first phase shifter having at least a first port coupled to one of the first and second ports of said quadrature hybrid.

11. The arrangement according to claim 10 further including a second power adder/divider having a first port coupled to a second port of said first phase shifter and a second port of said first phase shifter and a second port coupled to said second means.

12. The arrangement according to claim 11 wherein said first phase shifter is a dual-channel phase shifter having first and third ports respectively coupled to said first and second quadrature hybrid ports and a second port coupled to said second power adder/divider, and wherein the second port of said second power adder/divider is coupled to the in-phase port of said first power adder/divider by way of a predetermined fixed phase shift means.

13. The arrangement according to claim 12 wherein trimming means are coupled between said dual-channel phase shifter and said second power adder/divider in order to optimize the cardioid pattern characteristics.

14. The arrangement according to claim 10 wherein said second power adder/divider is coupled to the inphase port of said first power adder/divider by way of first trimming means and is coupled to said first phase shifter by way of second trimming means, said first and second trimming means being provided for trimming the relative amplitudes of the signal energy at the first and second ports of said second power adder/divider in order to optimize the null of the cardioid pattern.

15. The arrangement according to claim 11 further including a third power adder/divider having a first port coupled to the other of said first and second quadrature hybrid ports, a second port coupled to the second port of said first phase shifter and an in-phase port coupled to the first port of said second power adder/divider, and a second phase shifter coupled to said first power adder/divider in-phase port via a predetermined fixed phase shift and further coupled to the second port of said second power adder/divider, said first and second phase shifters being in a ganged relationship in order to provide a two-to-one phase shift ratio.

16. The arrangement according to claim 14 further including trimming means coupled between said second and third power adders/dividers for controlling the amplitude of the energy at the first port of said second power adder/divider relative to the energy at the second port thereof in order to optimize the cardioid pattern characteristics.

17. The arrangement according to claim 10 wherein said first phase shifter is a dual-channel phase shifter having first, second and third ports, said first and third ports respectively coupled to said first and second quadrature hybrids ports, and further including variable resolver means having a first port coupled to the second port of said dual-channel phase shifter and a second port coupled to the in-phase port of said first power adder/divider, said resolving means providing variable angular separation of the nulls of the resultant antenna pattern.

18. The arrangement according to claim 17 wherein said resolver means provides a dual-null angular separation which varies from 0° to 360°.

19. The arrangement according to claim 7 wherein said first means further include a first variable resolving means having first and second ports coupled respectively via fifth and sixth lines to the balanced port of said first and second balanced hybrids, said fifth and sixth lines having the same electrical length.

20. The arrangement according to claim 19 wherein said second means further include a first power adder/divider having an in-phase port and first and

second ports coupled via seventh and eighth lines respectively to the in-phase port of said first and second balanced hybrids, said seventh and eighth lines being of the same electrical length.

21. The arrangement according to claim 20 further including a second power adder/divider having a first port coupled via trimming means to a third port of said resolving means and a second port coupled to the in-phase port of said first power adder/divider, said trimming means controlling the amplitude of the energy at the first port of said second power adder/divider relative to the energy at the second port thereof in order to optimize pattern characteristics.

22. The arrangement according to claim 20 further including a second variable resolving means having a first port coupled to a third port of said first resolving means and a second port coupled to the inphase port of said first power adder/divider, said second resolving means providing variable angular separation of the nulls of the resultant antenna pattern.

23. An electronically steerable antenna arrangement capable of having patterns with a plurality of steerable nulls comprising:

- a. a plurality of omnidirectional antenna elements arranged to provide at least two orthogonal element pairs with the separation of each pair being equal and less than $\frac{1}{2}\lambda$;
- b. first means coupled to said plurality of antenna elements for providing reference antenna pattern signal energy;
- c. second means coupled to said plurality of antenna elements for providing a first antenna pattern signal energy;
- d. continuous phase shifting means coupled to said first means for varying the phase of the signal energy of said first means relative to said second means in order to provide a steering of the resultant antenna pattern; and
- e. continuous resolver means coupled between said phase shifting means and said second means for providing variable angular separation of the nulls in the resultant antenna pattern.

24. The arrangement according to claim 23 wherein each said plurality of omnidirectional antenna elements include a pair of omnidirectional radiators of predetermined separation, said elements being arranged in pairs about a central point substantially equally spaced from each other, with the paired members being on opposite sides thereof and oriented such that the radiators comprising each element pair form a straight line which includes the center point.

25. The arrangement according to claim 24 wherein said elements are end-fired to provide individual lobes directed outward in azimuth from said central point, each loop having a phase which is independent of the others.

26. The arrangement according to claim 25 wherein said first means are coupled to said plurality of antenna elements to provide a multiphase first antenna pattern signal energy.

27. A non-physical steerable antenna arrangement capable of having patterns with a plurality of steerable nulls comprising:

- a. first means providing an omnidirectional omniphase reference first excitation having a predetermined initial phase;

b. second means providing a substantially omnidirectional multiphase second excitation simultaneously with said first excitation, said multiphase excitation having a predetermined initial rate of change of phase per azimuth angle, said first and second excitations combining to provide a resultant pattern excitation having a plurality of nulls, the number and azimuthal position thereof being dependent upon the phase of said reference first excitation in combination with the rate of change of phase per azimuth angle of said mul-

- tiphase second excitation;
- c. third means for varying the phase of said reference first excitation;
- d. fourth means for varying the rate of change of phase per azimuth angle of said multiphase second excitation; and
- e. steering means causing the resultant pattern excitation to be oriented in azimuth to any predetermined direction.

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