April 19, 1955 R. H. DU HAMEL 2,706,780

ANTENNA ARRAY

Filed July 31, 1952 2 Sheets-Sheet 1

Fig. 1.

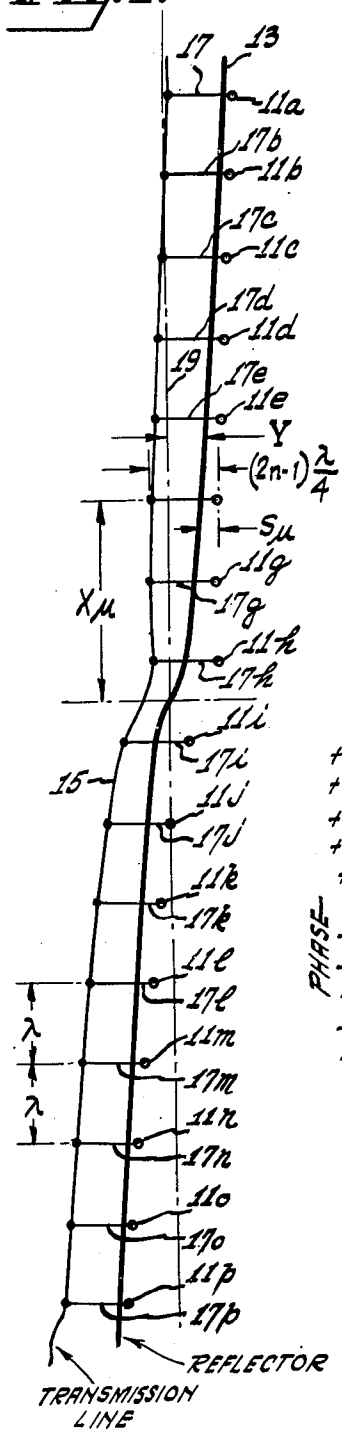


Fig. 2.

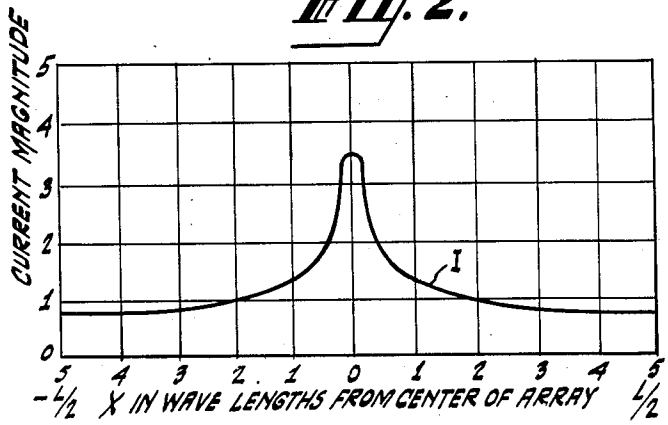
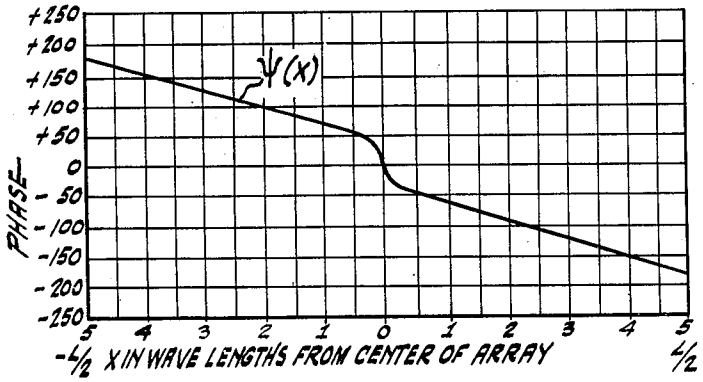


Fig. 3.



