

Sept. 2, 1941.

S. GODET

2,254,697

ANTENNA SYSTEM

Filed March 25, 1940

4 Sheets-Sheet 1

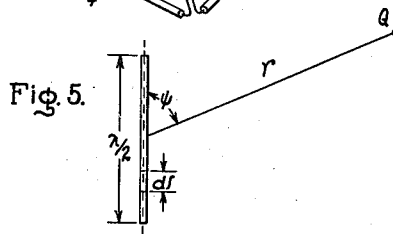
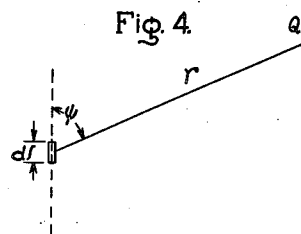
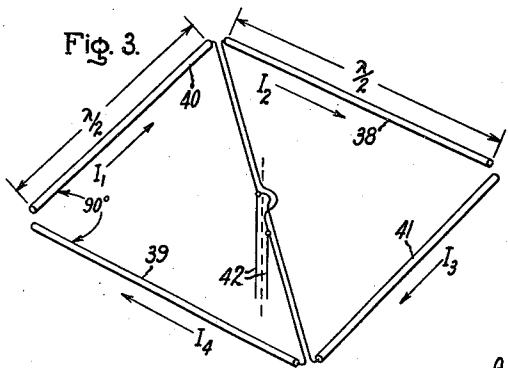
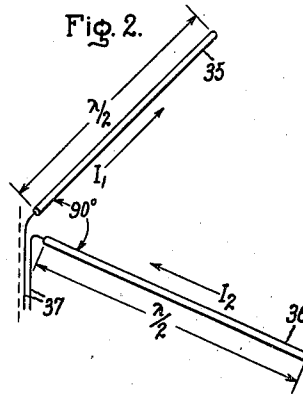
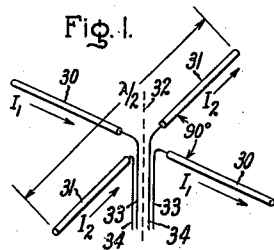
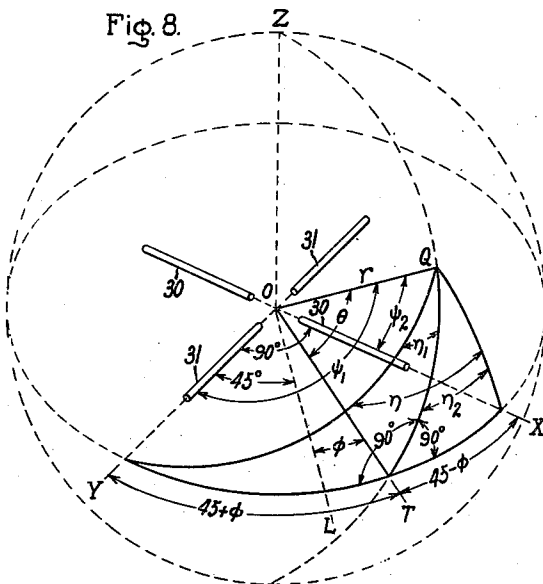
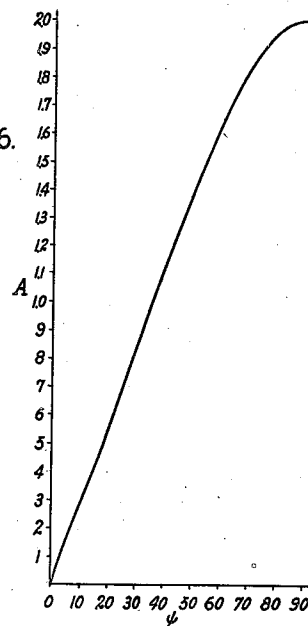


Fig. 6.



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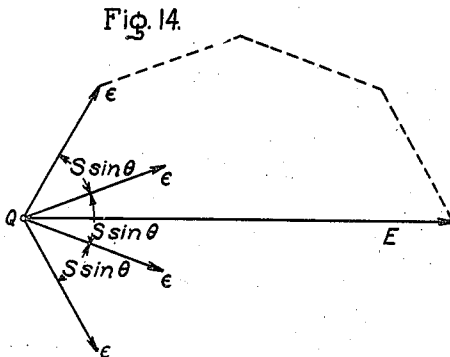
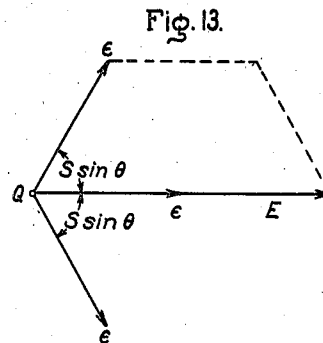
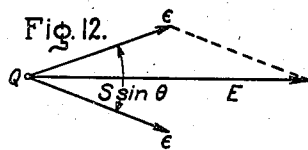
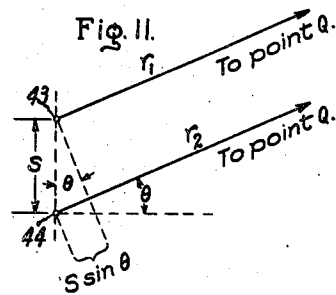
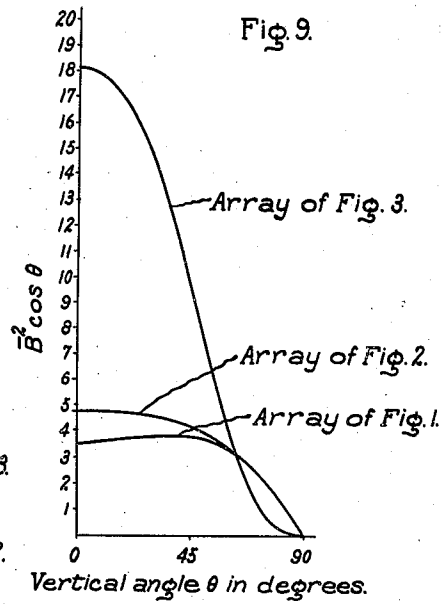
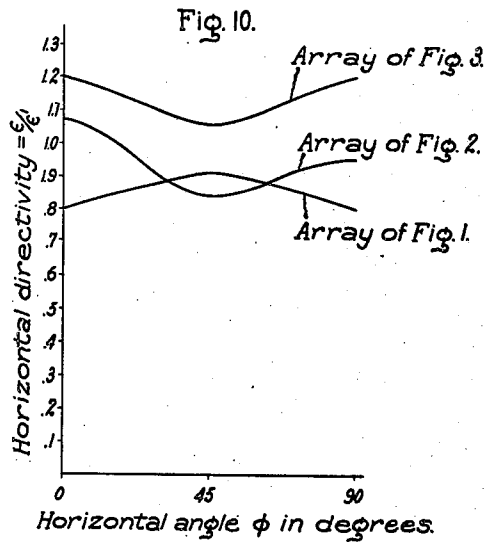
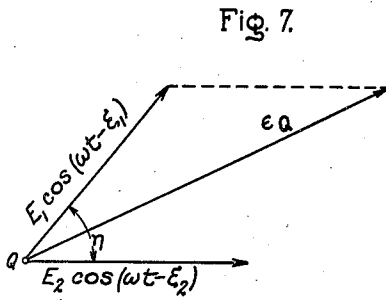
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4 Sheets-Sheet 2



