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FINITE FOCUS WAVE ENERGY ANTENNA ARRAY

4 Sheets-Sheet 1



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June 12, 1962

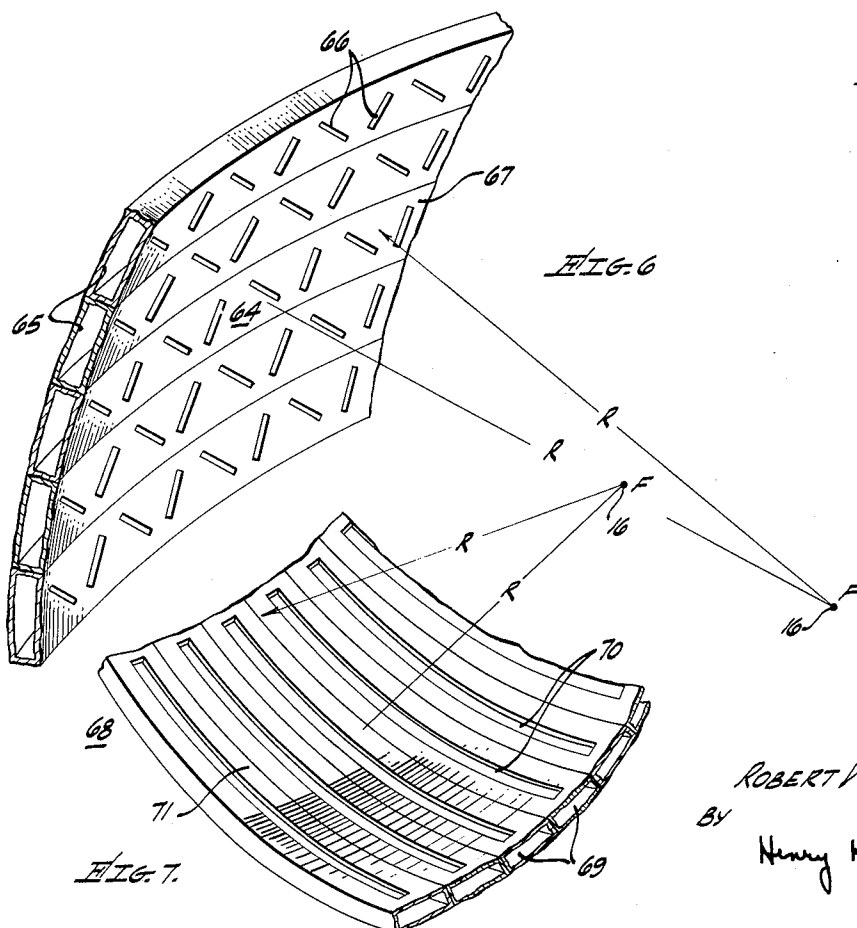
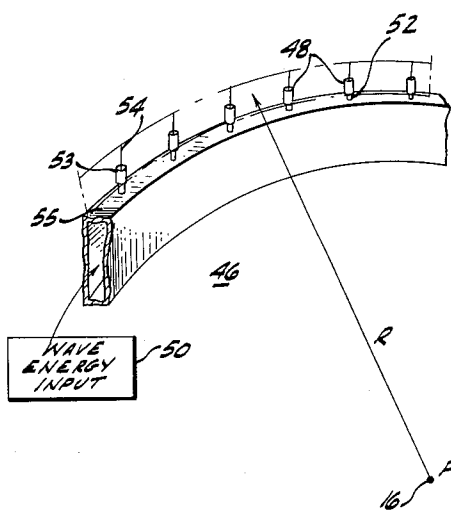
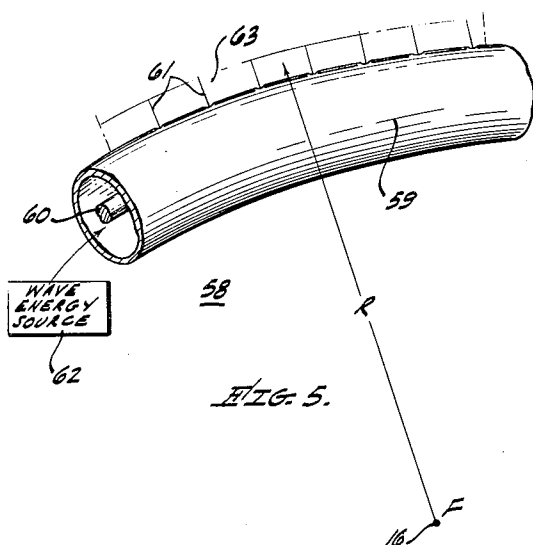
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FINITE FOCUS WAVE ENERGY ANTENNA ARRAY