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April 19, 1955 R. H. DU HAMEL 2,706,780

ANTENNA ARRAY

Filed July 31, 1952 2 Sheets-Sheet 2

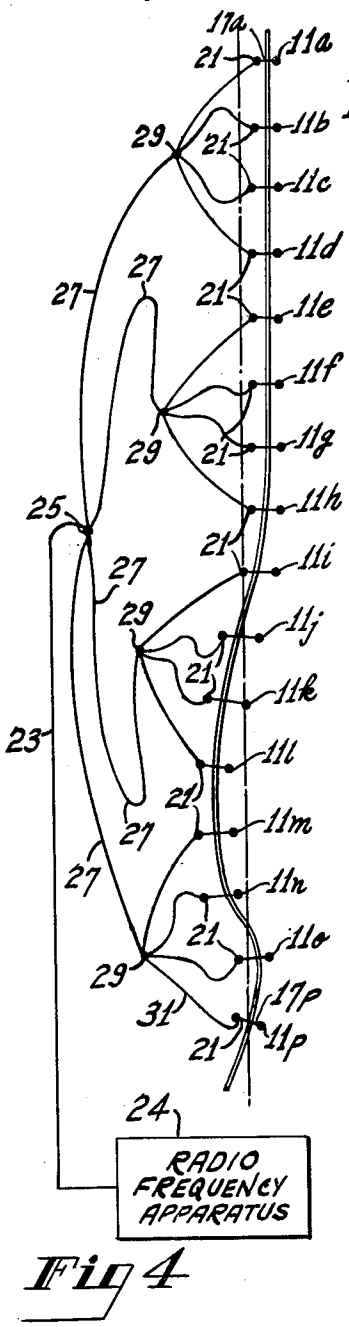

Fig. 4

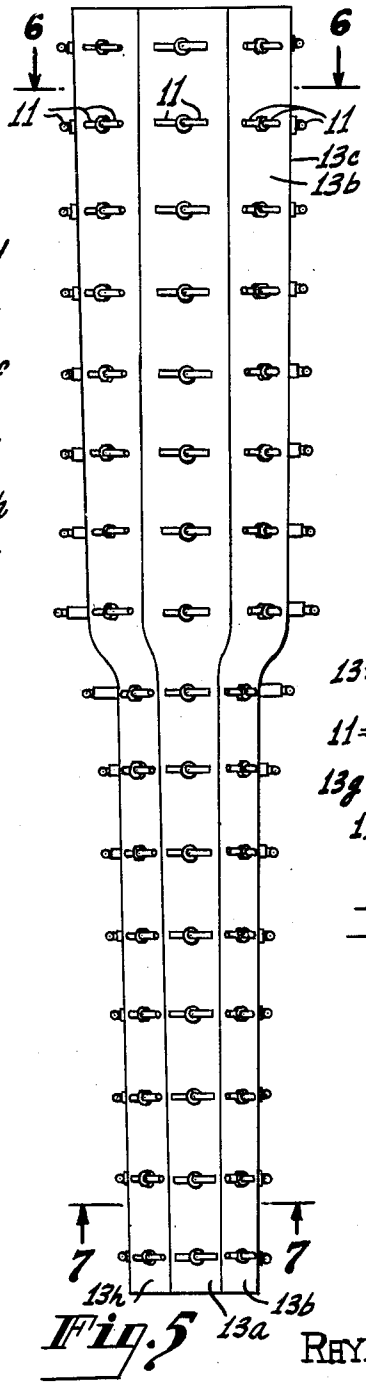

Fig. 5

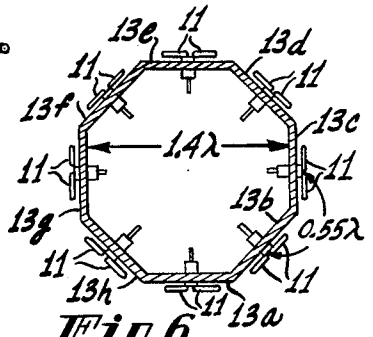

Fig. 6

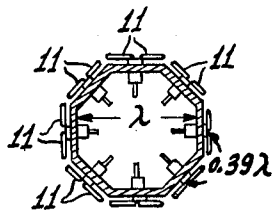

Fig. 7

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2,706,780

ANTENNA ARRAY

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The terminal fifteen years of the term of the patent to be granted has been disclaimed

12 Claims. (Cl. 250—33.53)

This invention relates to antennas and particularly to antenna arrays in which the field pattern is shaped to provide a desired pattern characteristic.