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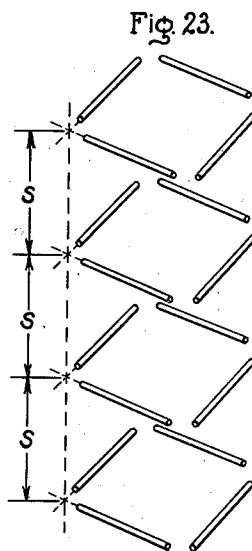
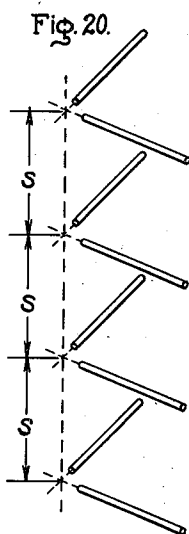
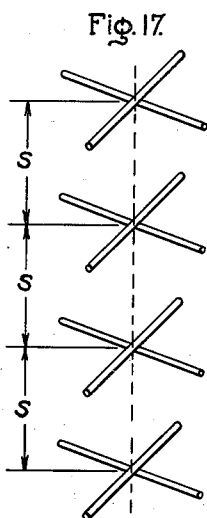
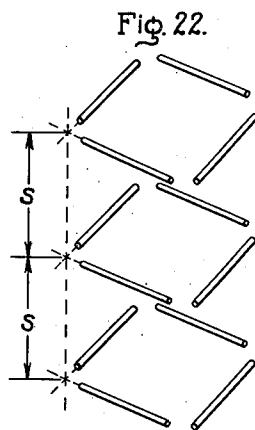
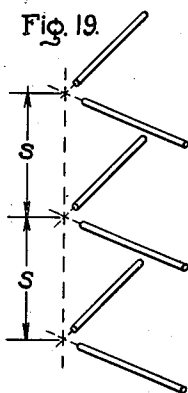
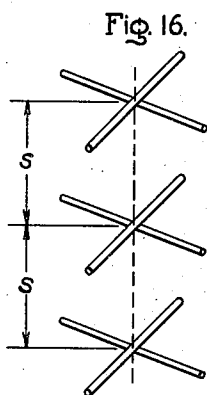
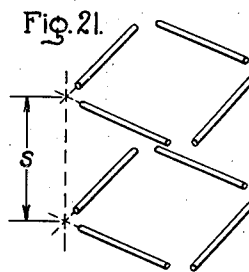
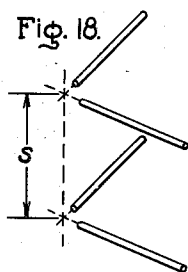
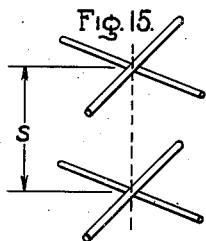
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ANTENNA SYSTEM

Filed March 25, 1940

4 Sheets-Sheet 3



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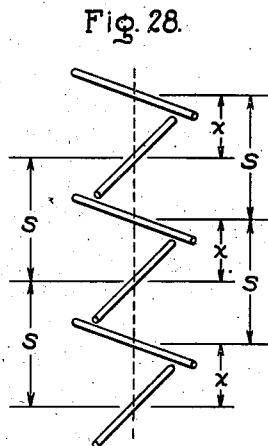
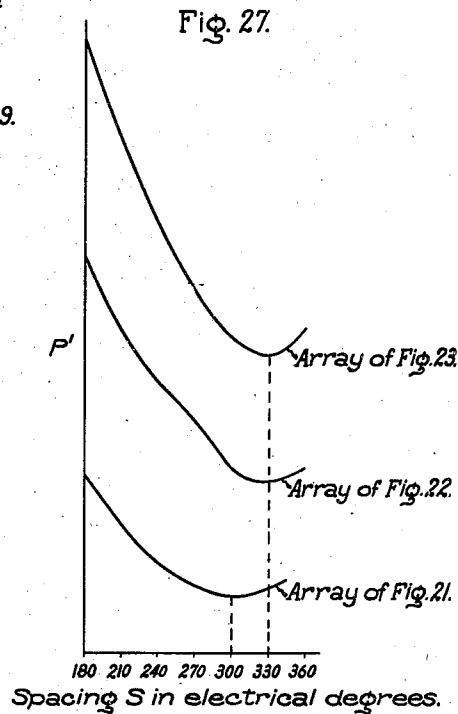
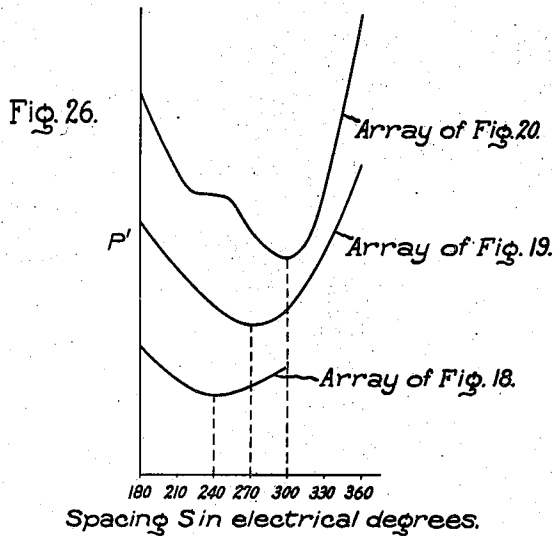
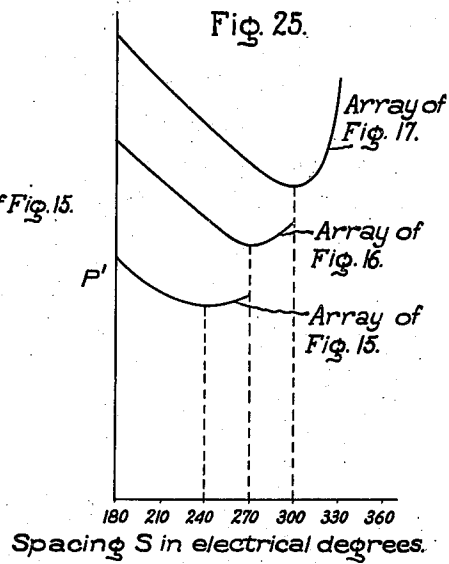
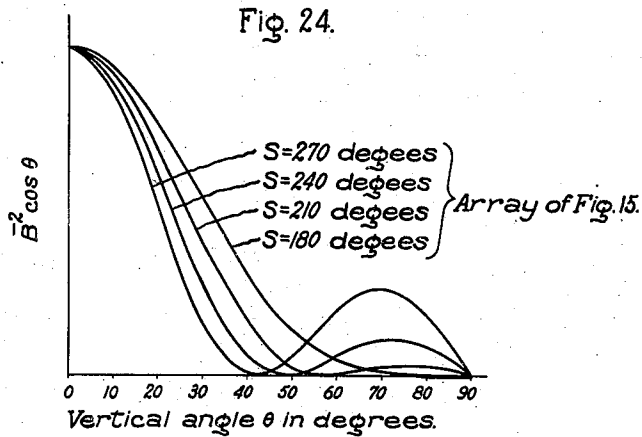
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ANTENNA SYSTEM