Original Filed Oct. 31, 1955

4 Sheets-Sheet 2



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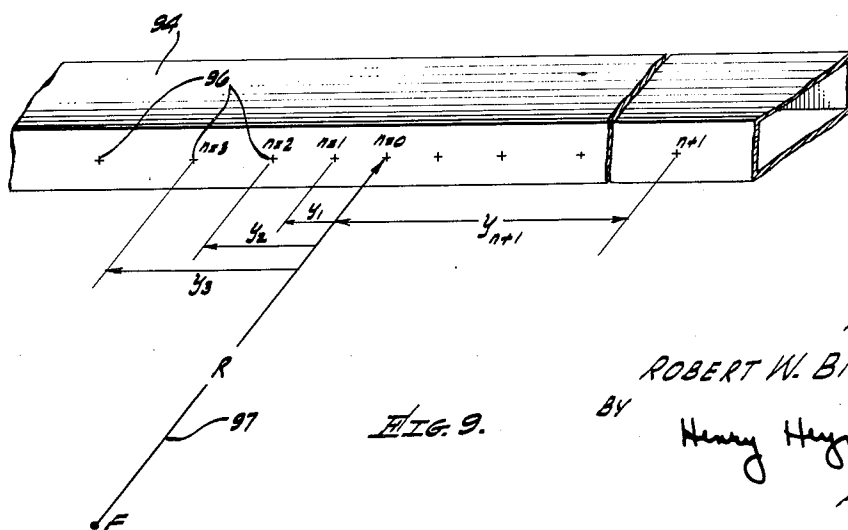
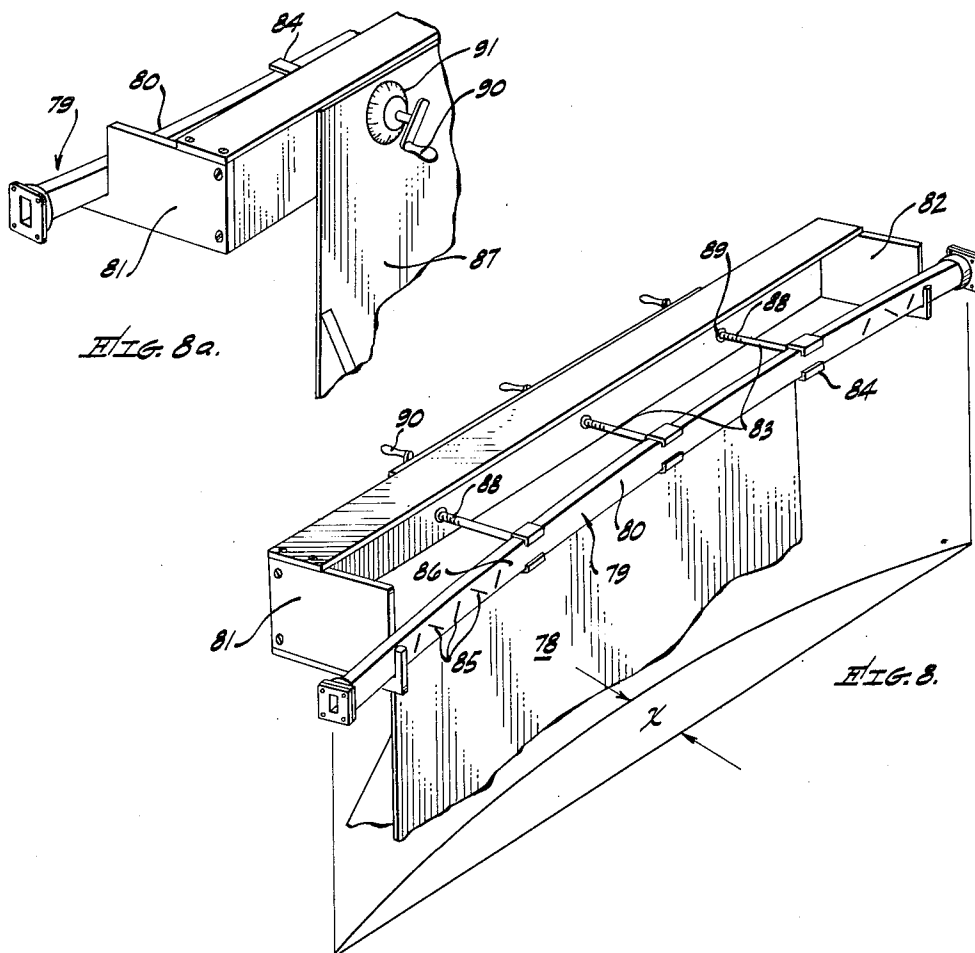
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FINITE FOCUS WAVE ENERGY ANTENNA ARRAY

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4 Sheets-Sheet 3



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4 Sheets-Sheet 4

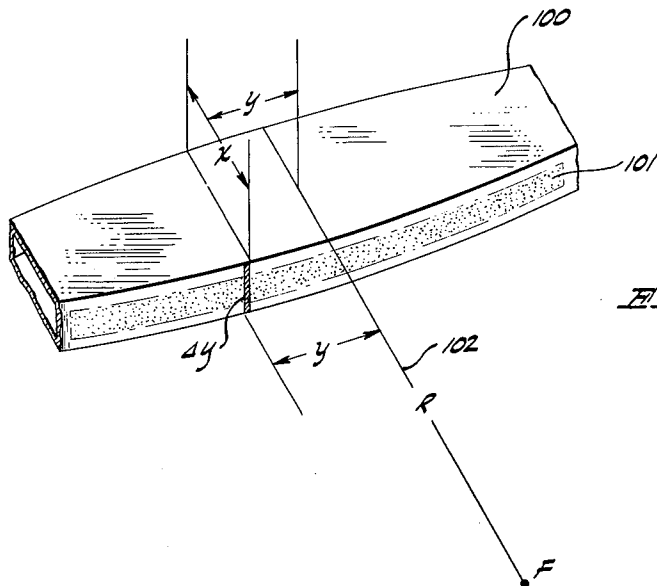


FIG. 10.

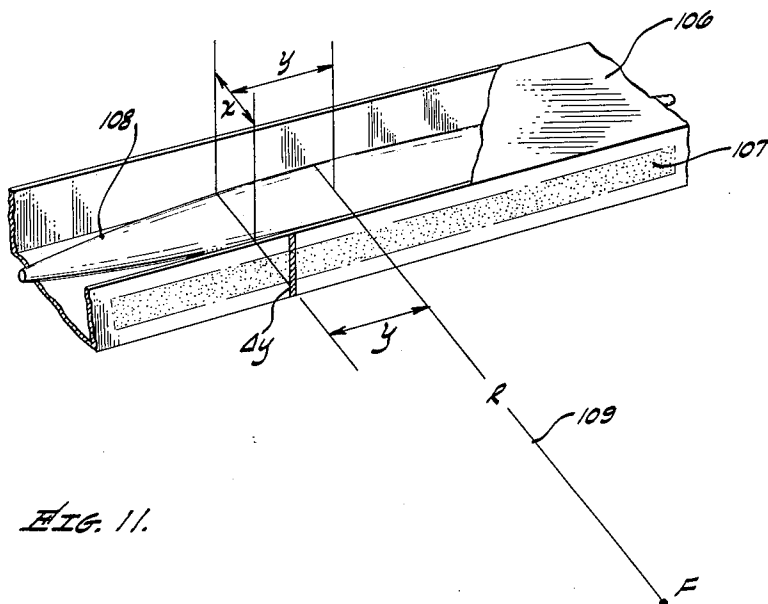


FIG. 11.