In the development of broadcasting services, antennas which are directional, as well as antennas which are omnidirectional in the azimuthal plane, have been employed. The generation of large amounts of radio frequency power at ultrahigh frequencies is not, at the present state of the art, as efficient or economical as is desired. Antenna systems heretofore used at frequencies up to 300 megacycles are not sufficiently efficient themselves to recommend them for widespread use as broadcast antennas for ultrahigh frequency signals. The problem is therefore presented in ultrahigh frequency television broadcasting, for example, as to how most efficiently and economically to use radio frequency energy in the range from 470 to 890 megacycles.

For the most economical use of the avaliable radio frequency energy, the radiated field intensity throughout the primary service area of the broadcasting establishment should be as constant as possible. A specially shaped vertical radiation pattern may be used to obtain a substantially constant field strength over the primary service area of an ultrahigh frequency broadcasting installation.

The present invention is directed to antenna arrays in which the field pattern characteristic can be shaped to provide a desired field pattern with extremely low radiation loss due to energy being wasted in undesired directions. Antenna arrays in accordance with the invention may be built to present a wide variety of field patterns, but it is expected that an important application thereof will be for ultrahigh frequency broadcasting services utilizing horizontal polarization to provide maximum coverage of the broadcast service area.

An object of this invention is to provide an antenna array of simple physical arrangement capable of producing specially shaped field pattern characteristics.

Another object of this invention is to provide an antenna array capable of producing a shaped beam radiation pattern characteristic which makes use of a straightforward and uncomplicated transmission line coupling arrangement.

A further object of this invention is to provide an antenna array for horizontally polarized waves in which the vertical radiation pattern may be simply controlled by the physical shape of the array.

Yet another object of this invention is to provide a new method of designing an antenna array to produce a specified radiation pattern.

Still another object of this invention is to simplify design methods of antenna arrays to produce a specified field pattern.

In accordance with the present invention, these and other objects are attained by an antenna array which includes a plurality of antenna elements closely spaced to a current sheet reflector structure. All of the currents in the antenna elements are made equal and in phase by arranging the transmission line connections so that each element is coupled through a quarter-wave of line to a common voltage point. The amount that each of the antenna elements in the array contributes to the field pattern characteristic is determined and controlled by the spacings of the individual antenna elements from the current sheet reflector structure. The effective phase of the currents in the individual antenna elements relative to a far field point is controlled by deviating or warping the sheet reflector from a linear reference base. The spacing

between the individual antenna elements and the reflector sheet may vary from one-quarter wavelength to as little as $\frac{1}{100}$ of a wavelength. In general, the warping of the sheet reflector at any point along the array relative to the linear base reference will be less than one-half wavelength, although greater variation in the reflector sheet is contemplated under certain conditions. The resultant array produces a field pattern characteristic which is simply controlled by physical adjustments of the shape of the antenna array itself, and the antenna coupling networks are kept very simple.

A more detailed explanation follows in conjunction with the accompanying drawings, in which:

Fig. 1 is an elevation of an array of antenna elements in front of a current sheet reflector, embodying the principles of this invention;

Figs. 2 and 3 are curves explanatory of certain features of the invention;

Fig. 4 is an elevation of another antenna array in accordance with the invention;

Fig. 5 is an elevation of an antenna array, in accordance with this invention, which has an omnidirectional pattern in the horizontal plane and a shaped vertical pattern characteristic;

Fig. 6 is a cross section along the line 6 of Fig. 5; and

Fig. 7 is a cross section along the line 7 of Fig. 5.