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4 Sheets-Sheet 4



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UNITED STATES PATENT OFFICE

2,254,697

ANTENNA SYSTEM

Sidney Godet, Schenectady, N. Y., assignor to
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New York

Application March 25, 1940, Serial No. 325,680

18 Claims. (Cl. 250-11)

My invention relates to an antenna system, and more specifically to a high frequency directional antenna system.

In broadcasting radio programs in the ultra high frequency bands, for example television programs, it has been found desirable to distribute the energy radiated from the transmitting antenna as uniformly as possible in all horizontal directions and, at the same time, to concentrate as much of the total radiated energy as possible in a horizontal plane. In other words, it is desirable to have the horizontal field strength pattern as nearly circular as possible and the directivity in the horizontal plane a maximum for most effective broadcasting service. It is further advantageous to polarize the transmitted waves horizontally rather than vertically for reasons apparent to those skilled in the art.

Various types of horizontally polarized antenna arrays are known which possess fairly uniform field strength patterns in the horizontal plane. However, such arrays in general do not possess a high degree of directivity. Therefore, it has been proposed to increase the strength of the horizontal field pattern without altering its configuration by arranging two or more identical arrays in a tier, spaced apart equally along a common vertical axis. Such a multisection array possesses greater directivity in the horizontal plane than a single array, the degree of improvement depending upon the geometry of the system.

In compound antenna arrays, as just described, it has previously been thought most desirable, to the best of my knowledge, to space the adjacent unit sections from each other by a vertical distance substantially equal to one-half wave length at the operating frequency, i. e., 180 electrical space degrees. Now I have discovered that it is possible materially to increase the directivity in the horizontal plane by increasing the spacing. I have also found that there is a definite optimum spacing between adjacent unit sections at which the directivity in the horizontal plane is a maximum. I have further found that this optimum spacing is substantially greater than one-half wave length at the operating frequency and that it varies for different systems depending upon the geometry of the unit sections and upon the number of sections employed. It is therefore a primary object of my invention to provide an improved directive antenna system having maximum directivity in a particular plane.

It is a further object of my invention to provide an improved directive antenna system particularly adapted for operation at ultra high frequencies.

Still another object of my invention is to provide a high frequency transmitting antenna system for radiating horizontally polarized waves and for concentrating a maximum portion of the total radiated energy in the horizontal plane.

The features of my invention which I believe to be novel are set forth with particularity in the appended claims. My invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in which Figs. 1, 2 and 3 are diagrammatic illustrations of three different types of unit arrays which may be employed successfully in my antenna system; Figs. 4 through 14 and 24 are diagrams and graphs helpful in understanding the mathematical analysis of my antenna system; Figs. 15 through 23 and 28 represent diagrammatically various forms of antenna systems embodying my invention, and Figs. 25 through 27 are graphs illustrating certain characteristics of the systems of Figs. 15 through 23 and 28.

In order to determine the geometry of a compound array constructed in accordance with my invention, it is first necessary to determine the radiation characteristics of the individual component sections.

Figs. 1, 2 and 3 are illustrative of antenna arrays which I have found to be particularly suitable as component sections of my compound antenna system. Each of these arrays comprises a combination of dipoles each substantially one-half wave length long at the operating frequency. When positioned horizontally and properly excited these arrays radiate horizontally polarized waves and produce field strength patterns suitable for broadcast service.

Referring to Fig. 1, two half-wave dipoles 30 and 31 are illustrated. They are positioned at right angles to each other in the form of a cross with their centers lying on a common axis 32. The instantaneous directions of the currents I_1 and I_2 in the respective radiators are denoted by the arrows. These currents, which are equal, are supplied from the output of any suitable radio transmitter, not shown, and are maintained in phase quadrature by any suitable phase-shifting means known to the art, also not shown. The dipoles 30 and 31 are illustrated as doublets which are center-fed from the transmitter by means of transmission lines 33 and 34 in a conventional manner. It will of course be understood that they may be end-fed, as are the dipoles of Figs. 2 and 3 described below, though for practical reasons the center feed is usually preferable.

Referring now to Fig. 2, a pair of half wave dipoles 35 and 36, arranged in the form of a V with legs at 90 degrees, is illustrated. The instantaneous currents are indicated as in Fig. 1. These dipoles are energized from a suitable transmitter, not shown, with equal, inphase currents. They are illustrated as end-fed from the transmission line 37. With the legs of the V at 90 degrees the horizontal field strength pattern is not exactly circular, as will be shown later. It can be shown that the pattern is most nearly circular when the legs are approximately 83 degrees apart. Thus, it will be understood that the illustrated angular spacing is not critical, although for practical reasons and for simplification of design calculations the 90 degree spacing is generally to be preferred.

Fig. 3 illustrates an antenna array comprising four half wave dipoles 38, 39, 40 and 41 arranged in the form of a square. As is evident, it is structurally a combination of two systems shown in Fig. 2 fed with equal, inphase currents from a common transmission line 42. The notation of the instantaneous directions of the respective currents is as before.

It is to be understood that the arrays shown in Figs. 1, 2 and 3 are illustrative only and not exhaustive of antennae which may be employed in my system.

The method by which the radiation characteristics of arrays, such as those just described, may be determined, will now be outlined briefly. The following assumptions have been made in subsequent analysis: first, that the current in each radiating element varies sinusoidally with distance along the element; second, that standing waves exist on each element; third, that the currents in each element are equal, and fourth, that the effect of ground is negligible. These assumptions do not introduce appreciable departures from actual operating conditions. The effect of ground reflection is in fact negligible at high frequencies, particularly since the antenna system is always positioned a considerable distance above the ground.

Referring to Fig. 4, as is known from the fundamental antenna theory, the electric field produced at any remote point Q, due to the radiation from an elemental radiator comprising a dipole dl , may be expressed as follows:

$$d\epsilon = \frac{2\pi I dl}{r\lambda} \sin \psi \cos(\omega t - Kr) \quad (1)$$

where

$d\epsilon$ = instantaneous electric field in statvolts per meter at point Q

$I \cos \omega t$ = current in dipole dl

dl = elemental length of dipole

r = distance from dipole to point Q in meters

λ = wave length in meters

ψ = angle between radius vector r and axis of dipole

ω = 2π times the operating frequency

$$K = \frac{2\pi}{\lambda} = \frac{\omega}{3 \times 10^8}$$

The average power radiated through a unit area perpendicular to r at this remote point Q is also known to be

$$\bar{P} = 238.5(\bar{\epsilon})^2 \text{ watts per square meter} \quad (2)$$

where $\bar{\epsilon}$ is the root mean square value of the instantaneous electric field at point Q.