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3,039,098 FINITE FOCUS WAVE ENERGY ANTENNA ARRAY

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Continuation of application Ser. No. 543,718, Oct. 31, 1955. This application Sept. 21, 1959, Ser. No. 842,174
13 Claims. (Cl. 343—771)

This invention relates to directional wave energy antenna arrays and is a continuation of earlier filed application, Serial No. 543,718, Finite Focus Wave Energy Antenna Array by Robert W. Bickmore, filed October 31, 1955, now abandoned. More particularly, it relates to antennas of the multiple element and extended source type having a finite focal length. The invention also relates to a method of focusing antenna arrays of the multiple element and extended source type and to a method of determining the Fraunhofer pattern of such antennas in the Fresnel region.

In application in which wave energy antennas of either the multiple element type or the extended source type are employed it has become desirable to extend the useful operating range to a point inside the Fresnel region of the antenna array. Antenna arrays heretofore employed of the multiple element or the extended source type radiate a parallel beam of wave energy and in the absence of microwave lenses performed unsatisfactorily in the Fresnel region. As is well known in the art, the operation of an antenna array of the type described at distances closer than the transition point causes increasingly greater loss in gain and resolution as this distance from the antenna decreases. Consequently, antenna arrays radiating a parallel beam of wave energy and therefore having their focal point at infinity perform satisfactorily at all distances between the transition point and infinity but deteriorate in performance at distances closer than the transition point.

In certain applications such as antenna arrays attached to aircraft, it has become desirable to control the useful range of the array for different conditions encountered in tactical use. For example, in air-borne ground reconnaissance the transition point associated with the particular antenna array determines the minimum height at which the reconnaissance plane may effectively operate. It is also true that the resolution of the antenna array is related to its transition point, i.e., the greater the distance to the transition point the greater is the resolution of the antenna array. In order to permit effective reconnaissance at different altitudes without sacrificing the degree of resolution afforded by an antenna array having a small distance to its transition point, it has been necessary to equip a reconnaissance aircraft with more than one antenna array. The geometry of each of these antenna arrays is selected to give an acceptable resolution at its respective height of operation.

The method heretofore employed relating to pattern measurements of antenna arrays has entailed great cost in setting up a suitable pattern survey range in the Fraunhofer region. In order to retain the Fraunhofer pattern as a means of pattern specification, the pattern measurements have to be conducted at a minimum distance of approximately twice the transition point distance. If this criteria is applied to antenna arrays approaching a thousand wavelengths of effective aperture dimension the pattern survey range may be required to be several miles long.

It is therefore a principal object of this invention to provide an antenna which avoids the performance degradation of prior art antenna arrays which appears in the

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form of wide beam widths, high side lobes and decreased gain when an antenna of the multiple element or extended source types are used operationally in their Fresnel zones.

It is another principal object of this invention to provide an antenna array of the multiple element or extended source type having a finite focal length.

It is another object of this invention to provide a multiple element or extended source type antenna array whose useful range may be extended into the Fresnel region of said antenna.

It is another object of this invention to provide an antenna array of the multiple element or extended source type whose focal length and therefore whose useful range is continuously adjustable.

It is a further object of this invention to provide a method whereby the useful range of an existing antenna array of the multiple element or extended source type may be extended into the Fresnel region of said antenna.

It is a still further object of this invention to provide a method whereby the focal length and therefore the useful range of an existing antenna array of the multiple element or extended source type may be continuously adjustable.

It is a still further object of this invention to provide a method whereby the Fraunhofer pattern of an antenna array of the multiple element or extended source type may be obtained by direct measurements from a point within the Fresnel region of said antenna array.

It is a still further object of this invention to provide a method whereby the Fraunhofer pattern measurements of an antenna array of the multiple element or extended source type may be conducted on a pattern survey range whose overall length is substantially smaller than the width of the Fresnel zone of said antenna array.

A finite focus wave energy antenna array device in accordance with this invention may utilize a multiple element or an extended source type of radiation means included within a closed elongated wave energy transmission line. The radiation means extends parallel to the direction of elongation and is excited by wave energy flowing thereacross. The radiation means defines an aperture surface which is made to radiate a converging wavefront.

Wave energy antenna arrays heretofore known of the type utilizing a closed elongated wave energy translator such as a rectangular, circular, or coaxial waveguide, and which include radiation means extending substantially along the direction of wave energy flow inside the energy translator, and which radiate a beam of wave energy into space having a beam axis substantially perpendicular to the direction of such energy flow have carefully been designed to produce a radiation beam having a planar wavefront in order to radiate a parallel beam of wave energy. Such antenna arrays are considered to have their focal point at infinity. Wave energy antenna arrays in accordance with this invention have their apertures controlled to produce a converging wavefront in order to give rise to a converging beam of wave energy. Such antenna arrays are said to have a finite focus, whose beam of wave energy converges upon the focal point.

In accordance with this invention there are two ways for controlling the aperture of the antenna array to produce a converging wavefront; one being in the nature of controlling the electrical excitation path length to the individual elements making up the array, while the other one is achieved by geometrically deforming the aperture of the array so that its radiation elements or its surface containing the extended source is juxtaposed with a cylindrical or spherical surface. These two ways result in an

electrical and a geometrical converging aperture respectively. A planar aperture of an array can be converted to launch a converging wavefront by the production of the commonly called quadratic phase effect over the surface of the aperture. Another way of stating the same requirement is that a noncircular aperture is made electrically convergent by the utilization of appropriate phasing, space wise or time wise, equivalent substantially to the distance between corresponding portions of the non-circular aperture and the desired convergent aperture. There are three ways of accomplishing this. First, the radiation elements constituting the aperture may be spaced at predetermined positions so as to produce a quadratic phase effect and thereby give rise to a converging wavefront. Second, the interior of the wave energy translator which feeds equispaced radiation elements or an extended source may be provided with a phase shifter such as a dielectric whose cross section varies along its length to produce the desired quadratic phase effect. Third, the length of a transmission line which feeds equispaced radiation elements or an extended source may vary along its length in such a manner as to produce the desired quadratic phase effect. The center of curvature of the quadratic phase effect is the point of convergence of the wavefront from the planar aperture and therefore the focal point of the array.

