

[54] ANTENNA ARRAY FOR GRATING LOBE
AND SIDELOBE SUPPRESSION

[75] Inventor: Dennis W. Holst, Littleton, Colo.
[73] Assignee: Martin Marietta Corporation,
Friendship International Airport,
Md.
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[58] Field of Search..... 343/844, 854, 853

[56] References Cited

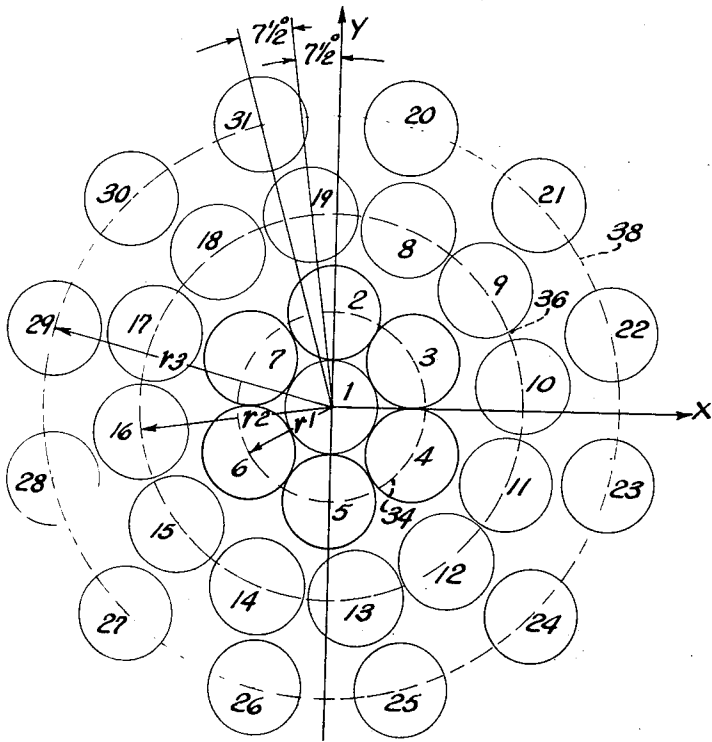
UNITED STATES PATENTS			
2,218,487	10/1940	Terman et al.	343/844
3,702,481	11/1972	Koller et al.	343/844
2,126,531	8/1938	Carter	343/844

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[57] ABSTRACT

A circular antenna array comprises module antennas arranged generally in rings in a plane. Although the module antennas are arranged in a systematic pattern on centers which are so far apart that grating lobes would ordinarily occur, the grating lobes are substantially eliminated because of the particular locations selected for the modules. The centers of the modules in each ring are unsymmetrically located with respect to the centers of the modules in the other rings. The level of sidelobes is reduced by providing space density tapering in only the outermost ring of module antennas. In rings other than the outermost ring, the module locations permit achievement of a high aperture illumination efficiency.