Referring now to Fig. 1, a plurality of antenna elements **11***a* through **11***p* are arranged in close proximity to a current sheet reflector **13**. For the purpose of this discussion, the antenna elements **11***a* through **11***p* are assumed to be identical elements in which the currents are parallel to the sheet reflector **13**. Simple half-wave dipoles may be utilized as the antenna elements **11***a* through **11***p*, although it should be understood that simple dipoles of other lengths, folded dipoles, unipoles, full-wave loops parallel to the sheet reflector, and certain continuous wire arrays may also be employed. The current sheet reflector **13** may be of solid metallic or conductive material, or may consist of a conductive screen; or a grid or network of conductors may be used to approximate a solid sheet reflector.

Each of the plurality of antenna elements **11***a* through **11***p* is coupled to a transmission line network having a main transmission line **15** and a plurality of quarter-wave coupling lines **17***a* through **17***p*. The transmission lines **15** and **17** are indicated by a single line on the drawing. This representation is intended to be schematic, and includes as well transmission lines having either single or plural conductors, such as waveguides, coaxial lines and parallel wire lines.

All of the antenna elements **11***a* through **11***p* in the array are fed with equal and in-phase currents. The transmission line connection system shown in Fig. 1 is arranged to produce equal in-phase currents in all of the antenna elements **11***a* through **11***p* as follows: The current feed point of each antenna element **11***a* through **11***p* is coupled through an odd quarter-wavelength coupling line **17***a* through **17***p* to an equal and in-phase source of voltage. The length of the coupling lines **17** is selected as an odd multiple of a quarter-wavelength since the receiving-end current of a line having a length equal to

$$(2n-1)\frac{\lambda}{4}$$

is independent of terminating end impedances and is determined by the sending-end voltage.

By connecting the odd quarter-wavelength coupling lines **17** at multiples of a wavelength in electrical distance along the transmission line **15**, equal and in-phase voltages are impressed across the quarter-wavelength coupling lines **17** yielding equal currents in the identical antenna elements **11***a* through **11***p*. It will be apparent to those skilled in the antenna art that the spacing of the antenna elements along the line of the array may be any integral number of half-wavelengths in electrical distance along the transmission line **15** for such a coupling arrangement. For odd multiples of a half-wavelength, such as one-half or three-halves wavelength spacing, the connection of the quarter-wave coupling line **17***h* associated with any one

antenna element, **11***h*, for example, will be coupled in opposite sense across the transmission line to that of a next adjacent coupling line **17***g* or **17***i*. As shown in Fig. 1 of the drawing, however, each of the quarter-wave coupling lines **17** will be connected in the same sense across the equal voltage points on the main transmission line **15**.

Other simple coupling networks to feed all of the antenna elements **11***a* through **11***p* with equal currents may readily be devised. An equal-length branching system like the one shown in connection with Fig. 4 may also be employed.

The field pattern in a plane perpendicular to the antenna elements **11***a* through **11***p* is controlled by the physical shape of the array. Knowing the desired field pattern and the aperture of the array, it is relatively simple to calculate the current distribution across the given aperture required to produce the desired pattern. This required current distribution across the aperture of the array will have certain values of magntiude and phase. In this invention, the effective magnitude of the field from each antenna element **11***a* through **11***p* is proportional to the sine of the spacing in radians of the antenna element **11***a* through **11***p* from the current sheet reflector **13**. The effective phase of the field from each element is proportional to the displacement from a linear base reference line **19** of the current sheet reflector **13** near the element in question.

It might appear to the worker in the art that a plane reflector can be utilized in which the current magnitude across the aperture of the array is controlled by the spacing of the antenna elements from a sheet reflector, and at the same time a simple transmission line network used to produce the required phase distribution function. Such an arrangement gives rise to a serious design problem. If the transmission lines from points of equal voltage are varied in length to alter the phase of the current in the individual antenna elements, then the transmission line connection system will no longer produce equal currents in all of the antenna elements and the effective current magnitude across the aperture will be altered. Such an arrangement therefore is subject to interaction between the adjustments of current magnitude and phase, and the design of sufficiently isolated transmission line coupling circuits capable of some degree of adjustment to duplicate the action of the preferred arrangement of the present invention becomes extremely complicated and tedious.