A geometrically converging aperture in accordance with this invention is established by either a cylindrical or spherical array. For a one-dimensional array the radiating elements or the extended source are positioned along the loci of a surface of a segment of a cylinder whose radius is equal to the desired focal length of the wave energy antenna array. For a two-dimensional array the radiating elements or the extended sources are placed on the loci, a segment of a sphere whose radius is equal to the desired focal length of the wave energy antenna array. The plurality of elements or extended source constituting the array in cylindrical or spherical form radiates a converging wavefront whose focal point is determined by the geometrical shape of the array.

Many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings in which like reference numerals designate like parts throughout the figures thereof and wherein:

FIG. 1 is a diagrammatic view of the optical analogue of the finite focus wave energy antenna array in accordance with this invention.

FIGS. 2 to 5 are perspective views of different embodiments of one-dimensional finite focus wave energy antenna arrays in accordance with this invention employing geometric aperture control.

FIGS. 6 and 7 are perspective views of different embodiments of two-dimensional finite focus wave energy antenna arrays in accordance with this invention employing geometric aperture distortion.

FIG. 8 and FIG. 8a are perspective views of a focusing frame pertaining to the method of controlling the focal point distance of a wave energy antenna array.

FIGS. 9 to 11 are perspective views of different embodiments of one-dimensional finite focus wave energy antenna arrays in accordance with this invention and employing electrical aperture control.

Referring now to the drawings, FIGURE 1 shows an antenna array 12. The array 12 is a circular arc having a radius R and a center of curvature 16 coincident with the focal point F of the antenna and on the array axis 18. The aperture 14 of the array has an effective aperture length denoted by L, a dimension of length. The antenna array 12 is coupled to a wave energy source 20 which supplies the antenna with wave energy of wavelength λ , a dimension of length.

Wave energy antenna arrays heretofore known have had their focal point located at infinity. This would cor-

respond to a radius of curvature R which is infinitely great. In connection with these conventional antenna arrays it has been found that their useful range commenced at the well known transition point 22, located on the array axis 18 at a distance T from the aperture. The transition point 22 also lies on the transition zone boundary line 24 separating the Fraunhofer region 25 and the Fresnel region 26. An antenna array having its focal point located at infinity gives satisfactory performance in the Fraunhofer region 25 but not in the Fresnel region 26. The transition point distance T is found to be characteristic of the aperture, depending only on its effective length L and the working wavelength λ . The relation between the transition point distance T, the effective aperture length L and the working wavelength λ is given by

$$T = \frac{L^2}{\lambda} \quad (1)$$

an expression well known in the art.

For the purpose of explaining the characteristics of the finite focus wave energy antenna array of this invention it is useful to employ an optical analogue to the array wherein the array occupies the place of an optical lens. In this way it is possible to employ terms like near-point, far-point, and depth of field which will further illustrate the purpose and application of this invention. The near-point 28 is defined as the point along the array axis closest to the aperture at which satisfactory performance is obtained. The far-point 30 is defined as the point along the array axis farthest from the aperture at which satisfactory performance is obtained. The distance between the near-point 28 and the far-point 30 is called the depth of field of the antenna.

In geometrical optics the near-point and the far-point are the positions at which the circle of confusion has an acceptable diameter for the particular purpose to which the optical system is intended. In photography the depth of field being the distance between the near-point and the far-point is determined by the resolution of the photographic emulsion and the acceptable diameter of the circle of confusion is determined by the graininess of the emulsion.

Using this nomenclature on an antenna array having its focal point at infinity it may be said that the near-point 28 of such an antenna coincides with the transition point 22 and that the focal point 16 and the far-point 30 both are in infinity. The depth of field of such an array would be infinite and extend from the near-point 28 to infinity.

The finite focus wave energy antenna array device of this invention is made to radiate a converging wavefront having a focal point 16 at a distance R from its aperture. For such an array it can be shown that the near-point 28 is located at a distance given by the expression

$$\frac{T}{\frac{T}{R} + 1} \quad (2)$$

and the far-point 30 is located at a distance given by the expression

$$\frac{T}{\frac{T}{R} - 1} \quad \text{for } T \geq R \quad (3)$$

from its aperture 14. Therefore, the depth of field of such an array is given by the expression

$$\frac{2T}{\left(\frac{T}{R} + 1\right)\left(\frac{T}{R} - 1\right)} \quad \text{for } T \geq R \quad (4)$$

If R is greater than T, i.e., the focal point 16 is located in the Fraunhofer region 25, the far-point 30 recedes to infinity and therefore the depth of field becomes infinitely great. If R is smaller than T, i.e., the focal point 16 is located in the Fresnel region 26, the far-point 30 is at a

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finite distance from the aperture and the depth of field is finite as shown by Equations 3 and 4. A special case arises when R is equal to T , i.e., the focal point 16 is located at the transition point 22. The far-point 39 is still at infinity but the near-point 28 distance is equal to $(\frac{1}{2})T$ or midway between the aperture 14 and the transition point 22. It is therefore seen that if an array has its focal point 16 coinciding with the transition point 22, its useful range is extended over that of an array having its focal point at infinity by a distance $(\frac{1}{2})T$ and the depth of field is a maximum.

FIG. 2 is a three-dimensional view of a section of a multiple element finite focus wave energy antenna array wherein the curved hollow rectangular waveguide 34 is provided with a plurality of discrete slot elements 36. Wave energy is fed to the rectangular waveguide 34 from a wave energy source 38. The rectangular waveguide 34 is a segment of an annulus whose inner surface establishes the radiating aperture 39 of the array. The radiating aperture 39 has a radius of curvature R and its center of curvature is located at F . This center of curvature F , as described in conjunction with FIG. 1, is also the focal point 16 of this antenna.