13 Claims, 6 Drawing Figures



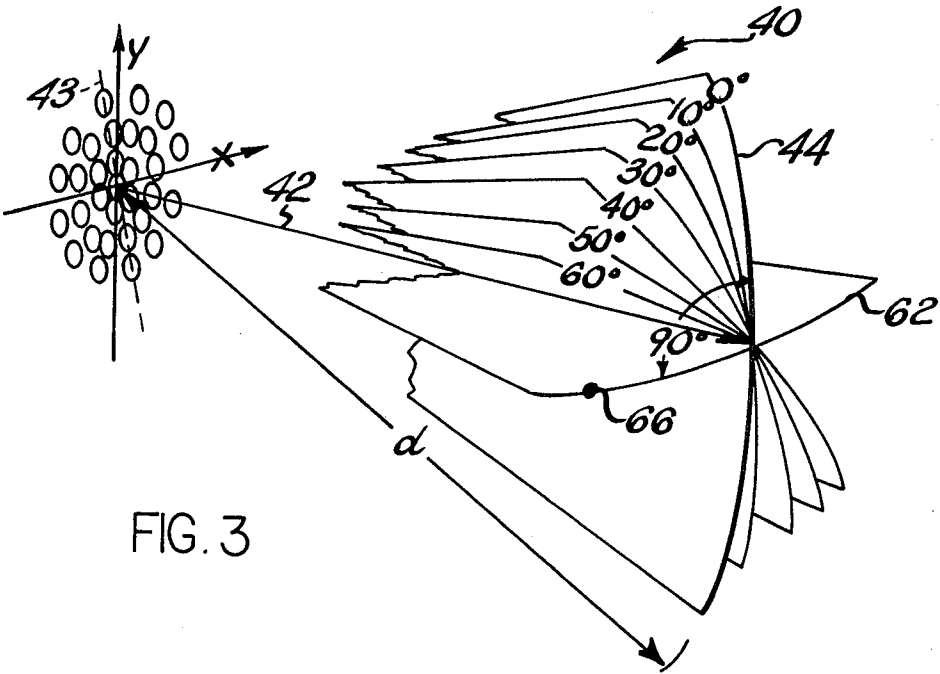


FIG. 3

FIG. 2

MODULE	X-CO-ORD.	Y-CO-ORD.	MODULE	X-CO-ORD.	Y-CO-ORD.
1	0	0	17	-27.7164"	11.4804"
2	0	15.0000"	18	-18.2628	23.8005
3	13.0000"	7.5000	19	-3.9159	29.7432
4	13.0000	-7.5000	20	11.6469	43.4669
5	0	-15.0000	21	31.8200	31.8200
6	-13.0000	-7.5000	22	43.4669	11.6469
7	-13.0000	7.5000	23	43.4669	-11.6469
8	11.4804	27.7164	24	31.8200	-31.8200
9	23.8005	18.2628	25	11.6469	-43.4669
10	29.7432	3.9159	26	-11.6469	-43.4669
11	27.7164	-11.4804	27	-31.8200	-31.8200
12	18.2628	-23.8005	28	-43.4669	-11.6469
13	3.9159	-29.7432	29	-43.4669	11.6469
14	-11.4804	-27.7164	30	-31.8200	31.8200
15	-23.8005	-18.2628	31	-11.6469	43.4669
16	-29.7432	-3.9159			