Referring now to Figs. 2 and 3 as well as to Fig. 1, let it be assumed that the required phase and magnitude of the current distribution have been determined. Fig. 2 illustrates a representative desired current magnitude distribution across an aperture having a length L. The aperture of an antenna is used in this specification to denote the equivalent area over which the antenna interchanges energy with free space. Fig. 3 is illustrative of a desired phase of the current across the same aperture of length L relative to a far field point. It is convenient for analytical purposes, although not necessary, to use the concept of a continuous current distribution across the entire aperture length L.

The current sheet reflector **13** of the antenna array is shaped or warped with respect to the linear base reference **19** according to the phase curve shown in Fig. 3. Let Y represent the distance from the linear base reference **19** to the surface of the current sheet reflector **13** at any point, the current sheet reflector **13** is shaped so that

$$Y=\left(\frac{\lambda}{2\pi}\right)\psi(X) \qquad (1)$$

where $\psi(X)$ is the required phase variation.

The antenna elements **11***a* through **11***p* are spaced from the current sheet reflector **13** a distance such that

$$R(X_\mu)=\sin\left(\frac{2\pi}{\lambda}S_\mu\right) \qquad (2)$$

where X is the distance measured from the center of the aperture of the array to any element and X_μ is the distance to the position of the μ'th element, S_μ is the spacing of the element from the current sheet reflector **13** and R (X_μ) is the normalized magnitude of the current I as X_μ.

The curves of Figs. 2 and 3 illustrate current magnitude and phase distribution across an antenna array having a vertical aperture of ten wavelengths to secure a good approximation of a cosecant squared vertical pattern characteristic.

The following table is representative of the dimensions of a unidirectional antenna array having a linear aperture of ten wavelengths with sixteen dipole antenna elements in front of a conductive current sheet reflector. The absolute values of current for the dipole element positions chosen represent those shown in Fig. 2. The phase variation $\psi(X)$ for the distance of the current sheet reflector from the linear base reference is taken from the curve of Fig. 3. The spacings of each of the elements in the sixteen element array in centimeters is given for a midband frequency of 940 megacycles.

Antenna Element (λ/2 Dipole)	Wavelengths from Center of Array X	Absolute Current Magnitude (I)	Normalized Current Magnitude R (X_μ)	Spacing $S/\mu\lambda$	Spacing in Centimeters, 940 mc. S_μ	Phase ψ (X)	Phase Deviation in Wavelengths Y
a	4 1/16	.68	.31	.078	2.50	171°	+.475
b	4 1/16	.70	.32	.080	2.55	155°	+.431
c	3 7/16	.75	.34	.085	2.72	139°	+.386
d	2 13/16	.81	.37	.093	2.97	123°	+.342
e	2 3/16	.92	.42	.105	3.36	104°	+.290
f	1 9/16	1.08	.49	.122	3.97	86°	+.238
g	1 5/16	1.4	.64	.16	5.11	65°	+.180
h	5/16	2.2	1.0	.25	8	42°	+.116
i	5/16	2.2	1.0	.25	8	−42°	−.116
j	1 5/16	1.4	.64	.16	5.11	−65°	−.180
k	1 9/16	1.08	.49	.122	3.97	−86°	−.238
l	2 3/16	.92	.42	.105	3.36	−104°	−.290
m	2 13/16	.81	.37	.093	2.97	−123°	−.342
n	3 7/16	.75	.34	.085	2.72	−139°	−.386
o	4 1/16	.70	.32	.080	2.55	−155°	−.431
p	4 1/16	.68	.31	.078	2.50	−171°	−.475

In Fig. 4 there is shown an alternative feeding arrangement for an antenna array in accordance with this invention. To insure that all of the antenna elements **11***a* through **11***p* are supplied with equal current, they are coupled by means of odd quarter-wavelength coupling lines **17***a* through **17***p* to points of equal voltage **21** with respect to the remainder of the transmission line system.

The points of equal voltage **21** are formed by a transmission line branching system. A main transmission line **23** from the radio frequency apparatus **24** (such as a transmitter or receiver), to which the antenna system is to be coupled, has a first branching point **25**. From this first branching point **25**, a plurality of equal-length transmission lines **27** extends to secondary branching points **29**. From each of these secondary branching points **29** a plurality of also equal-length transmission lines **31** extend to the points of equal voltage **21**.