To determine the radius of curvature R of an array of the type shown in FIG. 2 which is to have predetermined operational characteristics, resort may be had to the relationships given by Equations 2, 3 or 4. The transition point distance T is, as mentioned before, a property of the antenna array given by the relationship of Equation 1. The effective aperture dimension L is approximately equal to the distance between the first and the last slot elements 36. To illustrate the application of the equations, assume an antenna array of the type shown in FIG. 2 having 200 slot elements, each element being a distance of one-half wavelengths from the next. The effective aperture dimension L is therefore approximately equal to 100λ . The transition point distance T as given by Equation 1 is approximately equal to $10,000\lambda$. Assume further a working wavelength λ equal to one centimeter so that the distance T is equal to 100 meters. For an antenna array having its focal point F at infinity, this implies that the distance to the near-point is 100 meters. If it is desirable to design a finite focus antenna having its near-point at a distance of 50 meters, the relation given by Equation 2 shows that the radius of curvature R must be equal to 100 meters. In other words, the focal point is changed from infinity to a distance of 100 meters from the aperture of the array. This is also the distance at which the depth of field is a maximum since the far-point as given by the relation of Equation 3 is still at infinity.

FIG. 3 is a three-dimensional view of a section of the extended source type finite focus wave energy antenna array wherein a curved hollow rectangular waveguide 40 is provided with an extended slot element 42. Wave energy is fed to the rectangular waveguide 40 from a wave energy source 44. The rectangular waveguide 40 is a segment of an annulus whose inner surface serves as the radiation aperture 45. The radiating aperture 45 has a radius of curvature R and its center of curvature is at F . This center of curvature F , as described in conjunction with FIG. 1, is also the focal point 16 of this antenna.

FIG. 4 is a three-dimensional view of a modification of the finite focus wave energy antenna array of FIG. 2. A curved hollow rectangular waveguide 46 is provided with a plurality of discrete dipole elements 48. Wave energy is fed to the rectangular waveguide 46 from a wave energy source 50. The dipole elements 48 may be of any of the forms well known in the art and as an example are shown here as comprising essentially a coaxial cable 52 having an outer conductor 53 and an inner conductor 54. The outer conductor 53 is folded back upon itself a distance of one-quarter of a wavelength and the inner conductor 54 projects from the folded end of the outer conductor a distance of one-quarter of a wavelength. The method of coupling the radiator 48 to the waveguide 46 is well known in the art. The waveguide 46 is a seg-

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ment of an annulus such that the dipole elements form an imaginative cylinder of radius R and thereby establishes the radiation aperture 56. The radiation aperture 56 has therefore a radius of curvature R and its center of curvature is at F . This center of curvature F , as described in conjunction with FIG. 1, is also the focal point 16 of this antenna array.

FIG. 5 is a three-dimensional view of a further modification of the finite focus wave energy antenna array of FIG. 4. A curved coaxial line 58 having an outer conductor 59 and an inner conductor 60 is provided with a plurality of discrete dipole elements 61. Wave energy is fed to the line 58 from a wave energy source 62. The line 58 is a segment of a form such that the dipole elements 61 lie on an imaginary cylinder of radius R and thereby serve as the radiation aperture 63. The radiation aperture 63 has therefore a radius of curvature R and its center of curvature is at F . This center of curvature F is also the focal point 16 of this antenna.

The illustrative example given in connection with FIG. 2 is equally applicable to the finite focus wave energy antenna arrays of FIGS. 3, 4 and 5. Obviously many modifications and variations of the present inventions are possible in the light of the above teachings. For example, any general wave energy translator may be provided with a radiation aperture surface to effect an exchange of wave energy between the translator and free space. To apply to such an antenna the above teachings and thereby to convert an antenna array having its focal point at infinity to a finite focus wave energy antenna array, it is only necessary that the wave energy translator be deformed so that the effective aperture surface, which is assumed equiphased, has the shape of a circular arc of radius R . The center of curvature then forms the focal point of this generalized antenna array. The translator here referred to may be a hollow or a coaxial waveguide of any suitable cross section. The effective aperture with which the energy translator is provided may be an extended source such as the long slot, or it may comprise multiple elements such as discrete radiators of the dipole, slot or probe type. The one-dimensional antenna arrays shown in FIGS. 2, 3, 4 and 5 have in common, in the case of multiple type antenna arrays, radiation elements distributed along a circular arc and in the case of extended source type antennas an aperture surface contained on the inner side of an annulus segment.

FIGS. 6 and 7 respectively are perspective views of two-dimensional antenna arrays employing the teachings of the one-dimensional antenna arrays shown in FIGS. 2, 3, 4 and 5.

FIG. 6 is a two-dimensional array of a multiple element finite focus wave energy antenna. The spherical array 64 comprises a number of curved hollow rectangular waveguides 65 which are provided with discrete slot elements 66. FIG. 7 is a two-dimensional array of an extended source finite focus wave energy antenna array. The spherical array 68 comprises a number of curved hollow rectangular waveguides 69 each of which is provided with an extended slot element 70. Both the arrays 64 and 68 are segments of a spherical shell whose inner surfaces are the radiation apertures 67 and 71, respectively. The radiation aperture has a radius of curvature R and its center of curvature is located at F . The centers of curvature are the focal points 16 of these antennas respectively.

The illustrative example given in connection with FIG. 2 is equally applicable to the finite focus wave energy antenna arrays employed to operate as two-dimensional arrays. The radius of curvature R is determined as above by the use of Equations 2, 3 or 4, depending on the required operational characteristics of the two-dimensional array.

Obviously many modifications and variations of the two-dimensional arrays are possible in the light of the above teachings. For example, any general wave energy translator may be provided with a two dimensional radiation

aperture to effect an exchange of wave energy between the translator and free space. To apply to such an antenna the above teaching and thereby to convert a two-dimensional antenna having its focal point at infinity to a finite focus wave energy antenna array, it is only necessary that the wave energy translator be deformed so that the effective aperture has the shape of a spherical surface of radius R. The center of curvature then forms the focal point of this generalized antenna array.