Since the radiating elements of the antennae illustrated in Figs. 1, 2 and 3 are dipoles each one half wave length long at the operating frequency, an expression for the field at a point remote from a half wave dipole is next developed. Referring to Fig. 5, it can easily be shown, by integration of the fields due to the elemental radiating sections dl as expressed by the fundamental Equation 1, that the field ϵ at a remote point Q due to radiation from a half wave dipole with sinusoidal current distribution is

$$\epsilon = \left[\frac{.1I}{r} e^{i(\omega t - Kr)} \right] A \quad (3)$$

in which

$$A = \left| \frac{e^{i(\pi \cos \psi)} + 1}{\sin \psi} \right| \quad (4)$$

where

ϵ = instantaneous electric field at point Q in statvolts per meter

I = maximum instantaneous current at center of dipole

e = base of Napierian logarithms

r = radius vector to point Q measured from the center of the dipole

It will be apparent from Equation 3 that the maximum value of the instantaneous field at point Q is

$$E = \left[\frac{.1I}{r} \right] A \quad (5)$$

If, in accordance with a well-known method of antenna analysis, the dipole is considered to be at the center of a large imaginary sphere of radius r , Equation 3 gives an expression for the instantaneous field at any point on the surface of this sphere in terms of the coordinates of that point. Since the distance r , the antenna current I and the frequency remain constant, it will be seen that the field ϵ at any point on the surface of the sphere is proportional to A . From Equation 2 it is also evident that the power per unit area, commonly known as "Poynting's vector," is proportional to A^2 . Since A is a function of the angle ψ alone, it may be determined for any value of ψ . The graph of this relationship is shown in Fig. 6. Due to symmetry of the field surrounding a half-wave dipole it is only necessary to determine the values of A for values of ψ between zero and 90 degrees.

The field pattern due to an array, such as is illustrated in Figs. 1, 2 or 3, is the resultant of the fields due to the individual dipoles composing the array. Referring to Fig. 7, if two electric fields, which may differ both in time phase and space phase, are acting at a common point Q, they may be represented vectorially as shown and the resultant field at point Q is their vector sum. The resultant field may be expressed algebraically in terms of the component fields as follows:

$$\bar{\epsilon}^2 = \frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1 E_2 \cos \eta \cos(\epsilon_2 - \epsilon_1) \quad (6)$$

where

$\bar{\epsilon}$ = R. M. S. value of the resultant field at the point Q

E_1 = maximum value of the first field at point Q

E_2 = maximum value of the second field at point Q

η = space angle between directions of the two fields at Q

$\epsilon_2 - \epsilon_1$ = the difference in time phase between the two fields.

Consider now that a pair of dipoles, rather than

a single dipole, is located at the center of the large imaginary sphere of radius r . Since the radius vector r , the current I in each dipole and the frequency are again to remain constant, it follows from combining Equations 2, 5 and 6 that the average power per unit area at point Q (Poynting's vector for the array) may be expressed as

$$\bar{P} = K[A_1^2 + A_2^2 + 2A_1A_2 \cos \eta \cos (\xi_2 - \xi_1)] \quad (7)$$

where K is a constant and A_1 and A_2 are the expressions obtained from Equation 4 for each of the two dipoles. If the expression in brackets in Equation 7 is set equal to B^2 for convenience in further calculations, the expression for Poynting's vector becomes

$$\bar{P} = KB^2 \quad (8)$$

The quantity B for the array corresponds in all respects to the quantity A for the single dipole. It is therefore a measure of the electric field and power produced by the array at any particular remote point Q in terms of the spherical coordinates of that point.

As an illustration of how the method described in the preceding paragraph is carried out, its application to the particular antenna array of Fig. 1 will be indicated. Referring to Fig. 8, the array of dipoles 30 and 31 of Fig. 1 is diagrammatically represented at the origin of a large imaginary sphere of radius r , sketched in three-dimensional coordinates. The point Q represents any point on the surface of the sphere, shown as lying in the first octant, at which the resultant radiated power is to be determined. The other notation used is as follows:

r = radius vector from intersection O of the dipoles to the point Q

OL = bisector of the angle XOY between the dipoles from which the horizontal angle ϕ is measured

ϕ = horizontal angle from OL to the vertical plane OTQ

θ = vertical angle between r and the horizontal plane

ψ_1 and ψ_2 = angles between r and the respective dipoles

η_1 = dihedral angle between planes OYQ and OTQ

η_2 = dihedral angle between planes OXQ and OTQ

η = dihedral angle between planes OXQ and OYQ

The electric field at the point Q due to each dipole 30 and 31 is in the plane determined by the dipole and radius vector r and is perpendicular to r . Hence, the space angle between the two fields equals the dihedral angle η between the planes OXQ and OYQ. For any chosen values of the horizontal angle ϕ and the vertical angle θ , which with the vector r constitute the spherical coordinates of the point Q, the angles ψ_1 , ψ_2 and η can be calculated from spherical trigonometry, since

$$\cos \psi_1 = \cos \theta \cos (45^\circ + \phi) \quad (9)$$

$$\cos \psi_2 = \cos \theta \cos (45^\circ - \phi) \quad (10)$$

$$\tan \eta_1 = \frac{\tan (45^\circ + \phi)}{\sin \theta} \quad (11)$$

$$\tan \eta_2 = \frac{\tan (45^\circ - \phi)}{\sin \theta} \quad (12)$$

$$\eta = \eta_1 + \eta_2 \quad (13)$$

From the graph of Fig. 6, values of A_1 and A_2

corresponding to these values of ψ_1 and ψ_2 can be found for the respective dipoles. Since the time phase angle ($\xi_2 - \xi_1$) between the fields is known, all the quantities appearing in Equation 7 are known and the value of B^2 for the particular point Q can be ascertained.

To complete the determination of the radiation characteristics of the unit array, the directivity is next found in the manner outlined in the following paragraphs.

The total average power radiated from the array may be determined by the well-known method of integrating the average power per unit area (Poynting's vector) over the entire surface of the imaginary sphere. Since, from Equation 8, B^2 is proportional to the average power per unit area at any point on the sphere, the total power P_T can be expressed mathematically as

$$P_T = K \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} B^2 \cos \theta d\theta d\phi \quad (14)$$

and the average power which would result at any point on the sphere if energy were radiated uniformly in all directions is equal to KP' , where

$$P' = \frac{\int_0^{2\pi} \int_{-\pi/2}^{\pi/2} B^2 \cos \theta d\theta d\phi}{4\pi} \quad (15)$$

The quantity 4π is the total solid angle subtended by the sphere and P' is the average value of B^2 over the entire sphere.

In view of the extreme complexity of the quantity B^2 , which varies with both θ and ϕ , the integration to obtain P' must in general be carried out graphically. For any fixed value of θ an average value of B^2 can be obtained graphically over the total variation of ϕ , completing the ϕ integration. Knowing this average value,

$$\bar{B}^2$$

the integrand

$$\bar{B}^2 \cos \theta$$

may next be plotted against θ , as illustrated in Fig. 9 which shows curves for the three specific arrays of Figs. 1, 2 and 3. The physical significance of these curves is as follows: the total power radiated by the array is proportional to the area under the curve and the ordinate of any point on the curve is proportional to the power radiated through a ring of unit width lying on the surface of the sphere at the corresponding angle of elevation θ . The quantity of P' is therefore equal to the area under this curve divided by the total solid angle over which the ϕ and θ integrations have been carried. In view of the symmetry of the fields produced by the arrays of Figs. 1, 2 and 3, these integrations were carried only over one octant of the sphere. Thus the areas under the curves of Fig. 9 must be divided by the solid angle $\pi/2$ in order to obtain P' .

If the directivity of the antenna array in the horizontal plane is defined as the ratio of the electric field ϵ actually resulting at any point Q in the horizontal plane to the average electric field ϵ^1 which would result at that point if the power were radiated uniformly in all directions, then the directivity D in the horizontal direction of Q is, from Equations 2, 8 and 15,

$$D = \frac{\epsilon}{\epsilon^1} = \sqrt{\frac{KB^2}{KP'}} = \frac{B}{\sqrt{P'}} \quad (16)$$

As will be apparent to one skilled in the art, the same general treatment can be applied to determine the radiation characteristics of any particular antenna array. The physical arrangement of the component radiating elements and the current phase relations must of course be taken into consideration in deriving the various equations from the fundamental Equations 1, 2 and 7. For example, in determining the characteristics of the array shown in Fig. 2, a fixed reference point, preferably the apex of the V, must be considered to be at the center of the imaginary sphere of Fig. 8. This in turn requires the expression for the field due to each dipole to be referred to one end rather than to its center. It will be recalled that Equation 5 applies only when the radius vector r is referred to the center of the dipole. Similarly, the expressions for the array shown in Fig. 3 are preferably referred to one corner of the square. It is thought unnecessary to detail the steps in deriving the particular equations applicable to these or other special cases. Equations 1, 2 and 7 are general and from them expressions for any particular geometrical system may be derived.

The directivity curve for each of the three types of antennae shown in Figs. 1, 2 and 3 is plotted graphically in Fig. 10. The curves are shown only for one quadrant, but are similar for the other quadrants because of symmetry. The horizontal angle ϕ is in all cases measured from the bisector of the angle between adjacent dipoles. It will be observed from Fig. 10 that the directivity of these three types of arrays is not absolutely uniform in all horizontal directions. However, it is sufficiently uniform for all practical purposes. As previously mentioned, the array of Fig. 2 can be made to give a more nearly uniform horizontal pattern if the angle between the legs of the V is slightly less than 90 degrees.

Having now completely determined the radiation characteristics of a unit array, it remains to investigate the characteristics of a compound array comprising a plurality of superposed unit arrays, as previously described.

Referring to Fig. 11, consider a pair of identical, superposed antennae 43 and 44 of any type, the corresponding elemental radiators of which are spaced apart vertically by a distance S and energized by equal, inphase currents. It is desired to determine the resultant electrical field at a remote point Q due to radiation from the pair. If the point Q is considered to be very remote and on the surface of an imaginary sphere with the antennae 43 and 44 at its center, the radii r_1 and r_2 to the point Q may be considered parallel and at an angle of elevation θ above the horizontal. The effect of the difference in the lengths of r_1 and r_2 upon the amplitudes of the individual fields at Q may be neglected. Thus it may be said that the field ϵ due to antenna 43 at the point Q equals the field ϵ due to antenna 44 at the point Q.

Applying the same principle previously used to determine the resultant field due to an array of radiators located at a single point, the resultant instantaneous field at Q must be the vector sum of the individual instantaneous fields. However in this case, although the individual currents are in time phase, the distances r_1 and r_2 are unequal and the radiated waves will arrive at Q at different times, this being the equivalent of a phase angle between them. If the distance S is expressed in electrical space degrees at the operating frequency, this difference in distance is

$S \sin \theta$ and the phase angle ($\xi_2 - \xi_1$) between the fields is likewise $S \sin \theta$.

As is illustrated by the vector diagram of Fig. 12, the individual fields ϵ acting at point Q are equal, are in the same space direction, and differ in time phase by an angle $S \sin \theta$. The resultant field E is expressed mathematically by the relation:

$$E^2 = \epsilon^2 + \epsilon^2 + 2\epsilon^2 \cos (S \sin \theta) \quad (17)$$

which can also be written as

$$\left(\frac{E}{\epsilon}\right)^2 = \left[2 \cos \left(\frac{S \sin \theta}{2}\right)\right]^2 \quad (18)$$

Since from Equation 2 the power at Q is proportional to the square of the electric field, the above ratio expresses the factor by which the field produced at Q by a single radiating system is augmented by combining the two systems. It may be termed the "reinforcing factor."

The reinforcing factor for any compound system of n identical radiating systems equally spaced apart by S electrical space degrees may be determined in the same manner by taking the vector sum of the n equal electrical fields, each differing in phase from the adjacent fields by $S \sin \theta$. For example, in a compound system having three unit sections the reinforcing factor becomes

$$\left(\frac{E}{\epsilon}\right)^2 = [1 + 2 \cos (S \sin \theta)]^2 \quad (19)$$

This is shown vectorially in Fig. 13. In a system of four sections the factor reduces to

$$\left(\frac{E}{\epsilon}\right)^2 = \left[4 \cos (S \sin \theta) \cos \left(\frac{S \sin \theta}{2}\right)\right]^2 \quad (20)$$

This is shown vectorially in Fig. 14.

The individual unit radiating sections of the compound system may of course be of any form. In the particular embodiments which I have found most practical the unit sections are arrays as shown in Figs. 1, 2 or 3. Also while any number of unit sections may be employed, as a practical matter it is seldom economical to employ more than four.

Figs. 15, 16 and 17 diagrammatically illustrate compound antenna systems comprising two, three and four identical, superposed unit arrays, respectively, of the type shown in Fig. 1. Figs. 18, 19 and 20 show corresponding systems comprising unit arrays as shown in Fig. 2 and similarly, Figs. 21, 22 and 23 show systems built up of arrays as shown in Fig. 3. In all cases the unit antenna arrays are aligned on a common vertical axis and the corresponding elements in adjacent arrays are spaced equally by the distance S along lines parallel to this axis. For simplicity of illustration only the component radiating dipoles are shown. It will be understood that any suitable supporting structures may be provided to maintain the elements in proper space relationship, and that any suitable means may be employed to energize the correspondingly positioned elemental radiators in each array with equal, inphase currents. In practice I have found it advisable to supply the high frequency currents to each unit section over separate transmission lines and to phase each line independently. The transmission lines may be connected to the respective sections as indicated in Figs. 1, 2 and 3. These and other details of my system will be apparent to those skilled in the art and form no part of my invention.

It can be shown from fundamental antenna theory that the manner in which the field intensity varies with variation in the angle ϕ at any constant value of the vertical angle θ is not affected by superposing a plurality of antennae along a vertical axis. Thus the system comprising a tier of arrays may be treated mathematically in the same manner as a single array, taking into account the effect of the reinforcing factor upon the field distribution. A new value of the integrand

$$\bar{E}^2 \cos \theta$$

for the compound system may be found at any particular spacing S merely by multiplying the value of

$$\bar{E}^2 \cos \theta$$

for a unit array by the reinforcing factor computed for a corresponding value of θ . The directivity of the compound system is then computed exactly as for a single array in the manner previously described.

To determine the optimum value of spacing S for any particular system the graphical method is again the most logical. Taking the compound system illustrated in Fig. 15 as an example, curves of the integrand

$$\bar{E}^2 \cos \theta$$

against θ are drawn for various arbitrarily selected values of S . Fig. 24 shows such curves for values of S equal to 180, 210, 240 and 270 degrees. As for the unit arrays, values of P' and D then can be found from each curve. It will be observed from these curves that variation in the spacing S does not affect the distribution of power radiated in the horizontal plane since the ordinates of the curves are the same at values of θ equal to zero. This is also evident from the fact that the radii r_1 and r_2 in Fig. 11 are of equal length when θ equals zero and the fields are consequently always in phase at any point in the horizontal plane. However, it will also be observed that the areas under the several curves of Fig. 24 are unequal. It will be recalled that the total power P_T and the power P' are proportional to these areas. Hence for equal currents in all radiators and constant values of B^2 in the horizontal plane, the power input to the system will vary with the spacing S . This may also be expressed in another way as follows. From the definitions set forth in connection with Equations 14 and 15, the power P' is directly proportional to the total power P_T radiated from the system. Therefore, since the currents in the respective unit antenna sections are constant, both the total power P_T and the power P' radiated from the system will vary with the spacing S in the same manner. At the same time, as pointed out immediately above, the power radiated in the horizontal plane is unaffected by changes in the spacing S and remains constant. Consequently, from the definition of directivity, as expressed by Equation 16, it will be apparent that the directivity is a maximum when P' is a minimum. Curves of P' plotted against the spacing S offer a simple graphical solution. Fig. 25 shows such curves for each of the arrays of Figs. 15, 16 and 17, Fig. 26 for the arrays of Figs. 18, 19 and 20, and Fig. 27 for the arrays of Figs. 21, 22 and 23. The minimum values of P' at which the spacing S is optimum for maximum directivity in the horizontal plane are seen to

be substantially the values given in the following tabulation:

Type of antenna system	Optimum value of spacing S in electrical degrees
Fig. 15.....	240
Fig. 16.....	270
Fig. 17.....	300
Fig. 18.....	240
Fig. 19.....	270
Fig. 20.....	300
Fig. 21.....	300
Fig. 22.....	330
Fig. 23.....	330

While there is a well defined minimum point on each of the curves of Figs. 25, 26 and 27 at which the spacing S is an optimum, it is also apparent that these points are not extremely critical. Substantial advantages in accordance with my invention are realized, and a definite improvement in directivity over prior art systems achieved, even though the value of the spacing S departs somewhat from the optimum value. In Fig. 27, for example, consider any values of the spacing S near an average value of approximately 315 electrical degrees. Over a considerable range of values there is marked improvement in directivity for any one of the three systems of Figs. 21, 22 and 23 as compared with the directivity for conventional 180 degree spacing. The same is true for the arrays of Figs. 15 through 20 near an average value of 270 electrical degrees, as appears from the curves of Figs. 25 and 26.

It is further apparent that the optimum spacing is greater than 180 degrees in all cases investigated. For the general case of a compound antenna system comprising two identical superposed unit radiating systems, it is easily proved that the optimum spacing must always be greater than 180 electrical degrees. Thus, examining Equation 18, let S_1 be some value of S less than 180 degrees. Then,

$$\frac{S_1 \sin \theta}{2} < \frac{180^\circ \sin \theta}{2} \leq 90^\circ \quad (21)$$

and, for values of θ other than zero degrees,

$$\left[2 \cos \left(\frac{S_1 \sin \theta}{2} \right) \right]^2 > \left[2 \cos \left(\frac{180^\circ \sin \theta}{2} \right) \right]^2 \quad (22)$$

Thus, the reinforcing factor for values of S equal to S_1 is always greater than for values of S equal to 180 degrees, at any value of the angle θ excepting zero (where the two values of the reinforcing factor are equal). It will be recalled that the values of P' likewise vary with the reinforcing factor. Hence, when S equals S_1 , a value less than 180 degrees, the minimum value of P' , which determines the optimum spacing between the unit systems, cannot occur.

While a rigorous proof as above cannot easily be given for a compound system comprising more than two unit sections, the results for the cases investigated serve to indicate that the optimum spacing is always increased as the number of unit systems is increased.

It may also be noted that the more nearly each unit radiating section concentrates radiation in a horizontal plane, the greater will be the optimum spacing S for a compound array of such sections. This may be seen from the way the curves of

$$\bar{E}^2 \cos \theta$$

of Fig. 24 vary as S is varied. As S is increased the area under the left-hand primary lobe is decreased, whereas the area under the right-hand secondary lobe is increased. The optimum spacing S represents a condition where the secondary lobe is increasing as fast as the primary lobe is decreasing. If a unit radiating section already materially decreases vertical radiation, then the secondary lobe will be smaller in value and the optimum condition will occur at a larger value of S .

The relationship of the individual arrays is so complex, as is evident from the foregoing analysis, that no simple rule can be derived for this optimum spacing to include all cases. The curves of Figs. 25, 26 and 27 extend only over the narrow range of spacings including one minimum point. It can be shown that, as the spacing S is further increased, the value of P' varies cyclically. However, as would be expected, the first minimum point gives the lowest possible value of P' .

It is significant to compare the directivity of a compound antenna system in which the spacing between adjacent sections is made optimum in accordance with my invention with the directivity of a compound system identical in all respects except that the spacing is made 180 electrical degrees in accordance with prior practice. The directivity of a compound system may conveniently be expressed in terms of the gain in directivity over that of a unit component antenna. Since this is a voltage ratio, it may be expressed in decibels. The following table summarizes, by way of illustration, the theoretical improvement in directivity obtainable by employing my invention in the particular systems illustrated in Figs. 15 through 23, inclusive.

Type of antenna system	Db. gain in directivity over unit antenna		Db. gain by increasing S from 180° to optimum value
	$S=180^\circ$	$S=\text{optimum}$	
Fig. 15.....	3.87	4.87	1.00
Fig. 16.....	5.63	7.22	1.54
Fig. 17.....	7.06	8.78	1.72
Fig. 18.....	3.46	4.44	.98
Fig. 19.....	5.24	6.64	1.40
Fig. 20.....	6.50	8.20	1.70
Fig. 21.....	2.26	3.75	1.49
Fig. 22.....	4.00	5.84	1.84
Fig. 23.....	5.16	7.22	2.06

It is evident that I achieve an increase in horizontal directivity in these systems of the order of one to two decibels over that of prior art systems. Expressed in another way, the fraction of the total radiated energy which is radiated in the horizontal plane is increased by substantial amounts ranging approximately from 25 to 60 per cent.

As pointed out previously, maximum horizontal directivity for any particular compound system comprising a plurality of groups of elemental radiators is attained when the corresponding elemental radiators of adjacent groups are separated by the optimum spacing. In general, both the directivity and the value of the optimum spacing will depend upon the relative orientation of the radiators within each group. However, in the particular case of a compound system built up of a plurality of unit arrays of the type shown in Fig. 1, it is immaterial whether or not the two dipoles of each array lie in a common horizontal plane. For example, Fig. 23 diagrammatically represents a system in which the optimum value of spacing S and horizontal

directivity are identical with that of the system illustrated in Fig. 16. As long as the corresponding dipoles of each pair lying in each of the mutually perpendicular vertical planes are spaced apart by equal distances S , the vertical spacing x between the dipoles of each pair is immaterial. This results from the particular radiation characteristics of this type of unit array. It is well known that there is no mutual impedance between the mutually perpendicular dipoles of each pair when the respective currents are in quarter phase, i. e., no field is produced on one dipole due to the currents flowing in the other dipole. Therefore, the total radiation resistance of the pair is independent of the spacing x between the mutually perpendicular dipoles and the field in the horizontal plane is likewise independent of the spacing x . The field distribution in any direction other than the horizontal varies with the spacing x , but this does not vary the total power radiated or the horizontal directivity.

Although my invention finds particular application in a transmitting antenna system, and although the foregoing analysis has been presented with emphasis on that fact, it will of course be apparent that my improved antenna system may be employed with receiving equipment. The fact that the directivity, current distribution and other characteristics of a particular antenna are the same whether it is employed to abstract energy from an incident high frequency electromagnetic wave or to radiate such a wave is so well known as to require no elaboration.

While I have shown certain particular embodiments of my invention, it will of course be understood that I do not wish to be limited thereto since modifications may be made, both in the circuit arrangement and instrumentalities employed, and I contemplate by the appended claims to cover any such modifications as fall within the true spirit and scope of my invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A high frequency directive antenna system comprising a plurality of identical antenna units spaced apart from each other along a common axis, each unit being composed of elemental sections, the corresponding elemental sections of all said units carrying substantially equal, inphase currents and being spaced from each other along lines parallel to said axis by equal physical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a point on the curve representing P' as a function of the spacing between adjacent units, where P' is proportional to the total power radiated from the system for constant currents in said sections, said curve having one or more minima, and said point lying in the vicinity of one of said minima and within a range of spacings for which P' has a substantially smaller value than for a half wave spacing, whereby the directivity of said system in the plane perpendicular to said axis is substantially greater than for a half wave spacing.

2. A high frequency directive antenna system comprising a plurality of identical antenna units spaced apart from each other along a common axis, each unit being composed of elemental sections, the corresponding elemental sections of all said units carrying substantially equal, inphase currents and being spaced from each other along lines parallel to said axis by equal physical dis-

tances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a minimum point on the curve representing P' as a function of the spacing between adjacent units, where P' is proportional to the total power radiated from the system for constant currents in said sections, whereby the directivity of said system is substantially a maximum in the plane perpendicular to said axis.

3. A transmitting antenna system for concentrating radiated high frequency energy in a horizontal plane comprising a plurality of identical radiating units placed one above the other along a common vertical axis, each unit being composed of elemental radiators, means to excite corresponding elemental radiators in all units with substantially equal, inphase, high frequency currents, and means to space adjacent units from each other by equal distances substantially greater than one half of a wave length at the frequency on which said antenna system operates and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a point on the curve representing P' as a function of the spacing between adjacent units, where P' is proportional to the total power radiated from the system for constant currents in said radiators, said curve having one or more minima, and said point lying in the vicinity of one of said minima and within a range of spacings for which P' has a substantially smaller value than for a half wave spacing, whereby the directivity of said system in the horizontal plane is substantially greater than for a half wave spacing.

4. A transmitting antenna system for concentrating radiated high frequency energy in a horizontal plane comprising a plurality of identical radiating units placed one above the other along a common vertical axis, each unit being composed of elemental radiators, means to excite corresponding elemental radiators in all units with substantially equal, inphase, high frequency currents, and means to space adjacent units from each other by equal distances substantially greater than one half of a wave length at the frequency on which said antenna system operates and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a minimum point on the curve representing P' as a function of the spacing between adjacent units, where P' is proportional to the total power radiated from the system for constant currents in said radiators, whereby the directivity of said system is substantially a maximum in the horizontal plane.

5. A compound antenna system adapted for operation on horizontally polarized high frequency waves comprising a plurality of identical unit antenna arrays disposed in a tier along a common vertical axis, each unit array comprising a plurality of horizontal dipoles, corresponding dipoles of said unit arrays lying in common vertical planes and carrying substantially equal, inphase currents of said high frequency, and means to maintain adjacent arrays spaced from each other by equal distances substantially greater than one half wave length at said frequency and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a point

on the curve representing P' as a function of the spacing between adjacent arrays, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, said curve having one or more minima, and said point lying in the vicinity of one of said minima and within a range of spacings for which P' has substantially smaller value than for a half wave spacing, whereby the directivity of said system in the horizontal plane is substantially greater than for a half wave spacing.

6. A compound antenna system adapted for operation on horizontally polarized high frequency waves comprising a plurality of identical unit antenna arrays disposed in a tier along a common vertical axis, each unit array comprising a plurality of horizontal dipoles, corresponding dipoles of said unit arrays lying in common vertical planes and carrying substantially equal, inphase currents of said high frequency, and means to maintain adjacent arrays spaced from each other by equal distances substantially greater than one half wave length at said frequency and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a minimum point on the curve representing P' as a function of the spacing between adjacent arrays, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, whereby the directivity of said system is substantially a maximum in the horizontal plane.

7. A high frequency transmitting antenna system comprising a plurality of pairs of horizontal dipoles, each substantially one half wave length long at the operating frequency, disposed with their centers on a common vertical axis, one dipole of each pair lying in a first vertical plane, the other dipole of each pair lying in a second vertical plane intersecting the first at right angles along said axis, means to energize the dipoles in said first plane with substantially equal, inphase, high frequency currents, means to energize the dipoles in said second plane with currents equal to but in phase quadrature to said first currents, and means to space the adjacent dipoles in each vertical plane from each other by identical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a point on the curve representing P' as a function of the spacing between adjacent dipoles in each plane, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, said curve having one or more minima, and said point lying in the vicinity of one of said minima and within a range of spacings for which P' has a substantially smaller value than for a half wave spacing, whereby the directivity of said system in the horizontal plane is substantially greater than for a half wave spacing.

8. A high frequency transmitting antenna system comprising a plurality of pairs of horizontal dipoles, each substantially one half wave length long at the operating frequency, disposed with their centers on a common vertical axis, one dipole of each pair lying in a first vertical plane, the other dipole of each pair lying in a second vertical plane intersecting the first at right angles along said axis, means to energize the dipoles in said first plane with substantially

equal, inphase, high frequency currents, means to energize the dipoles in said second plane with currents equal to but in phase quadrature to said first currents, and means to space the adjacent dipoles in each vertical plane from each other by identical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a minimum point on the curve representing P' as a function of the spacing between adjacent dipoles in each plane, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, whereby the directivity of said system is substantially a maximum in the horizontal plane.

9. A high frequency transmitting antenna system comprising a plurality of pairs of dipoles each substantially one half wave length long at the operating frequency, the dipoles of each pair being disposed and arranged in the form of a horizontal V with legs substantially at right angles to each other, means to align said pairs in superposed relation with corresponding dipoles lying in vertical planes, means to energize all said dipoles with substantially equal, inphase currents of said high frequency, and means to space the adjacent pairs of dipoles from each other by identical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a point on the curve representing P' as a function of the spacing between adjacent pairs of dipoles, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, said curve having one or more minima, and said point lying in the vicinity of one of said minima and within a range of spacings for which P' has a substantially smaller value than for a half wave spacing, whereby the directivity of said system in the horizontal plane is substantially greater than for a half wave spacing.

10. A high frequency transmitting antenna system comprising a plurality of pairs of dipoles each substantially one half wave length long at the operating frequency, the dipoles of each pair being disposed and arranged in the form of a horizontal V with legs substantially at right angles to each other, means to align said pairs in superposed relation with corresponding dipoles lying in vertical planes, means to energize all said dipoles with substantially equal, inphase currents of said high frequency, and means to space the adjacent pairs of dipoles from each other by identical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a minimum point on the curve representing P' as a function of the spacing between adjacent pairs of dipoles, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, whereby the directivity of said system is substantially a maximum in the horizontal plane.

11. A high frequency transmitting antenna system comprising a plurality of groups of dipoles each substantially one half wave length long at the operating frequency, each group comprising four dipoles disposed and arranged in the form

of a horizontal square, means to align said groups in superposed relation with corresponding dipoles lying in vertical planes, means to energize all said dipoles with substantially equal, inphase currents of said high frequency, and means to space the adjacent groups from each other by identical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a point on the curve representing P' as a function of the spacing between adjacent groups, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, said curve having one or more minima, and said point lying in the vicinity of one of said minima and within a range of spacings for which P' has a substantially smaller value than for a half wave spacing, whereby the directivity of said system in the horizontal plane is substantially greater than for a half wave spacing.

12. A high frequency transmitting antenna system comprising a plurality of groups of dipoles each substantially one half wave length long at the operating frequency, each group comprising four dipoles disposed and arranged in the form of a horizontal square, means to align said groups in superposed relation with corresponding dipoles lying in vertical planes, means to energize all said dipoles with substantially equal, inphase currents of said high frequency, and means to space the adjacent groups from each other by identical distances substantially greater than one half wave length at the operating frequency of said system and differing substantially from an integral multiple of a half wave length, said distances being of a value which corresponds substantially to a minimum point on the curve representing P' as a function of the spacing between adjacent groups, where P' is proportional to the total power radiated from the system for constant currents in said dipoles, whereby the directivity of said system is substantially a maximum in the horizontal plane.

13. A high frequency antenna system comprising a plurality of pairs of horizontal dipoles, each substantially one half wave length long at the operating frequency, disposed with their centers on a common vertical axis, one dipole of each pair lying in a first vertical plane and the other dipole of each pair lying in a second vertical plane intersecting the first at right angles along said axis, the dipoles in said first plane carrying substantially equal, inphase, high frequency currents and the dipoles of the said second plane carrying currents equal to but in phase quadrature to said first currents, and means to space the adjacent dipoles in each vertical plane from each other by identical distances of a value lying between substantially two-thirds and five-sixths of the wave length on which said system operates.

14. A high frequency antenna system comprising a plurality of pairs of horizontal dipoles, each substantially one half wave length long at the operating frequency, disposed with one end of each dipole substantially on a common vertical axis, one dipole of each pair lying in a vertical plane and the other dipole of each pair lying in a second vertical plane intersecting the first along said axis, all said dipoles carrying substantially equal, inphase, high frequency currents, and means to space the adjacent dipoles in each vertical plane from each other by identical

tical distances of a value lying between substantially two-thirds and five-sixths of the wave length on which the system operates.

15. A high frequency antenna system comprising a plurality of groups of dipoles each substantially one half wave length long at the operating frequency, each group comprising four dipoles disposed and arranged in the form of a horizontal square, said groups being disposed one above the other along a common vertical axis, all said dipoles carrying substantially equal, inphase, high frequency currents, and means to space the adjacent groups from each other by identical distances of a value lying between substantially five-sixths and eleven-twelfths of the wave length on which said system operates.

16. A transmitting antenna system for concentrating radiated waves of a high frequency in a horizontal plane comprising in combination two pairs of horizontal half wave dipoles disposed with their centers on a common vertical axis, one dipole of each pair lying in a first vertical plane, the other dipole of each pair lying in a vertical plane intersecting the first at right angles along said axis, means to energize the dipoles in said first plane with substantially equal, inphase, high frequency currents, means to energize the dipoles in said second plane with currents equal to but in phase quadrature to said first currents, and means to space the adjacent dipoles in each vertical plane from each other

by identical distances substantially equal to two-thirds of a wave length at the operating frequency.

17. A transmitting system for concentrating radiated waves of a high frequency in a horizontal plane comprising in combination two pairs of half waves dipoles, the dipoles of each pair being disposed and arranged in the form of a horizontal V with legs substantially at right angles to each other, means to align said pairs in superposed relation along a vertical axis, means to energize all the dipoles with substantially equal, inphase, high frequency currents, and means to space the pairs of dipoles from each other by a distance substantially equal to two-thirds of a wave length at the operating frequency.

18. A transmitting system for concentrating radiated waves of a high frequency in a horizontal plane comprising in combination two groups of half wave dipoles, each group comprising four dipoles disposed and arranged in the form of a horizontal square, means to align said groups in superposed relation along a vertical axis, means to energize all said dipoles with substantially equal, inphase, high frequency currents, and means to space the groups from each other by a distance substantially equal to five-sixths of wave length at the operating frequency.

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