For optimum operation, the transmission line coupling network should be arranged so that the equal length transmission lines **27** between the first branching point **25** and secondary branching points **29** are an integral multiple of half-wavelengths long, and the equal-length connection lines between the secondary branching points **29** and the points of equal voltage **21** are also selected to be some integral multiple of half-wavelengths long at the operating frequency. By selecting the first set of equal-length transmission lines **27** to be an integral number of half-wavelengths and the second set of equal-length transmission lines **31** to be also some integral number of

half-wavelengths (of course, not necessarily the same number of half-wavelengths as that for the first set of equal-length transmission lines **27**), the transmission line interconnection system presents equal voltage points at every branching point **25, 29** as well as the points of equal voltage **21.**

With the arrangement just described, if the antenna is used as a transmitting antenna, whatever voltage is impressed across the first branching point **25** by the radio frequency apparatus **24** (in this case, a transmitter) will also appear across each of the points of equal voltage **21** to which the antenna elements **11***a* through **11***p* are coupled by the odd quarter-wavelength coupling lines **17***a* through **17***p*. The antenna elements **11***a* through **11***p* are therefore all excited with equal and in-phase currents.

The arrangement shown in Figs. 5, 6 and 7 has eight arrays similar to that described above in connection with Figs. 1, 2 and 3 spaced around a polygonal structure. This array has an omnidirectional pattern in the horizontal plane and a cosecant squared vertical pattern characteristic. The separate faces **13***a* through **13***h* perform the same function and are each similar to the single sheet reflector **13** of Fig. 1. Each of the several reflector faces **13***a* through **13***h* is deviated from a linear base reference in the same manner as the current sheet reflector **13** of Fig. 1 to control the effective phase of the field due to each antenna element **11***a* through **11***p*. The amount of deviation from the linear base reference for each of the several reflector faces **13***a* through **13***h* is in accordance with the curves shown in Fig. 3 and described above. The linear base reference itself is referred to a vertical plane through the smallest dimension of the reflector face, and in this instance is tilted upward by 5.7 degrees to bring the maximum radiation for the particular array shown to have a downward tilt of 1.3 degrees from the horizontal.

A comparison of the spacing S_μ of the antenna elements **11** from the reflector sides **13***a* through **13***h* in Fig. 5 shows a representative variation in such spacing for an array to achieve a cosecant squared vertical pattern power distribution characteristic. The spacing of the individual elements **11** along each of the single reflector faces (for example, **13***c*) is in accordance with the table given above in the description of Figs. 1, 2 and 3.

By referring to Fig. 6, it may be seen that the perpendicular distance between any two opposite reflector sides (for example, **13***c* and **13***g*) may be of the order of $\frac{1}{4}\lambda$ at the top of the array for an embodiment having an octagonal cross section; and near the bottom of the array, as shown in Fig. 7, the cross-sectional dimension between the same two reflector sides is of the order of a wavelength. With such dimensions, the length of the sides of the polygon at the narrowest portion of the array becomes less than one-half wavelength. It is therefore necessary under certain conditions, like the one herein described, to make the individual antenna elements **11** shorter than one-half wavelength so that the sector occupied thereby will not overlap an adjacent sector. Normally, the spacing between the centers of adjacent dipole antenna elements **11** in a single layer like that shown in Fig. 6, will vary between $\frac{3}{8}\lambda$ and $\frac{5}{8}\lambda$ for an eight-sided array.

In the example shown, the spacing between the centers of adjacent antenna elements **11** in an upper layer as shown in Fig. 6 will be $.55\lambda$, while the spacing of similar elements in a lower layer like that of Fig. 7 will be $.39\lambda$. As was mentioned above, all of the antenna elements are preferably identical and will therefore be of the order of $\frac{1}{4}$ to $\frac{3}{8}$ wavelengths in length.