Shown in FIG. 8 and FIG. 8a is a focusing frame 78 which operates upon a wave energy antenna array 79. For the purpose of illustration the antenna array 79 is here shown as comprising a hollow rectangular waveguide 80 which is held at each extremity by support brackets 81 and 82 respectively and is subjected throughout its unsupported length to the pull from three draw bars 83 to effect its distortion. The draw bars 83 are coupled to the waveguide 80 by means of holding clamps 84. The waveguide 80 is provided with discrete slot elements 85 which form the radiation aperture 86. The support brackets 81 and 82 are rigidly attached to the base structure 87 of the focusing frame 78. The draw bars 83 have a threaded end 88 which passes through a threaded hole 89 in the base structure 87 and which are terminated in the handles 90. The handle 90 is provided with a Vernier scale 91 which accurately measures the deflection of the antenna array at the points of attachments.

On the rotation of the draw bar 83, the antenna array 79 may be distorted from a straight line. By the simultaneous use of all three draw bars 83 the distortion may be made to approach a circular arc of any desired radius of curvature. For instance, if the deflection of the center draw bar is equal to x and if the other draw bars are adjusted so that the antenna 79 is bent into a true circular arc, the approximate relationship between the deflection x caused by the center draw bar 83 and the resulting radius of curvature R of the antenna 79 is given by the expression

$$x \approx \frac{L^2}{8R} \quad (5)$$

where L is the effective aperture dimensions of the aperture surface 86.

The focusing frame shown in FIG. 8 represents only one method whereby an elongated wave energy translator may be subjected to circular deformation. If the translator is of great length, additional supports and draw bars may be required. Other methods of circular or spherical deformation, either continuously or step-wise adjustable to shape, wave energy translators may be readily devised by those skilled in the mechanical arts. The focusing frame such as shown in FIG. 8 may be utilized in conjunction with a wave energy antenna array to provide a new and novel method of determining the Fraunhofer pattern of such an antenna from a distance materially smaller than has been heretofore possible. Satisfactory Fraunhofer pattern determination heretofore involved a standard criterion that measurements ought to be conducted at a distance at least twice as large as the distance to the transition point, that is a distance larger than 2T. The method herein described makes it possible to conduct measurements for the determination of the Fraunhofer pattern at any desired distance. This is accomplished by focusing the antenna array so that the desired measuring distance lies within the depth of field and preferably coincides with the focal distance.

The method herein taught will be made clearer by considering the procedure to be adopted. First, it is ascertained what distance is convenient for the determination of the radiation pattern. This distance depends upon the existing facilities, such as a pattern range of limited size, or some other kind of limited space wherein the measurements have to be conducted. Second, if the maximum available measuring distance is larger than twice the transition point distance, the Fraunhofer pattern may be determined within the available space in the manner here-

tofore employed. If the maximum available measuring distance is less than twice this distance the antenna to be measured is focused so that the focal distance coincides approximately with the available maximum range distance. The maximum available measuring distance therefore gives the radius of curvature necessary to focus the antenna array. In the case of Fraunhofer pattern determination of finite focus antenna arrays, the focal distance should coincide with the range distance which may require re-focusing. Third, the antenna array is inserted into a focusing frame such as the one shown in FIG. 8 and distorted into a circular arc whose radius of curvature is approximately equal to the range distance.

An illustrative example may involve an antenna array having its focal point at infinity and comprising a linear array $\sqrt{40}$ meters long. If the wavelength is $\lambda=8.0$ millimeters, the transition point distance T by Equation 1 is equal to 5,000 meters. By the stated criteria this requires a measuring range should be 10,000 meters. If, however, the available pattern range is only 100 meters the Fraunhofer pattern of the antenna array can be determined by the above method which involves focusing the antenna array by imparting to it a radius of curvature of approximately 100 meters. This corresponds to a deflection by Equation 5 of approximately 5 centimeters of the center of the antenna array with respect to its ends.

The method shown for imparting a geometric curvature to the antenna array may also be used in applications where it is desirable to control the useful range of the antenna array. In airborne ground reconnaissance it may be attached to the aircraft by means of a focusing frame similar in operation to the one shown in FIG. 8. An operator inside the aircraft would be able to, by suitable means, change the radius of curvature of the antenna array and thereby control the useful range and maximize the resolution.

In view of the fact that any real aperture may be represented by a virtual aperture normal to the direction of propagation of wave energy, the finite focus wave energy antenna is not limited to Fraunhofer patterns having a zero squint angle. The squint angle depends on the phase relation of the wave energy contributions from adjacent radiation elements. In the antennas shown in FIGS. 2, 4, 5, 6 and 8, the wave energy contributions from each of the plurality of radiation elements are in phase with one another so that a broad side radiation pattern results. If a non-zero squint angle is desired the phase of the wave energy contributions from succeeding radiation elements must be changed linearly as is well known in the art. To convert an antenna array having its focal point at infinity and having a squint angle to a finite focus antenna array having the same squint angle, it is only necessary to geometrically distort the real aperture so that the virtual aperture assumes the necessary radius of curvature.

The above embodiments of this invention have in common with one another an aperture which radiates a converging wavefront by virtue of its geometrical shape. This implies that the aperture is itself an equiphased shell or zone so that the converging wavefront, when leaving the aperture, is at all times parallel to the aperture. The aperture itself might be referred to as a geometrically converging aperture. In contradistinction to generating a converging wavefront by physically deflecting the equispaced surface of the array into an array with a geometrically converging aperture, the array may be electrically compensated so as to establish a virtual electrically converging aperture. The term electrical compensation as used herein refers to the process of electrically creating an aperture which is not in itself an equiphased shell or zone by virtue of phase control.