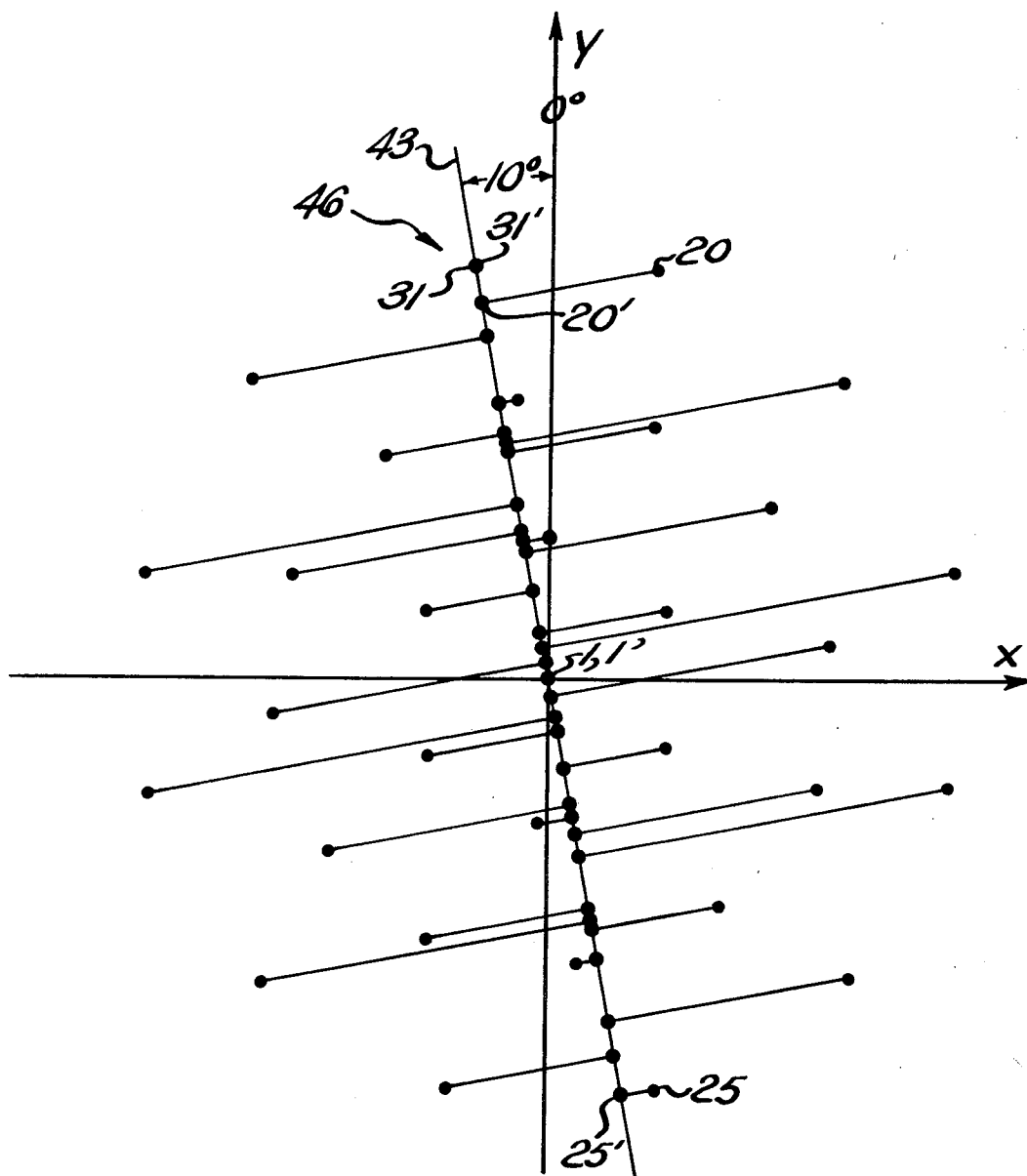
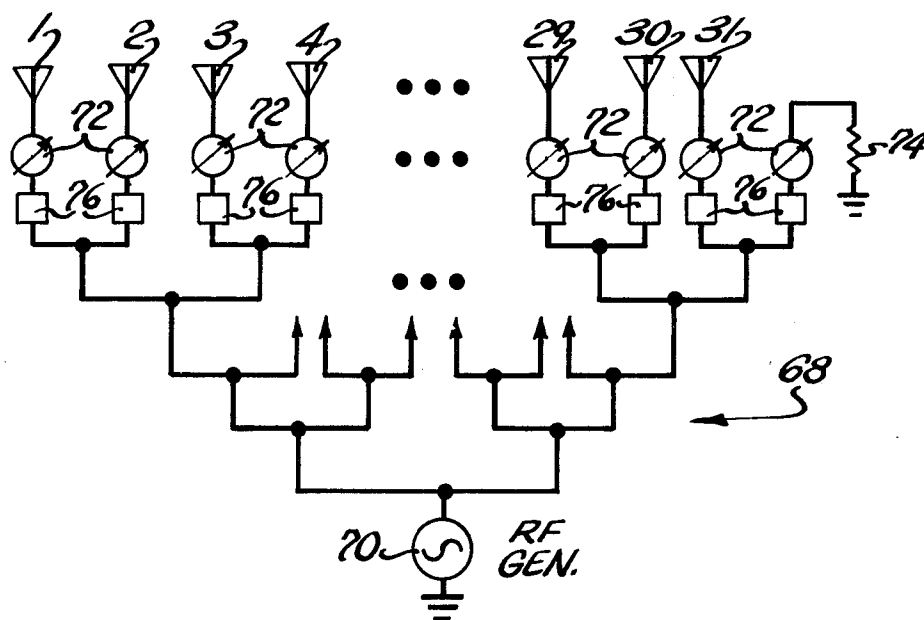
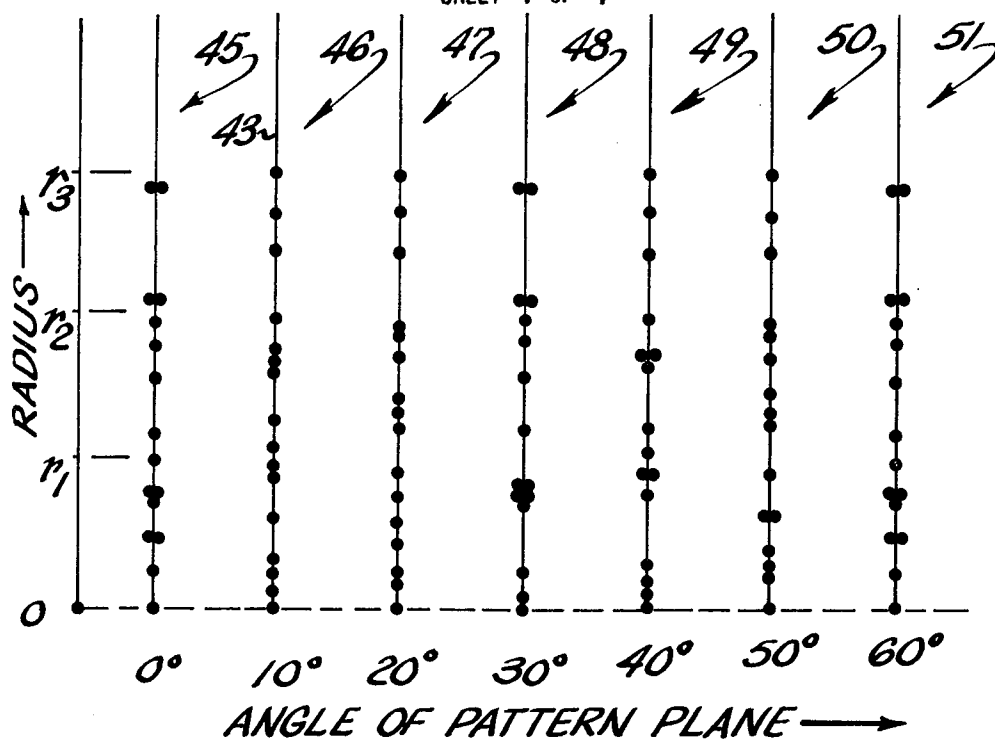