It will, of course, be apparent that if the number of sides of the polygon is increased to 10, 12 or 14, there will be less variation in cross-sectional dimensions between upper and lower layers, and the individual antenna elements **11** may be made longer and still achieve an additive field relative to some far field point from two adjacent radiating elements in a single layer.

The cross-sectional configuration of the closed figure approaches circularity as the number of sides is increased. The sheet reflector structure may be in fact made circular in cross section without changing the vertical pattern characteristic and without detrimental effects on the horizontal circularity where the minimum diameter of the figure thus formed is of the order of a wavelength or more.

All of the antenna elements in a longitudinal sector, like those associated with a single reflector face, **13***c* for example, in Fig. 5 are coupled by a simple transmission line network to a common voltage point as explained in conjunction with Figs. 1 and 4. Such networks are omitted from the drawing in Figs. 5, 6 and 7 for the sake of a clearer showing. All of the elements in the several sectors may be coupled to a common transmission line network, if the entire omnidirectional array is coupled in phase to the associated radio frequency apparatus, or a network individual to each sector (or oppositely disposed sectors) is necessary for phase rotational coupling, commonly called turnstile feeding.

Unidirectional antenna arrays having a cosine distribution pattern in the horizontal plane like those shown in Figs. 1 and 4 have further application in laboratory or experimental uses. Such directional arrays are especially convenient for pattern synthesis or analysis of broadside arrays. Since the antenna array of this invention provides separate and non-interacting physical adjustments of both the current magnitude and phase relative to a far field point, a desired pattern characteristic may be obtained by a trial and error method. Also, a calculated current and phase distribution across an aperture to produce a certain pattern may be verified experimentally by actual pattern measurements very rapidly and with extremely simple physical equipment. The number and complexity of the required physical adjustments for such pattern synthesis and verification are materially reduced over prior systems. Furthermore, the results obtained from an experimental verification using an antenna in accordance with this invention more nearly represent the actual pattern characteristic conditions than can be obtained by mathematical solution either manually or by pattern calculating devices.

What is claimed is:

1. An antenna array comprising a conductive sheet reflector and a plurality of antenna elements closely spaced to said sheet reflector, said sheet reflector being warped from a straight linear reference base extending along the length of the aperture of said antenna to control the effective phase of the field pattern characteristic due to each of said antenna elements relative to a far field point, the spacing of said elements from said reflector surface varying across the aperture of said array in accordance with the relative magnitude of the field due to the individual elements in the array with respect to a far field point.

2. An antenna array comprising a plurality of antenna elements distributed across an aperture, a current sheet reflector structure in the near zone of said plurality of elements, said current sheet reflector structure having a warped spatial deviation from a straight base reference line extending along the length of said aperture, said deviation varying therealong according to a required phase characteristic, said antenna elements being spaced from said current sheet reflector by different amounts in direct proportion to a desired current distribution across said aperture.

3. An antenna as defined in claim 2 wherein said spaced antenna elements are dipoles.

4. An antenna array comprising a plurality of antenna elements distributed across an aperture, a current sheet reflector structure in the near zone of said plurality of elements, said current sheet reflector structure having a spatial deviation from a straight base reference line extending along the length of said aperture, varying according to a required phase characteristic, said antenna elements being spaced from said current sheet reflector by different amounts in direct proportion to a desired current distribution across said aperture, and a transmission line coupling network connected to said antenna elements to couple in equal degree to each of said elements whereby equal instantaneous currents are produced in all of said antenna elements.

5. An antenna array comprising a plurality of antenna elements distributed across an aperture, a current sheet reflector structure in the near zone of said plurality of elements, said current sheet reflector structure having a spatial deviation from a straight base reference line along the length of said aperture varying according to a required phase characteristic, said antenna elements being spaced from said current sheet reflector by different amounts in direct proportion to a desired current distribution across said aperture, and transmission line coupling means for feeding each of said antenna elements with equal instantaneous currents.

6. An antenna array comprising a plurality of antenna elements distributed across an aperture, a current sheet reflector structure in the near zone of said plurality of elements, said current sheet reflector structure having a spatial deviation from a straight base reference line along the length of said aperture varying according to a required phase characteristic, said antenna elements being spaced from said current sheet reflector by different amounts in direct proportion to a desired current distribution across said aperture, and transmission line coupling means for feeding each of said elements from a common voltage reference point through a transmission line having a length of an odd multiple including unity of one-quarter wavelength at the operating frequency.

7. An antenna array comprising a plurality of antenna elements distributed along an aperture of several wavelengths, a continuous surface conduction current sheet reflector in the near zone of said plurality of elements, said current sheet reflector being spaced from a straight base reference along the length of said aperture by an amount which varies directly in free space wavelengths as a required phase characteristic of current in said elements across said aperture, said antenna elements being spaced from said current sheet reflector by different amounts each in direct proportion to a desired current magnitude distribution characteristic along the length of said aperture.

8. An antenna array comprising a plurality of antenna elements distributed along an aperture of several wavelengths, a continuous surface conduction current sheet reflector in the near zone of said plurality of elements, said current sheet reflector being spaced from a straight base reference line along the length of said aperture by an amount which varies directly in free space wavelengths as a required phase characteristic of current in said elements across said aperture, said antenna elements being spaced from said current sheet reflector by different amounts each in direct proportion to a desired current magnitude distribution characteristic along the length of said aperture, and transmission line coupling means for feeding each of said elements from a common voltage reference point through a transmission line having a length of an odd multiple including unity of one-quarter wavelength at the operating frequency.

9. An omnidirectional antenna array comprising a plurality of conductive sheet reflector structures forming the sides of a closed polygon, each of said plurality of conductive sheet reflector structures having a plurality of antenna elements closely spaced thereto, each of said plurality of conductive sheet reflectors being deviated in free space wavelengths from a linear reference base extending along the length of the aperture of said antenna in direct proportion to a predetermined phase characteristic, the antenna elements associated with each of said plurality of reflector structures being spaced therefrom by different amounts along the length thereof in direct proportion to a predetermined current distribution across said aperture.

10. An omnidirectional antenna array comprising a plurality of conductive sheet reflector structures forming the sides of a closed polygon, each of said plurality of conductive sheet reflector structures having a plurality of antenna elements closely spaced thereto, each of said plurality of conductive sheet reflectors being deviated in free space wavelengths from a linear reference base extending along the length of the aperture of said antenna in direct proportion to a predetermined phase characteristic, the antenna elements associated with each of said plurality of reflector structures being spaced therefrom by different amounts along the length thereof in direct proportion to a predetermined current distribution across said aperture, and a plurality of transmission line coupling networks, each of said networks being individual to all of said elements associated with one of said reflector structures and feeding each of said elements associated with said reflector structure from a common voltage reference point through a section of transmission line having a length of an odd multiple including unity of one-quarter wavelength at the operating frequency.

11. An omnidirectional antenna array comprising a plurality of conductive sheet reflector structures forming the sides of a closed polygon, each of said plurality of conductive sheet reflector structures having a plurality of antenna elements closely spaced thereto, each of said plurality of conductive sheet reflectors being deviated in free space wavelengths from a linear reference base extending along the length of the aperture of said antenna in direct proportion to a predetermined phase characteristic, the antenna elements associated with each of said plurality of reflector structures by different amounts along the length thereof in direct proportion to a predetermined current distribution across said aperture, and a transmission line coupling means common to all of said antenna elements for feeding each of said antenna elements with equal instantaneous currents.

12. An omnidirectional antenna array comprising a conductive sheet reflector forming a closed figure in cross section and having a length of several wavelengths at the operating frequency and having a longitudinal axis, a plurality of antenna elements arranged along each of a number of longitudinal sectors, said sheet reflector being deviated in distance from the longitudinal axis along the length thereof in direct proportion to a predetermined phase characteristic, said antenna elements in each of said sectors being spaced from said reflector by different amounts along the length thereof in direct proportion to a predetermined current distribution, and transmission line means for feeding each of said antenna elements in each sector with equal and in phase currents with respect to the remaining elements in said sector.

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