Another way of contrasting the two processes employed to generate a converging wavefront in accordance with the finite focus antenna array of this invention, becomes apparent when considering the necessary condition that any point from the aperture must be electrically equi-

distant from the focal point. This distance may be regarded as made up of two parts; the geometrical distance plus the phase distance, as is well known to those skilled in the fundamentals of wave propagation. The process which is termed geometrical aperture compensation pertains to the bending of an equiphase zone of the aperture into an annular sector whose center of curvature is the focal point. In this process, therefore, the distance from any point on the aperture to the focal point is made the same by adjusting the geometrical distance and keeping the phase constant. The process which is termed electrical aperture compensation pertains to the changing of the phase of each of the many wave energy contributors radiated from each part of the aperture by an amount so that the sum of the phase distance and the geometrical distance to the focal point is the same for each wave energy contributor. In this process, therefore, the distance from any point on the aperture to the focal point is made the same by adjusting the phase distance and keeping the geometrical distance constant. For a planar aperture, the phase is adjusted so as to make the surface generated by the radius sector from the focal point an equiphase surface.

In accordance with this invention an electrically converging aperture may be effected from a planar aperture by three processes. One process which is only applicable to multiple element antennas is to space the radiation elements in such a way that the energy radiated by each element is in quadratic phase relationship with the energy radiated by the adjacent element and which upon combination creates a converging wavefront. Another process which may be employed with either a multiple element or an extended source type of antenna is to impose a quadratic phase relationship upon the wave energy by changing the propagation factor of the translator so that the resulting wavefront converges. Propagation factor control inside the translator may be accomplished by either varying the energy translator dimension which affects the wave velocity or to insert into the wave energy translator a varying amount of a substance such as a dielectric which produces the equivalent effect.

FIG. 9 shows one embodiment of a finite focus wave energy antenna array using electrical aperture control wherein a wave energy translator such as the hollow rectangular waveguide 94 shown is provided with a plurality of radiation elements, such as dipoles, slots or probes, located along the waveguide 94 at the positions 96. For the purpose of providing electrical aperture control the distance y between the central radiation element position and any other radiation element position is given approximately by the equation

$$y_{n+1} = \frac{\lambda_0}{\lambda_g} \left[-R + \sqrt{R \left(R + \frac{\lambda_g^2}{\lambda_0^2} \right) + y_n \left(\frac{\lambda_g}{\lambda_0} \right)^2} \right] \left[y_n + 2R \left(\frac{\lambda_0}{\lambda_g} \right) \right] \quad (6)$$

where each radiation element position is further designated by a number $n=1, 2, 3 \dots$, and the central element position is $n=0$. The term y_{n+1} is the distance to the $(n+1)$ radiation element position from the central radiation element position so that $y_0=0$. λ_0 is the free space wavelength, λ_g is the guide wavelength and R is the distance to the focal point along the array center line 97 which passes through at the central radiation element position. The effect of spacing the radiation element at the positions computed by Equation 6 is to create a quadratic phase error over the surface of the radiation aperture. The center of curvature of the quadratic phase error is the focal point F located at a distance R along the array center line 97.

FIGS. 10 and 11 show two further embodiments of the finite focus wave energy antenna array using an electrical aperture control wherein a wave energy translator is provided with propagation factor control. Both of these embodiments of the finite focus wave energy an-

tenna arrays may be provided with an extended source, or with discrete equispaced radiation elements in contradistinction to the embodiments shown in FIG. 9.

FIG. 10 is a perspective view showing another embodiment of the finite focus wave energy antenna array using electrical aperture control wherein a hollow wave energy translator 100 which is provided with an aperture 101 has a nonuniform width to produce variations of the propagation factor. The aperture 101 may contain either an extended source or discrete equispaced radiation elements. The array axis 102 passes through the center of the aperture and is the axis of symmetry of the resulting radiation pattern. The translator 100 is shaped along its direction of elongation in such a way that the velocity of propagation of the wave energy therethrough will be a predetermined function of its position from the array axis 102. Since it is desired to produce a converging wave from the aperture 101, the phase of the wave energy over the aperture must have a quadratic relationship. The width x of the translator 102 at a distance y from the array axis 102 is such that the phase of the wave energy from an element Δy is a distance y from the array axis 102 is given by

$$\phi(y) = \frac{\pi y^2}{\lambda_0 R} \quad (7)$$

where λ_0 is the free space wavelength and R is the radius of curvature of the converging wavefront. R is measured along the array axis 102, and terminates at F , the focal point of the antenna array.

FIG. 11 is a perspective view showing a further embodiment of the finite focus wave energy antenna array using an electrical aperture control wherein a hollow rectangular waveguide 106 which is provided with an aperture 107, has a nonuniform dielectric cylinder 108 along its center line to produce variations of the propagation factor. The aperture 107 may contain either an extended source or discrete equispaced radiation elements. The array axis 109 passes through the center of the aperture and is the axis of symmetry of the resulting radiation pattern. The dielectric cylinder 108 may either be of nonuniform material or varying in thickness along its direction of elongation in such a way that the velocity of propagation of wave energy therethrough will be a predetermined function of its position from the array axis 109. Since it is desired to produce a converging wave from the aperture 107, the phase of the wave energy over the aperture must have a quadratic relationship. The width x of the dielectric cylinder 108 at a distance y from the array axis 109 is such that the phase of the wave energy from an element Δy at a distance y from the array axis 109, is given again by Equation 7. R is measured along the array axis 109 and terminates at F , the focal point of the antenna array.

Thus, there has been described an improved wave energy antenna array wherein the performance degradation in the Fresnel zone has been compensated. The improved wave energy antenna array has a finite focal length and its useful operation may be extended into the Fresnel region of said array. The improved wave energy antenna array in conjunction with the focusing frame has a useful range which is continuously adjustable. There has also been described a method whereby the useful range of an antenna array may be continuously varied and where the useful range may be extended into the Fresnel zone of said antenna. Last but not least, there has been disclosed a method whereby it is possible to obtain by direct measurements conducted from the point within the Fresnel region the Fraunhofer pattern of an antenna array.

What is claimed is:

1. An antenna array for radiating electromagnetic energy along an axis, said array comprising at least one active radiation means, energy transmission means opera-

tively interconnected with each of said radiation means for exciting said radiation means to cause said electromagnetic energy to be radiated therefrom and along said axis, said radiation means being disposed substantially symmetrically about said axis and positioned to create a focal point located on said axis and disposed within the Fresnel region of said array, said radiation means also being positioned to place the near-point of the array between said focal point and the array.