FIG.4

SHEET 4 OF 4



ANTENNA ARRAY FOR GRATING LOBE AND SIDELOBE SUPPRESSION

The far-field radiation pattern of an array of antennas can be expressed under certain circumstances as the product of an array factor and an element or module pattern. The term module is used herein to denote radiators of an antenna array that are either single antennas or groups of antennas. The product form of far-field radiation pattern is applicable where the array is large enough compared to a region of interaction among modules that the edge effects are negligible, and where the modules are nearly identical as to their construction, their impedances, and their environments in the array. The array factor has sidelobes in its far-field pattern in addition to the principal desired lobe, and also has large grating lobes if the elements are uniformly spaced and are spaced more than 1 wavelength apart.

Sidelobes other than grating lobes can be reduced by tapering the excitation of the antenna array across the aperture so that the effective current density is smaller near the edges of the array than near the center. This is ordinarily accomplished by either of two methods, one of which is to excite the modules that are near the edges of the array with smaller current than is used to excite the modules near the center. The other method for tapering is to increase the spacing of the modules near the edges of the array as compared with their spacing near the center.

In some arrays of the prior art, grating lobes have been minimized by designing the module pattern so as to have nulls at the locations of the grating lobes of the array factor. Since the resultant array pattern is the product of the array factor and the module pattern, a resultant array pattern achieved by this method has small grating lobes. However, in applications of array antennas in which the beam is to be electronically steered, this approach has the disadvantage that grating lobes re-appear in the resultant array pattern when the beam is steered very far off the principal mechanical axis of the array because only the array factor is moved by electronic steering. The module pattern remains stationary in space, and its nulls no longer coincide with the grating lobes of the array factor when the beam is electronically steered far off the axis.

In arrays which contain a statistically large number of elements, the elements may be spaced at random so as to eliminate the grating lobes by smearing their energy throughout the pattern. When grating lobes are reduced in this way by the form of the array factor alone, without depending upon the module pattern, good patterns can be achieved even when the beam is steered far off the axis.

A difficult problem of the prior art has been that antenna arrays having a statistically small number of modules spaced far apart have not been usable without grating lobes unless the module patterns were constrained to have their nulls at the locations of the grating lobes. With a small number of elements, it is especially difficult to find locations for the elements which are sufficiently random in every direction from the antenna so that pattern cuts made in the far field in planes passing through the axis of the antenna array at various angles, all have low grating lobes simultaneously.

Where a high aperture illumination efficiency is desired, as is often the case, the modules should effectively fill the aperture of the array. It is desirable for the

modules to nearly touch each other at their edges, from the standpoint of maximizing aperture illumination efficiency. At the same time, the spacing between module antennas must be such that no pattern plane cut through the array axis should show significant grating lobes or high sidelobes, and the beam should be symmetrical as to shape and size of the main beam. Moreover, it is often desirable that all of the foregoing requirements be fulfilled not only for a single frequency of excitation but also for a wide band of frequencies.

SUMMARY OF THE INVENTION

One object of the present invention is to provide an antenna array with a small number of module antennas and having low grating lobes in every angular pattern plane through the antenna axis.

Another object of the present invention is to provide an antenna array having a radiation pattern with a high degree of angular symmetry of the main lobe.

A further object is to provide an antenna array capable of high aperture illumination efficiency, diminished slightly by space density tapering.

Still another object of the invention is to provide an antenna array whose grating lobes are made low over a great frequency bandwidth without necessarily relying upon the nulls of a single module-in-array pattern for suppression of grating lobes.

Yet another object is to provide an antenna array that is phase-steerable without incurring significant increases in strengths of the grating lobes.

The foregoing objects and others can be accomplished by the arrangement of modules in the antenna array so that the centers of antenna modules are located in respective concentric rings about a center module with the centers in each ring being equally spaced and arranged unsymmetrically with respect to the centers in the other rings. The circularly systematic nature of the arrangement permits a high aperture illumination efficiency because the modules can be placed close together. The location of the modules produces a randomness of behavior as to grating lobes permitting grating lobe energy to be smeared across the sidelobe pattern. This is true even though a relatively low number of module antennas are employed.

The preferred form of the array has a module at the center, six modules 60° apart at a first radius, 12 modules 30° apart at a second radius twice as great as the first radius, and 12 more modules 30° apart at a third radius three times as great as the first radius. The second ring is angularly displaced $7\frac{1}{2}^\circ$ from the first ring; the third ring is angularly displaced $7\frac{1}{2}^\circ$ farther in the same direction. The non-symmetrical characteristic of the present array is one distinguishing feature over known arrays such as shown in U.S. Pat. No. 3,553,706.

BRIEF DESCRIPTION OF THE FIGURES

Other objects and features of the invention will become more apparent upon a consideration of the description which follows, taken in conjunction with the accompanying drawings wherein:

FIG. 1 is a diagrammatic view of a planar antenna array laid out in accordance with the present invention;

FIG. 2 is a table of rectangular coordinates of centers of modules of the array for one size of array;

FIG. 3 is an isometric view of various planes in which antenna field strength patterns are measured in the far field;

FIG. 4 illustrates an equivalent linear array constructed by projecting the module centers onto a line; and

FIG. 5 shows halves of equivalent linear arrays for pattern planes 10° apart over a range of 60° , after which the patterns repeat; and

FIG. 6 is a feed system for the array.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The preferred array comprises a module antenna 1 mounted at a center and surrounded by rings of module antennas 2 through 31 on concentric circles with the modules of each ring angularly displaced from the modules of neighboring rings by particular angular displacements in order to yield the low levels of grating lobes being sought, (FIG. 1). In a preferred form of the invention, all of the module antennas 1-31 are identical. The smallest concentric ring 34 of modules surrounding the center module 1 has six module antennas 2-7 spaced 60° apart with their centers at a particular radius r_1 . In the preferred embodiment of the invention radius r_1 is only slightly greater than the diameter of a module antenna. Grating lobes are minimized even when r_1 is greater than one wavelength of the excitation signal. A second concentric ring 36 upon which the centers of module antennas are located has a radius r_2 equal to twice the first radius r_1 , and hence equal to or slightly greater than twice the diameter of a module in the preferred form of the invention. The centers of 12 module antennas 8-19 are located on the second ring 36, angularly spaced 30° apart so as to fill the ring 36 and have a high degree of circular symmetry. No modules on the second ring 36 lie upon radial lines extending from the center of the array upon which the modules 2 through 7 of the first ring 34 lie. Instead, the second ring 36 is angularly displaced preferably about $7\frac{1}{2}^\circ$ from the modules of the first ring as shown in FIG. 1. Thus, module 18 of the second ring 36 is displaced $37\frac{1}{2}^\circ$ from module 2 of the first ring 34. This provides an unsymmetrical arrangement of the module centers in the second ring with respect to the centers in the first ring and a cluster of a total of 19 antenna modules 1-19 that very efficiently fill the space enclosed by an imaginary circle whose radius is $2\frac{1}{2}$ times the radius r_1 of the first circle 34, giving an illumination efficiency for this portion of the antenna array which tends to approach the maximum illumination efficiency that is achievable in an array comprising modules whose general outline approximates a circle. The arrangement of module antennas is not limited, however, to modules whose periphery is approximately circular; any shape of module antenna can be employed.

In the illustrated embodiment of the antenna array, a third group of modules is included, with their centers on a ring 38 concentric with the first two rings 34, 36. The radius r_3 of the third ring 38 is three times the radius r_1 of the first ring 34 and the third ring consists of 12 modules 20-31 spaced 30° apart around the circle 38. The modules 20-31 of the third ring are angularly displaced $7\frac{1}{2}^\circ$ from the modules 8-19 of the second ring, in the same direction of angular displacement as alternate modules of the second ring 36 are displaced from the modules of the first ring 34. Consequently, in

the illustrated form of the invention, alternate modules of the third ring 38 are displaced 15° from the modules of the first ring 34 and in the same direction as the $7\frac{1}{2}^\circ$ displacement of the modules of the second ring 36 with respect to the first ring 34. The third ring 38, having the radius r_3 specified, has sufficient circumference to accommodate more than the 12 modules 20-31 which are placed upon it. The use of only 12 modules for the third ring 38 represents concessions to the requirements for grating lobe suppression and also space density tapering.

Locations of the modules 1-31 are expressed in FIG. 2 in rectangular coordinates X and Y, which are defined in FIG. 1, for an array in which r_1 is 15 inches, r_2 is 30 inches, and r_3 is 45 inches.

Some field strength patterns in the far field which are of particular interest are patterns measured in planes 40 which include a principal mechanical axis 42 of the array, as shown in FIG. 3. For example, the vertical plane 44 through the axis 42 is a plane in which an electric field strength pattern measured at a distance from the array, is of interest. This pattern is designated the 0° plane pattern herein. Other pattern measurement planes 40, designated 10° , 20° , 30° , 40° , 50° , 60° and 90° are also shown on FIG. 3.

The behavior of a planar arrangement of module antennas 1-31 as regards production of grating lobes can be determined for any particular pattern plane 40 by considering an equivalent linear array of modules. An example for a 10° pattern plane 40 is given in FIG. 4. The equivalent linear array 46 is an array of modules 1'-31' distributed on a single line 43 instead of on a plane, with each module 1'-31' of the equivalent linear array 46 corresponding to a module of the original planar array. The locations of the modules 1'-31' in the linear array 46 are points, shown as small circles, found by perpendicularly projecting the location of each module 1-31 of the planar array onto the line 43 as shown in FIG. 4. The line 43 on which the modules 1'-31' of the equivalent linear array 46 lie is the intersection line of the mechanical plane in which the original planar array lies, and the plane 40 in which a pattern is to be considered, in this example, a 10° plane. The plane in which the pattern is to be considered is a plane including the line which is the principle mechanical axis 42 of the original planar array, as shown in the isotropic view of FIG. 3.

Equivalent linear arrays 45-51 for the 31-module planar array are shown in FIG. 5 for seven values of angular orientation of the measurement plane 40 in 10° steps from 0° to 60° , which completes a cell of the angular arrangement beyond which the far-field patterns repeat themselves. The 10° planes are angularly close enough together to show that the projections on a linear array of the modules of the planar array have an apparently random character everywhere despite the systematic pattern with which they are located in the antenna plane, i.e., the 10° spacings are close enough to prevent surprises between the linear arrays shown.

FIG. 6 shows a corporate feed system 68 by which a radio frequency energy source 70 feeds the modules 1-31, through individual phase shifters 72. A resistor 74 serves as a substitute for a 32nd antenna to balance the corporate feed 68. The radiation pattern can be steered by individually adjusting the phase shifts that are introduced by the phase shifters 72. The required phase shifts are linearly related to the spacings between

projected module positions such as are shown on FIG. 5; this is conventional. A situation in which all antennas are excited with identical phases is, of course, a particular case of the linear relationship between projected module positions and antenna phases.

When the preferred antenna array is electronically steered, the equivalent linear array (in a measurement plane which includes both the principal mechanical axis 42 of the array and the new location of the principle lobe), has all of its distances and spacings foreshortened by a factor of the cosine of the angle between the principal mechanical axis 42 and the axis of the steered main lobe. For example, when the center of the main lobe is steered, by phase shifting, so as to be directed to a point 66 of FIG. 3 instead of along the principal mechanical axis 42, the array is viewed slightly obliquely by an observer at point 66, and not perpendicularly. The resulting foreshortening of spacings between elements in the X direction is equivalent to a change of frequency so far as the production of grating lobes in planes through point 66 is concerned. If the spacings as foreshortened were expressed in terms of wavelengths, the pattern in the planes through point 66 would be no different than if the unforeshortened original spacings were expressed in terms of a different (shorter) wavelength. Therefore, when the positions of the modules 1-31 have been chosen so as to minimize grating lobes over a wide frequency range, that same choice of module locations produces a pattern having low grating lobes even when the pattern is electronically steered off the mechanical axis 42, at least insofar as pattern planes through the main lobe point are concerned, wherein the spacings between modules are effectively foreshortened. As to other pattern planes 40, the original unforeshortened linear array applies for the plane at right angles to the plane through the steering angle. It may be appreciated that with the grating lobes effectively suppressed in the aforementioned planes 40, the grating lobes will be suppressed also for intermediate angular orientations of the plane of pattern measurement, especially since such intermediate planes involve only a composite of two sets of effective module spacings, both somewhat foreshortened effectively as was described above.

Good pattern performance during steering will be achieved only to the extent that nulls of the module pattern were not relied upon for reduction of the grating lobes, because the module pattern does not steer upon electronic steering of the antenna array. Where the modules themselves are small arrays made of a number of element antennas, it is feasible, of course, to steer the module patterns simultaneously with the steering of the array factor so that some of the benefits gained by tailoring the module pattern to reduce the residual grating lobes can be maintained despite the beam steering.

Antenna arrays whose grating lobes are minimized by a pure randomization process inherently have low aperture illumination efficiency, because the module antennas themselves, if all identical, must be small enough not to overlap where their center spacings are close. The present invention has module spacings which are systematic as to their utilization of available aperture area in achieving high illumination efficiency, but which at the same time exhibit a minimum of systematic character as to the spacings of elements 1'-31' of the equivalent linear array, which is the principle factor determining suppression of grating lobes by smearing.

The equivalent linear spacings are pseudo-random, the pseudo-randomness being achieved by the relative angular locations of the rings.

In the present invention, aperture efficiency is diminished to the minor extent that diminishment is required for space density tapering in the outer ring 38. Thus, a high aperture illumination efficiency is achieved, consistent with a slight amount of space density tapering provided for reduction of sidelobes.

Although the present antenna array accomplishes low grating lobe levels only by placement of the module antennas, without reliance upon tailoring of the module pattern, further improvement of the final antenna patterns can be achieved for a frequency or frequency range by tailoring the module pattern so that its nulls fall on the most offensive of the remaining grating lobes. In this way the benefits of module pattern tailoring can be combined with the benefits of suppression of grating lobes by module placement, to achieve excellent final array pattern shapes for all orientations of the measurement plane.

The array embodying the invention not only accomplishes a low average sidelobe level but also accomplishes a low maximum sidelobe level wherein all sidelobes are near the average sidelobe level and no sidelobe is extremely offensive.

Because of module locations, the modules of antenna array of the present invention can be uniformly excited as to amplitude if that is desired without incurring a penalty of high sidelobes. Although the array can be operated with good results with uniform amplitudes of exciting currents in all of the modules, amplitude tapering can also be employed if desired for further improvement of the resultant array patterns. FIG. 6 shows individual attenuators 76 as one method for accomplishing this.

What is claimed is:

1. A broadside antenna array comprising a plurality of module antennas arranged on centers in a plane, each of said modules having a radiation pattern directed substantially perpendicularly to the plane of the array, said array comprising a first module at a reference point, a first plurality of modules equally spaced apart in the amount of a first angle between modules at a first radial distance from said reference point, the first radial distance being approximately equal to the aperture dimension of said first module, one module of said first plurality being on a first radial line extending from said reference point, and a second plurality of modules equally spaced apart angularly at a second radial distance from said reference point about twice as great as said first radial distance, one module of said second plurality being on a second radial line extending from the reference point, said second radial line lying between said first line and a radial line bisecting said first angle to produce pseudo-random spacings between locations, as perpendicularly projected on a straight line in said plane, of the modules of both of said pluralities.

2. A broadside antenna array as defined in claim 1 wherein said second plurality comprises a number of modules less than twice said first plurality.

3. A broadside antenna array comprising a plurality of module antennas arranged on centers in a plane, each of said modules having a radiation pattern directed substantially perpendicularly to the plane of the array, said array comprising a first module having a

center at a reference point, a first plurality of modules equally spaced apart in the amount of a first angle at a first radial distance from said reference point, the first radial distance being approximately equal to the aperture dimension of said first module, one module of said first plurality being on a first radial line extending from said reference point, a second plurality of modules comprising a greater number of modules than said first plurality and equally spaced apart angularly at a second radial distance from said reference point, one module of said second plurality being on a second radial line extending from the reference point, and a third plurality of modules equally spaced apart angularly at a third radial distance from said reference point about three times as great as said first radial distance, one module of said third plurality being on a third radial line extending from the reference point, said first, second, and third radial lines all having different directions from said reference point, said second radial line lying between said first line and a radial line bisecting said first angle to produce pseudo-random spacings between locations, as perpendicularly projected on a straight line in said plane, of the modules of all of said pluralities.

4. A broadside antenna array as defined in claim 3 and further comprising feed system means connected to said modules for receiving signals from said array in a receiving mode, corresponding by reciprocity to a transmitting mode in which said modules are excited with transmitting signals having predetermined relative amplitudes and having relative phases that are linearly related to a distance from said reference point to a point projected normally from each module onto a straight line in said plane extending through said reference point.

5. A broadside antenna array as defined in claim 3 and further comprising feed system means connected to said modules for exciting said modules in a transmitting mode with signals having predetermined relative amplitudes and having relative phases that are linearly related to a distance from said reference point to a point projected normally from each module onto a straight line in said plane extending through said reference point and for receiving signals from said array in a receiving mode, said receiving mode corresponding by reciprocity to said transmitting mode.

6. A broadside antenna array as defined in claim 3 wherein said third plurality comprises a number of modules less than three times the number of said first plurality.

7. An antenna array comprising a plurality of module antennas arranged on centers in a plane comprising a first module having a center at a reference point, a first plurality of modules equally spaced apart in the amount of a first angle at a first radial distance from said reference point, one module of said first plurality being on a first radial line extending from said reference point, a second plurality of modules comprising a greater number of modules than said first plurality and equally spaced apart angularly at a second radial distance from said reference point, one module of said second plurality being on a second radial line extending from the reference point, and a third plurality of modules equally spaced apart angularly at a third radial distance from said reference point about three times as great as said first radial distance, one module of said third plurality being on a third radial line extending from the

reference point, said first, second, and third radial lines all having different directions from said reference point, said second radial line lying between said first line and a radial line bisecting said first angle to produce pseudo-random spacings between locations, as perpendicularly projected on a straight line in said plane, of the modules of all of said pluralities, and wherein said first plurality of modules comprises six modules spaced 60° apart, said second plurality comprises twelve modules spaced 30° apart, and said third plurality comprises twelve modules spaced 30° apart.

8. An antenna array as defined in claim 7 and further comprising feed system means connected to said modules for exciting said modules with signals having predetermined relative amplitudes and having relative phases that are linearly related to a distance from said reference point to a point projected normally from each module onto a straight line in said plane extending through said reference point.

9. An antenna array as defined in claim 8 wherein said feed system means comprises means for exciting said modules with signals having unequal amplitudes.

10. An antenna array as defined in claim 7 wherein said second radial line extends in a direction about $7\frac{1}{2}^\circ$ different from the direction of said first radial line, measured in a sense of rotation about said reference point, and said third radial line extends in a direction about $7\frac{1}{2}^\circ$ different from the direction of said second radial line measured in the same sense of rotation about said reference point.

11. An antenna array as defined in claim 10 further comprising feed system means connected to said modules for exciting said modules with signals having predetermined relative amplitudes and having relative phases that are linearly related to a distance from said reference point to a point projected normally from each module onto a straight line in said plane extending through said reference point.

12. An antenna array comprising a plurality of module antennas arranged on centers in a plane comprising a first module at a reference point, a first plurality of modules equally spaced apart in the amount of a first angle between modules at a first radial distance from said reference point, one module of said first plurality being on a first radial line extending from said reference point, and a second plurality of modules equally spaced apart angularly at a second radial distance from said reference point about twice as great as said first radial distance, one module of said second plurality being on a second radial line extending from the reference point, said second radial line lying between said first line and a radial line bisecting said first angle to produce pseudo-random spacings between locations, as perpendicularly projected on a straight line in said plane, of the modules of both of said pluralities, and wherein said first plurality of modules comprises six modules spaced 60° apart, and said second plurality of modules comprises 12 modules spaced 30° apart.

13. An antenna array comprising a plurality of module antennas arranged on centers in a plane comprising a first module at a reference point, a first plurality of modules equally spaced apart in the amount of a first angle between modules at a first radial distance from said reference point, one module of said first plurality being on a first radial line extending from said reference point, and a second plurality of modules equally

spaced apart angularly at a second radial distance from said reference point about twice as great as said first radial distance, one module of said second plurality being on a second radial line extending from the reference point, said second radial line lying between said first line and a radial line bisecting said first angle to produce pseudo-random spacings between locations,

as perpendicularly projected on a straight line in said plane, of the modules of both of said pluralities, and wherein said second radial line extends in a direction about $7\frac{1}{2}^\circ$ different from the direction of said first radial line, measured rationally about said reference point.

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