2. An antenna array for radiating electromagnetic energy along an axis, said array comprising a plurality of active radiation means disposed substantially symmetrically about said axis, means for exciting said radiation means, means being operatively interconnected with each other and positioned to form a radiation pattern having a near-point and a far-point, said radiation means being disposed to form a focal point located on said axis of said array between said near-point and said far-point.

3. An antenna array for radiating electromagnetic energy along an axis, said array comprising a plurality of active radiation means disposed substantially symmetrically about said axis, said radiation means being positioned to form a radiation pattern disposed substantially symmetrically about said axis, said pattern having a Fresnel region and a Fraunhofer region separated from each other by a transition point, each of said radiation means being disposed substantially equidistant from a common center to form a focal point for said array located on said axis and between said array and said transition point and within said Fresnel region.

4. An antenna array comprising at least one active radiation means, means for exciting said radiation means whereby electromagnetic energy will be radiated from said array, said means being arranged to form a radiation pattern having a Fresnel region and a Fraunhofer region separated from each other by means of a transition point, said radiation means also being positioned to cause the focal point of said antenna array to be located between said array and said transition point and in said Fresnel region.

5. An antenna array comprising at least one active radiation means, means for exciting said radiation means whereby electromagnetic energy will be radiated from said array, said means being arranged to form a radiation pattern having a Fresnel region and a Fraunhofer region that are separated from each other by a transition point, said radiation means also being spaced substantially equidistant from a common center so that the focal point of the array will be positioned in said Fresnel region and the near-point of the array will be located between said array and said focal point.

6. An antenna array for radiating electromagnetic energy along an axis, said array comprising waveguide means disposed substantially normal to said axis for carrying electromagnetic energy therealong, radiation means on said waveguide coupled to said waveguide for radiating said energy in said waveguide in the direction of said axis, to produce a radiation pattern, said radiation means extending over a sufficient length to cause the Fresnel region thereof to terminate at a predetermined space from said array, said radiation means being disposed substantially symmetrically about said axis and equidistant from a common center, said distance being less than said space so that said array will have a focal point located on said axis and disposed within the Fresnel region of said array whereby the near-point of the array will be disposed between said focal point and said array.

7. An antenna array for radiating electromagnetic energy along an axis, said array comprising waveguiding means disposed substantially normal to said axis for carrying electromagnetic energy therealong, radiation means mounted on said waveguiding means and coupled thereto for radiating said energy along the direction of said axis, means for deflecting said waveguiding means so as to po-

sition said radiation means substantially symmetrically about said axis and equidistant from a common center so as to cause said array to have a focal point, said deflecting means being effective to reduce said distance to a sufficiently small amount to position said focal point on said axis and within the Fresnel region of said array so that the near-point of said array will be located between said focal point and said array.

8. An antenna array for radiating electromagnetic energy along an axis, said array comprising a waveguide disposed substantially normal to said axis for carrying electromagnetic energy therealong, a plurality of radiation slots in one wall of said guide for extracting at least a portion of said energy in said guide and radiating it into space, in a radiation pattern, said waveguide having sufficient length to cause the Fresnel region to terminate at a predetermined distance, means for deflecting said waveguide into predetermined shapes wherein said slots will be positioned substantially symmetrically about said axis and equidistant from a common center so as to cause said array to have a focal point, said second distance being less than said first distance to place said focal point within said Fresnel region.

9. An antenna array for radiating electromagnetic energy along an axis, said array comprising waveguiding means for carrying electromagnetic energy, a plurality of dipole radiator elements mounted on said means for extracting at least a portion of said energy therefrom and radiating it into space, said dipole elements being substantially equidistant from a common center located on said axis, said dipole elements extending over a sufficient length to cause the radiation pattern including Fresnel and Fraunhofer regions separated from each other by a transition point located a finite distance from said array, said equal distance being sufficiently short to place said focal point in said Fresnel region and between said transition point and said array.

10. Antenna means comprising a plurality of active radiator means disposed substantially equidistant from a common center to thereby form a portion of a spherical array, electromagnetic transmission means operatively interconnected with said radiators for exciting said radiators, said means being arranged to form a radiation pattern having a Fresnel region and a Fraunhofer region separated by a transition point, the radius of said sphere being less than the distance to said transition point so that the focal point of said array will be positioned in said Fresnel region and between said array and said transition point.

11. Antenna means comprising a plurality of arcuate waveguiding means disposed in juxtaposition and adapted to transmit electromagnetic energy therethrough, at least one radiation aperture in each of said waveguiding means for extracting at least a portion of said energy therein and radiating it into space, all of said apertures being disposed on a common radius from center point to form a radiation source that is at least a portion of a sphere and has a radiation pattern that includes a Fresnel region and a Fraunhofer region separated by a transition point, said radius being less than the distance to said transition point whereby the focal point will be located within said Fresnel region.

12. The method of measuring the Fraunhofer radiation pattern of a wave energy antenna array from a distance R which is smaller than the classical transition point distance T associated with said antenna array, said method comprising the steps of temporarily deflecting said antenna array into an annular sector of radius R, measuring the Fraunhofer radiation pattern of the deflected antenna array from a distance R, and thereafter releasing said antenna array to its original shape.

13. The method of measuring the Fraunhofer radiation pattern of a wave energy antenna array from a distance R which is smaller than the classical transition point distance T associated with said array, and where said array

includes a rectangular waveguide provided along one of its walls with radiation elements defining an aperture to effect the exchange of wave energy between said waveguide and free space, said method comprising the steps of temporarily distorting said array into an annular sector of radius R, with the wall containing the aperture being the inner surface of said annular sector, measuring the radiation pattern of said distorted array from a distance R, and thereafter releasing said array to its original shape.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,039,098

June 12, 1962

Robert W. Bickmore

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 2, line 71, for "sperical" read -- spherical --;
column 11, line 14, after "means," insert -- said --; column 12
line 35, after "said", second occurrence, strike out the comma.

Signed and sealed this 20th day of November 1962.

(SEAL)

Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents