United States Patent [19]

Gilbo

[11] **3,757,341**

[45] **Sept. 4, 1973**

[54] **LONG WIRE V-ANTENNA SYSTEM**

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[73] Assignee: **Sanders Associates, Inc.**, Nashua, N.H.

[22] Filed: **May 12, 1969**

[21] Appl. No.: **827,088**

Related U.S. Application Data

[63] Continuation of Ser. No. 665,111, Sept. 1, 1967, which is a continuation-in-part of Ser. No. 354,974, March 26, 1964, abandoned.

[52] **U.S. Cl.** **343/733**, 343/735, 343/739, 343/854

[51] **Int. Cl.** **H01q 11/06**

[58] **Field of Search** 343/731–740, 809, 854

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Primary Examiner—Eli Lieberman
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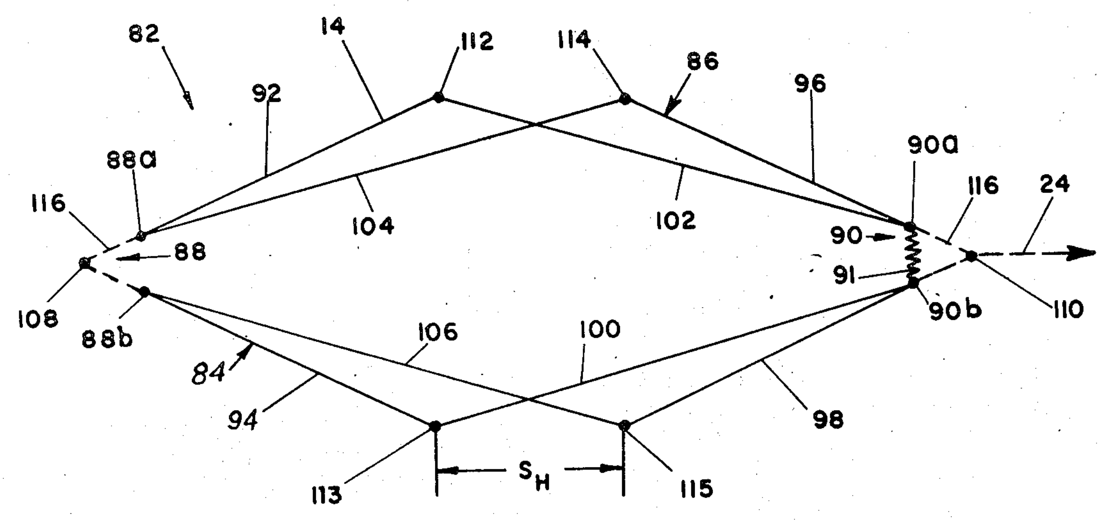
[57] **ABSTRACT**

Long wire antenna arrays comprising combinations of V antennas have wide-band directive characteristics when the antennas are inclined above ground and spaced from each other to make side lobe nulls and peaks of the pattern of each V antenna substantially coincide with peaks and nulls, respectively, of the array factor. Pairs of V antennas can be connected end-to-end with their apexes at the extreme ends to form tandem-V antennas, which can be arrayed with other tandem-V antennas. The arrayed antennas (V and tandem-V) are generally aligned laterally but offset from each other longitudinally and/or vertically.

Space-saving arrays of V and tandem-V antennas have corresponding apexes coincident in the lateral and longitudinal directions and have the intermediate connections of one antenna longitudinally spaced from the corresponding interconnections of the other antenna.

In other arrangements, V antennas having successively increasing apex angles are arrayed in circular sectors with all the V-antenna legs extending along radial paths from a common center.

17 Claims, 20 Drawing Figures



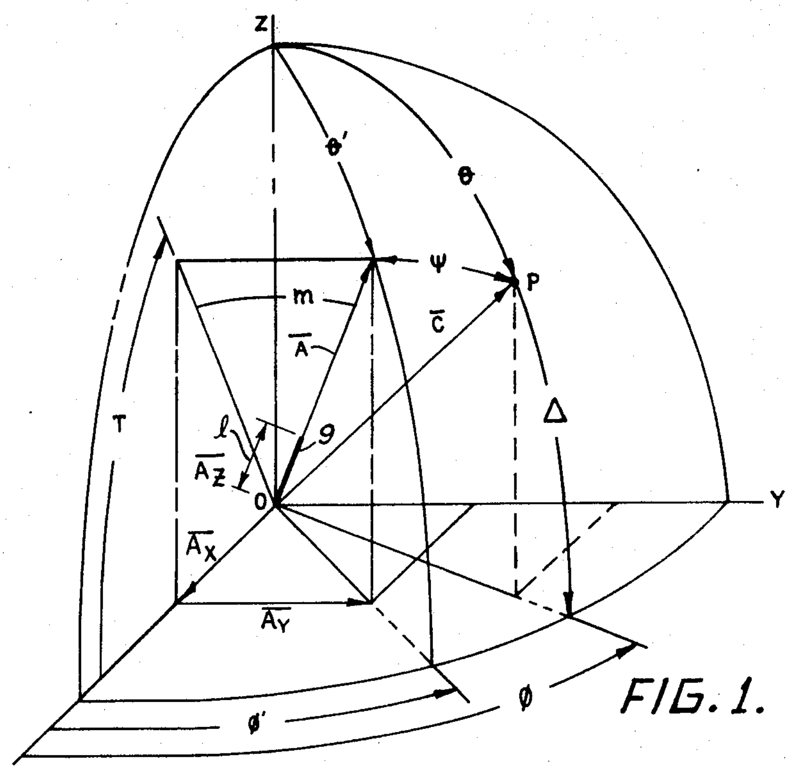


FIG. 1.

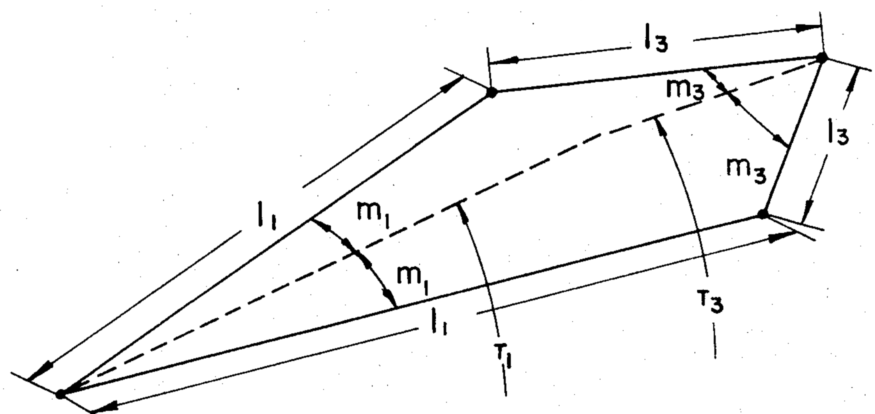


FIG. 2.

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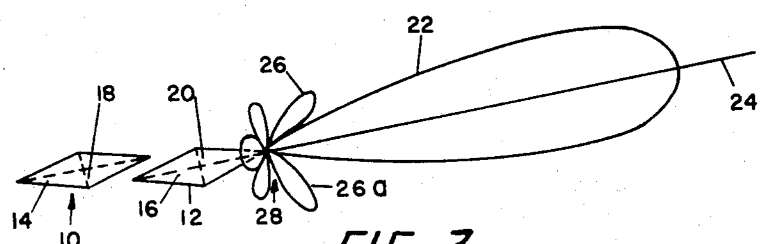

FIG. 3.

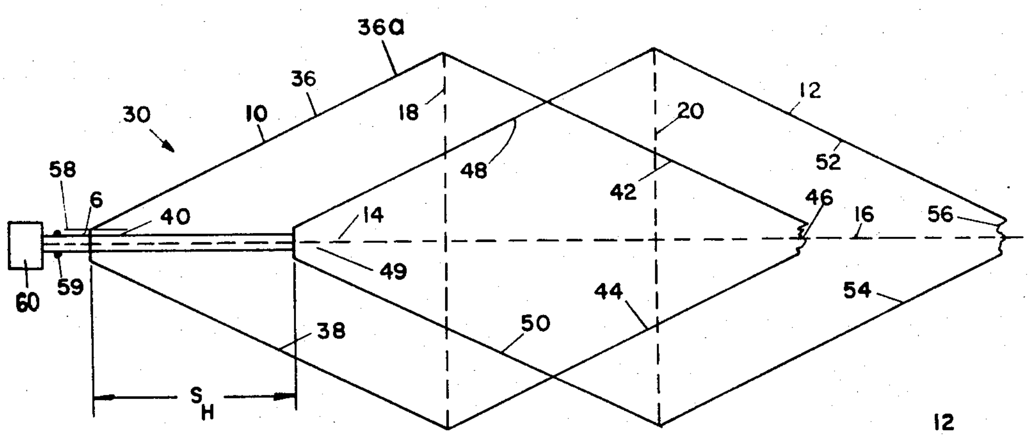

FIG. 4.

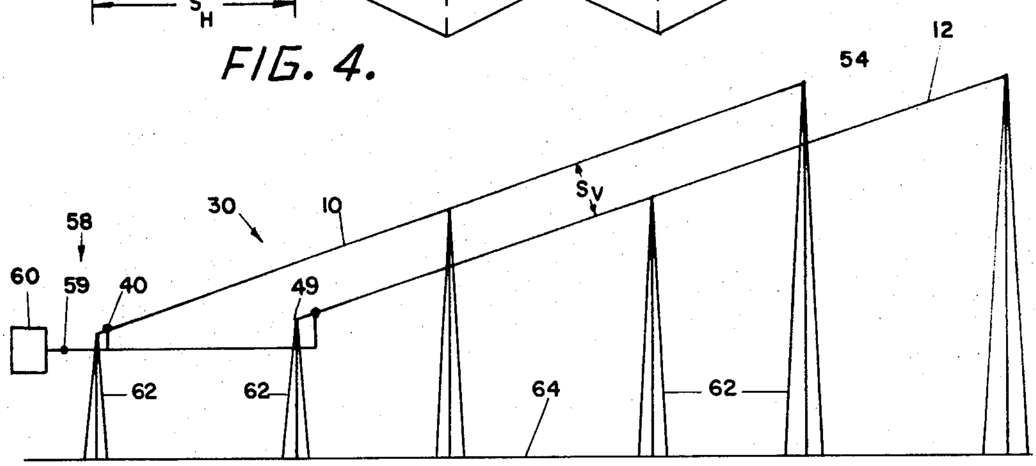

FIG. 5.

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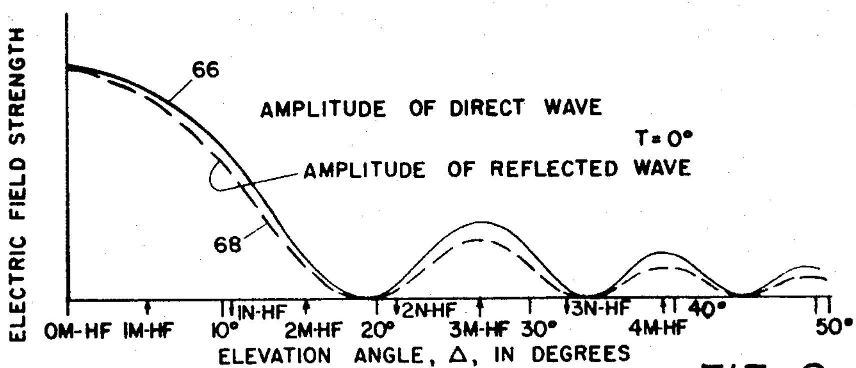

FIG. 6.

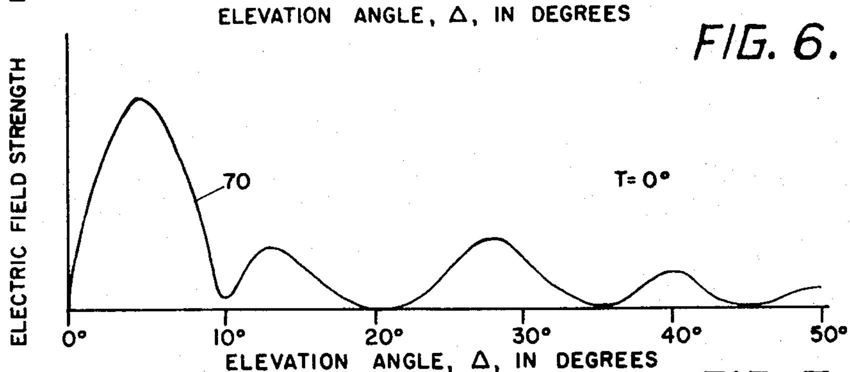

FIG. 7.

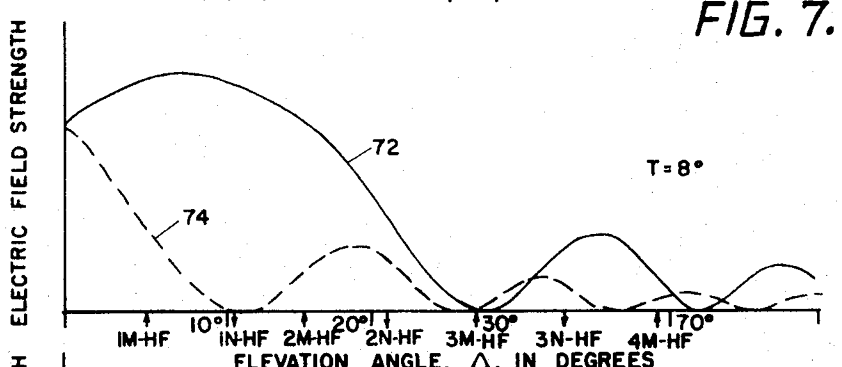

FIG. 8.

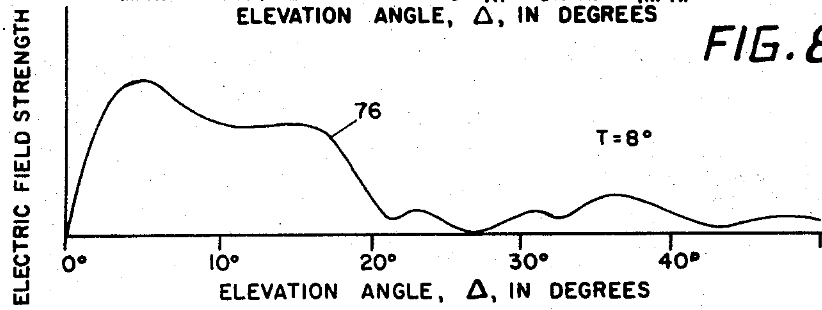

FIG. 9.

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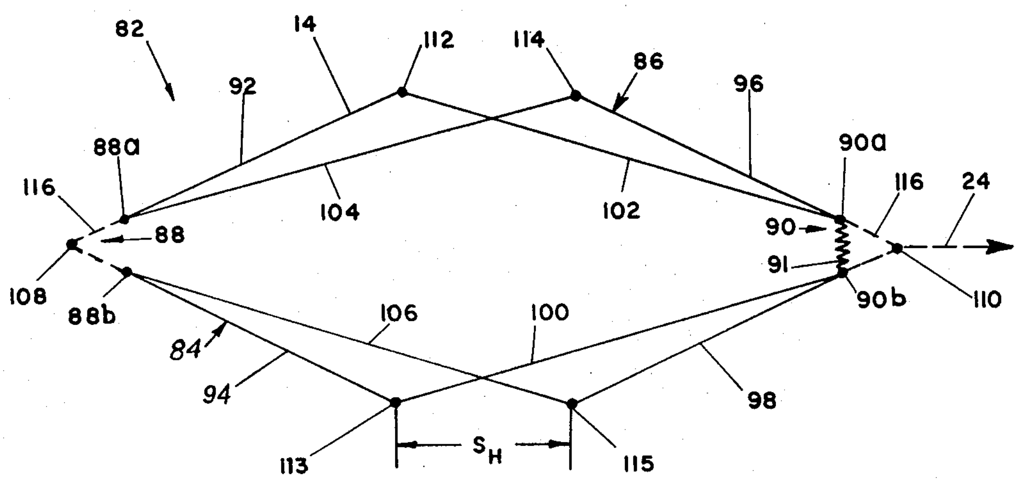
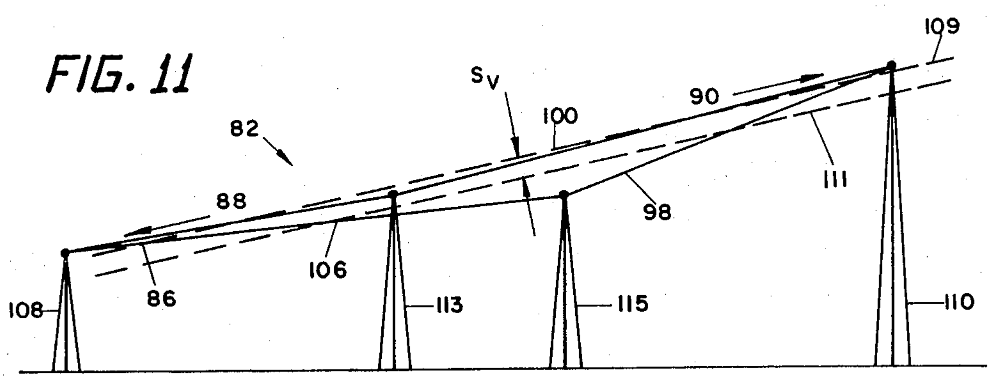


FIG. 10.

FIG. 11



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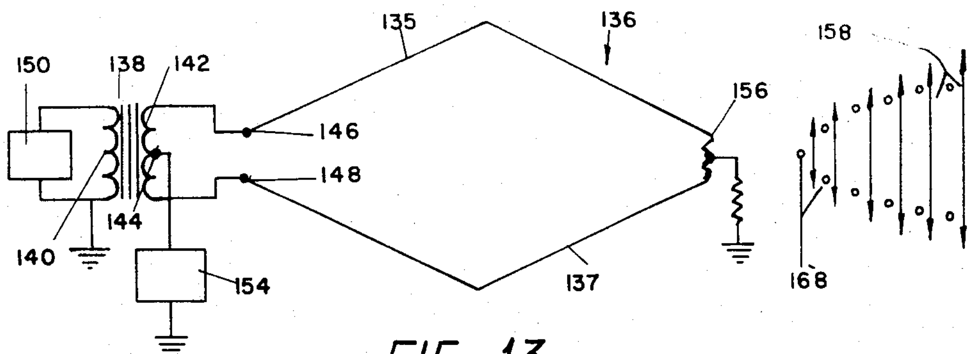

FIG. 13.

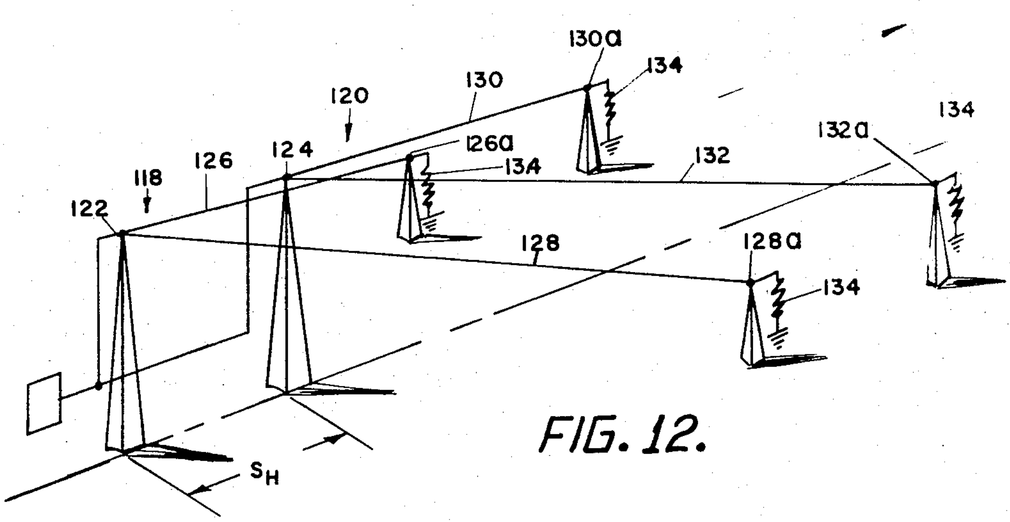

FIG. 12.

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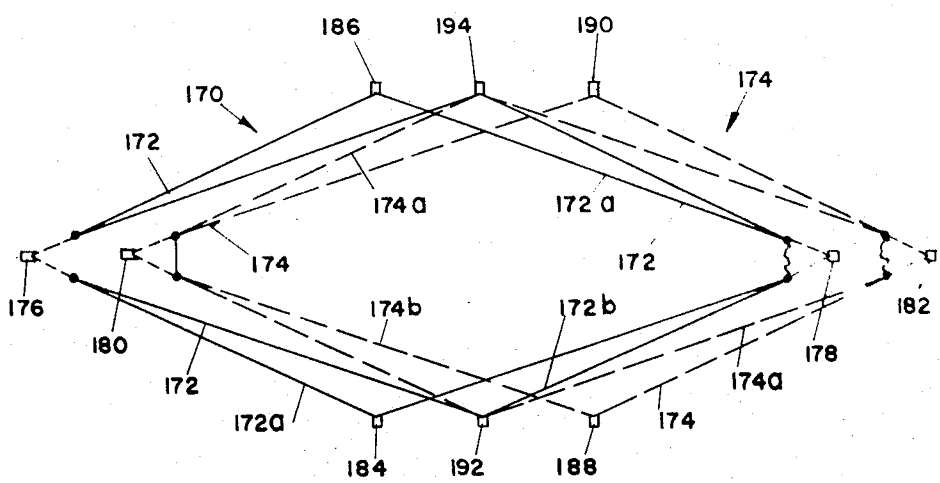

FIG. 14.

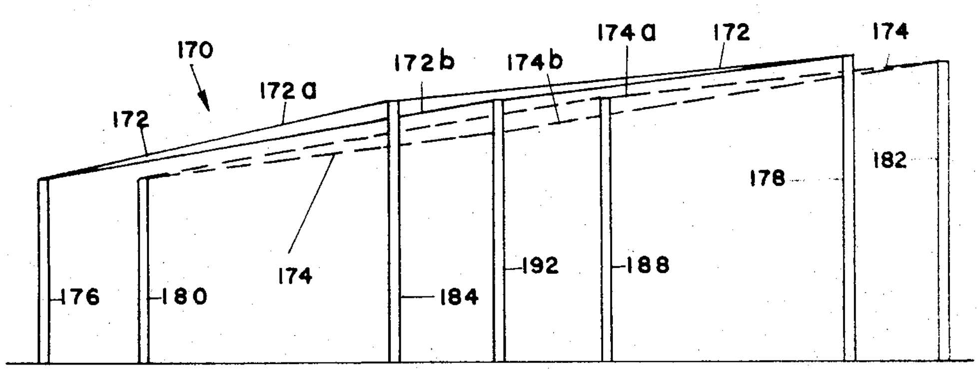

FIG. 15.

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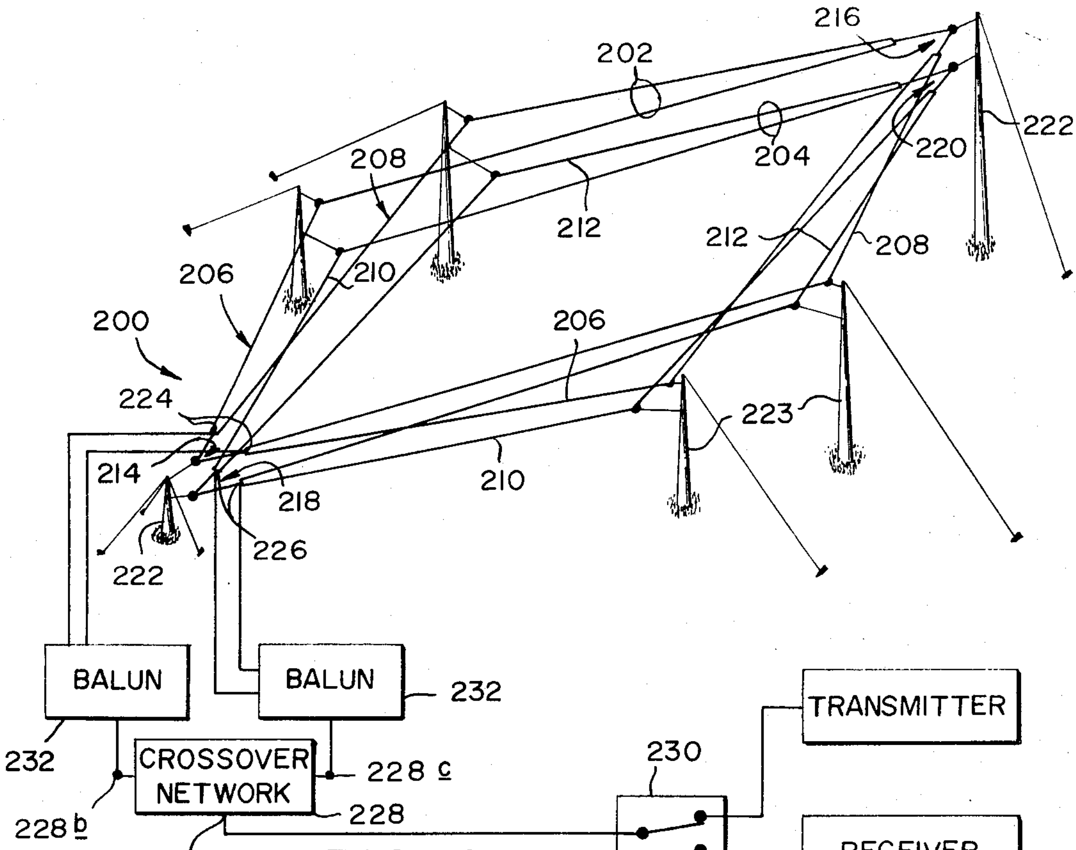

FIG. 16

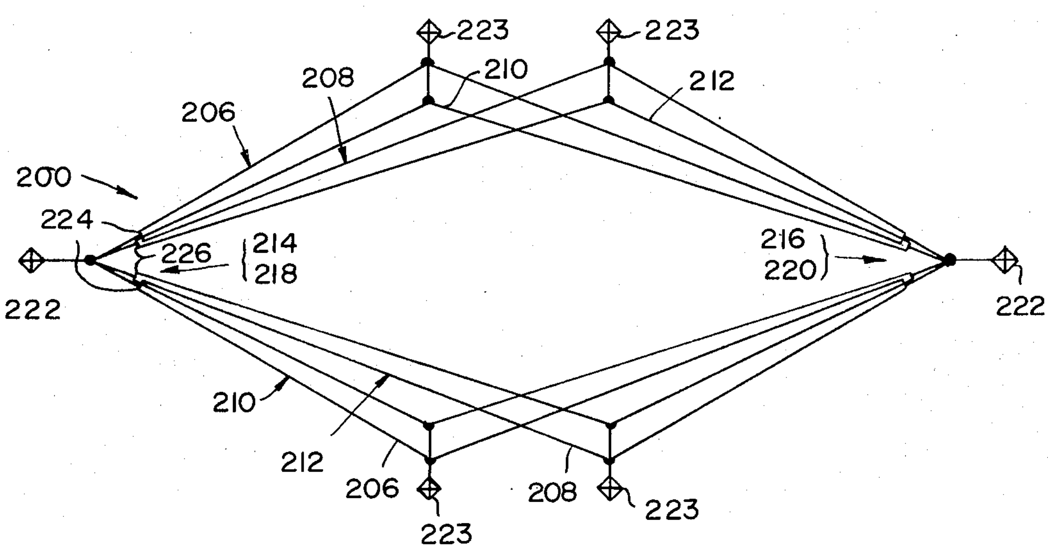

FIG. 17

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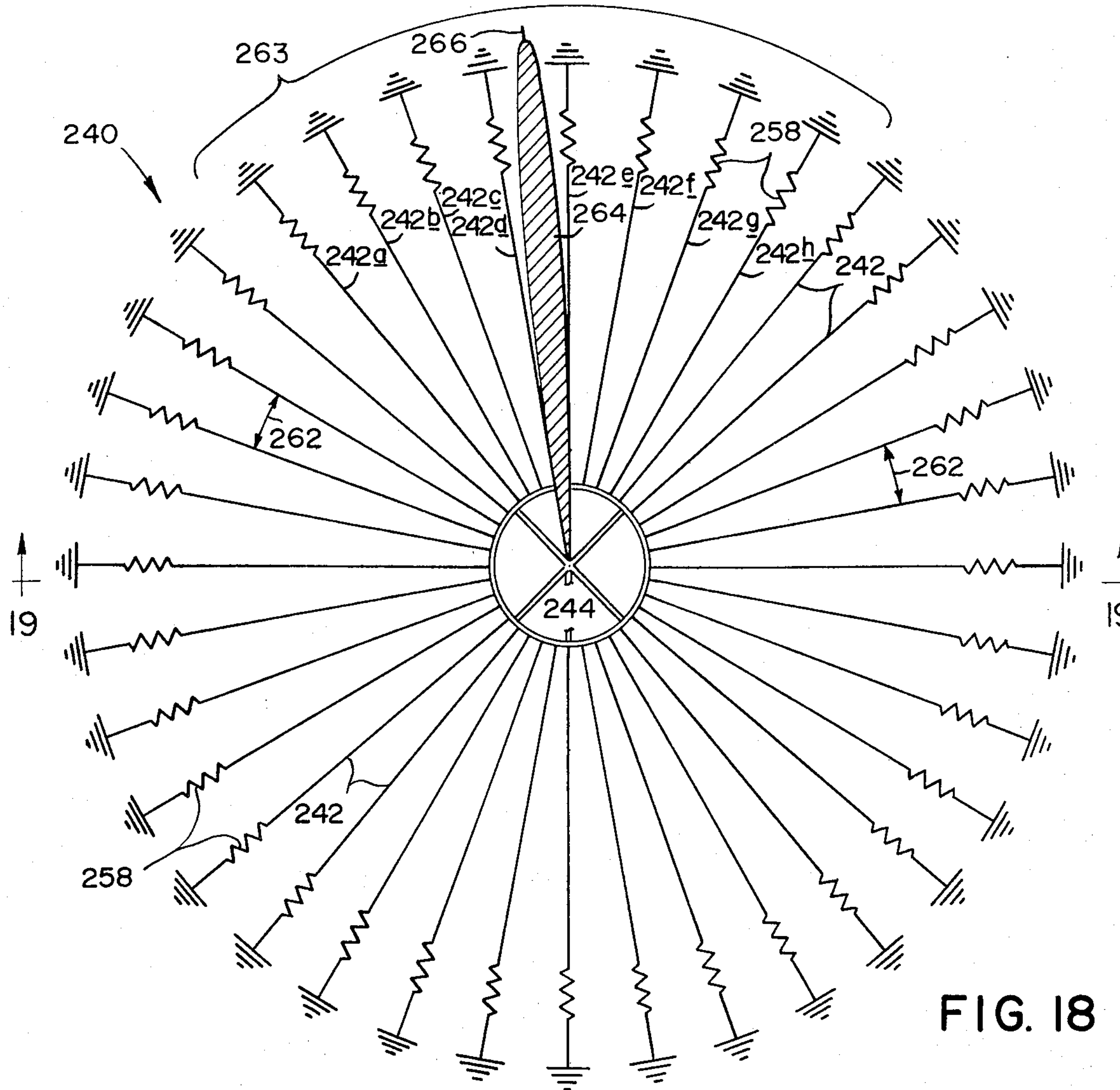

FIG. 18

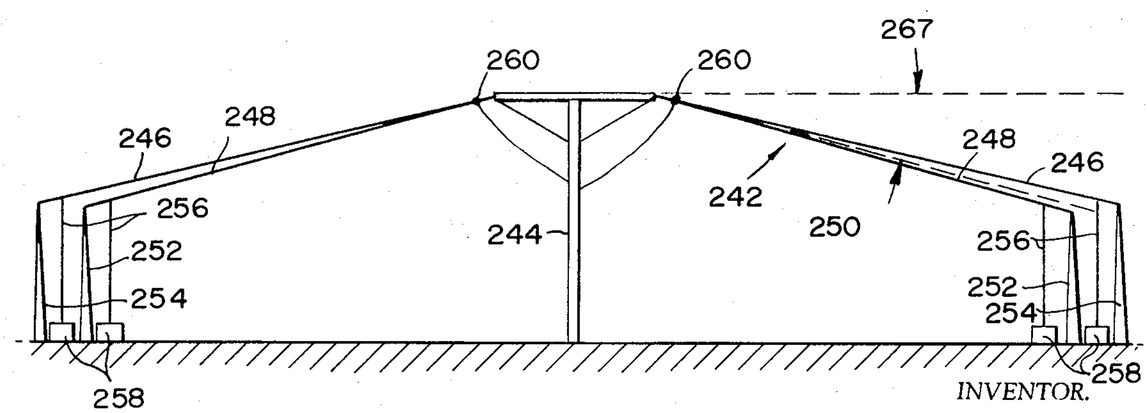

FIG. 19

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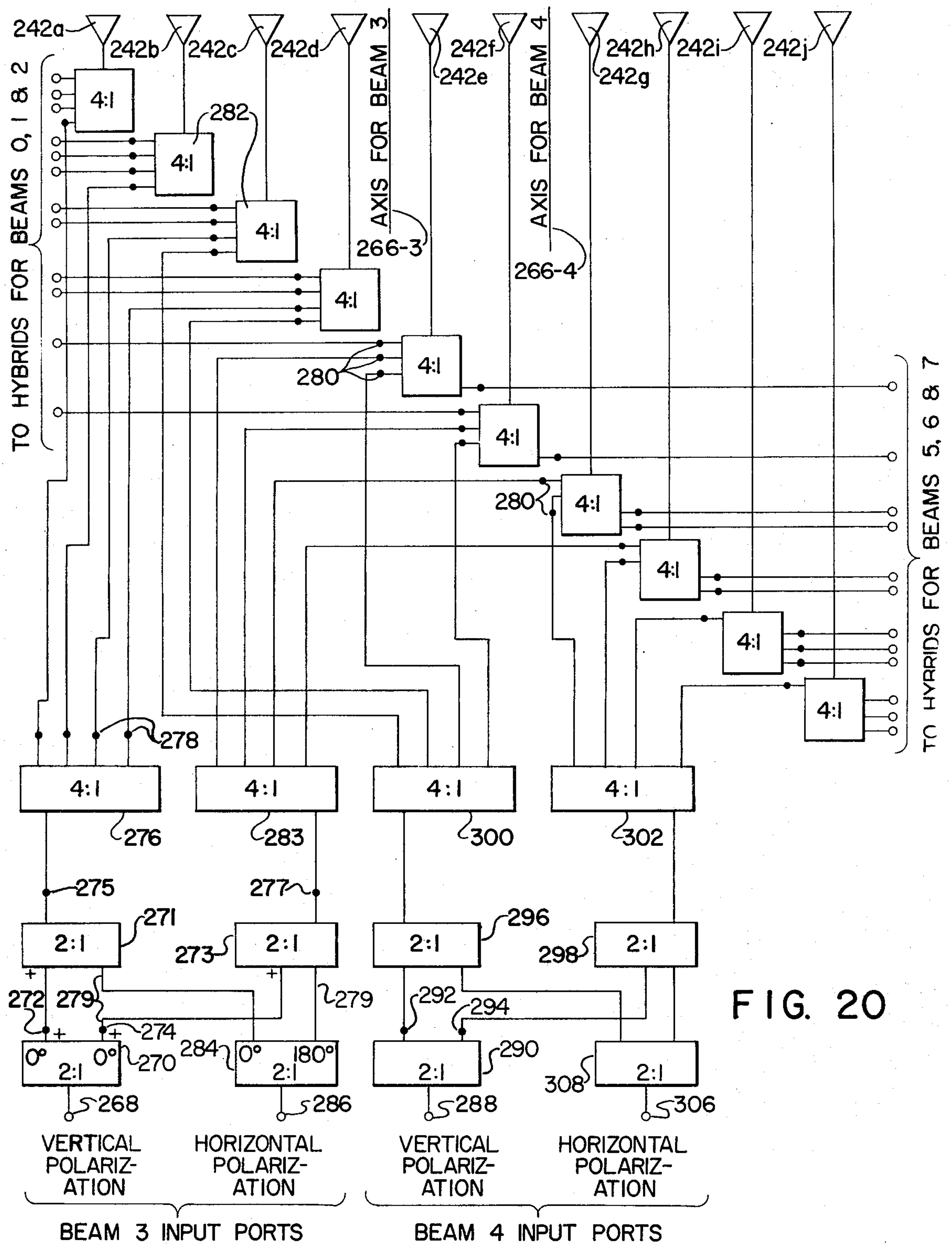

FIG. 20

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LONG WIRE V-ANTENNA SYSTEM

This is a continuation of application Ser. No. 665,111, filed Sept. 1, 1967 which in turn is a continuation-in-part of application Ser. No. 354,974, filed Mar. 26, 1964, now abandoned titled HIGH GAIN ANTENNA SYSTEM WITH LOW SIDE LOBES and assigned to the assignee hereof.

This invention relates to long wire antennas, particularly to long wire V-type and tandem-V antennas. More specifically, it relates to systems of such antennas providing high directive gain and unusually low side lobes over a wide range of frequencies.

The invention also comprehends a novel feed system that operates certain antennas with multiple polarization sensitivity, so that horizontally and vertically polarized signals can be received or transmitted simultaneously.

A V antenna comprises two diverging conductors generally fed at their apex. Terminating resistors are conventionally connected between the remote ends of the conductors and a common point, generally ground. The main lobe of the free space radiation pattern is directed along the center line of the V.

A tantem-V antenna comprises four conductors arranged in two oppositely disposed V's with their apexes spaced apart along the antenna's main lobe axis. The conductors extend between the apexes, with one conductor of each V connected in series with a conductor of the other V. The conductors are generally fed at one apex and terminated with a resistance at the other. When the antenna is electrically symmetrical about the main lobe axis, as in most conventional designs, the terminating resistor is connected between the two conductor ends forming the apex remote from the feed apex. In free space, the radiation pattern of a symmetrical tandem-V antenna having its conductors in one plane has a single main lobe directed along the main lobe axis.

A rhombic antenna is a tandem-V antenna in which the conductors of the two V's have the same length. However, the term "rhombic" antenna is also sometimes used in the art to refer to unequal-V tandem-V antennas.

Long wire tandem-V and V antennas are constructed with conductors that are more than a wavelength long at the frequencies of operation. The two conductors forming each V in such antennas can be regarded as forming a two-wire transmission line. The resistive termination is matched to the characteristic impedance of the line and, accordingly, absorbs substantially all energy reaching the terminated end of the antenna.

Under these circumstances, the current distribution along the conductors is somewhat similar to that in a conventional two-wire transmission line. Since the conductors generally do not correspond electrically to a half-wave length transmission line, the antennas are also referred to as nonresonant antennas.

As stated above, the radiation patterns of V and tandem-V antennas generally have relatively directional main lobes. The antennas do not require reflectors, and they can be made very large. Accordingly, they are used, for example, as ultra high power transmitting antennas and as highly sensitive receiving antennas. V and tandem-V antennas are thus particularly suited for long range communication and surveillance.

A further characteristic of long wire antennas, particularly V and tandem-V arrangements, is that they are generally operated as end-fire systems.

An antenna system has a space characteristic or radiation pattern generally including at least one main lobe containing most of the radiated power and a plurality of side lobes oriented in various directions and separated by deep nulls. Voids in the main lobe of the radiation pattern result in gaps in the range coverage that the antenna system provides. Such voids can cause loss of contact with a station, such as an aircraft, that is supposedly positioned within the main lobe. Main lobe voids are accordingly undesirable and much effort is often expended in eliminating them from the pattern of an antenna system.

During transmission, energy radiated in side lobes detracts from the intensity of the energy in the main lobe and is generally wasted.

Also, energy radiated in side lobes often interferes with communication being carried out at other stations.

Conversely, when an antenna system is connected with a receiver, energy intercepted in the side lobes produces undesirable noise and/or interference at the receiver. Such noise decreases the ability of the receiver-antenna system to detect at low signal to noise ratios and hence diminishes the range of the system.

Moreover, when a signal intercepted in a side lobe has substantial strength, it may be confused with a signal being intercepted in the main lobe. As a result, the existence of a source in the coverage of the main lobe, and its exact location, may be difficult to determine.

A further characteristic of antenna systems is frequency band over which the radiation pattern maintains a specified configuration. For a conventional horizontally disposed rhombic antenna, the operating frequency range is generally given as 2:1 or less.

A general object of the present invention is to provide improved long range antenna systems.

It is also an object of the invention to provide a long wire antenna system having high directive gain. Further objects are that the main lobe of the antenna system be free of nulls or minima and that the system maintain these characteristics over a wide range of frequencies.

Another object of the invention is to provide V and tandem-V antenna systems of the above character.

It is also an object of the invention to provide wideband (multi-octave) V and tandem-V antenna systems in which the amplitudes of the side lobes are much smaller than the amplitude of the main lobe.

A further object of the invention is to provide an antenna system characterized by the above features even though positioned near the earth's surface.

Another object of the invention is to provide a feed system for operating long wire antennas, particularly V and tandem-V antenna systems, with two relatively independent communication modes, wherein the two modes can utilize the same modulation and frequency.

A further object of the invention is to provide long wire, and particularly V and tandem-V, antenna systems that are sensitive simultaneously to polarizations in two different planes and can distinguish between such polarizations.

Other objects of the invention will in part be obvious and will in part appear hereinafter.

DESCRIPTION OF FIGURES

The invention accordingly comprises the features of construction, combinations of elements, and arrangement of parts which will be exemplified in the constructions hereinafter set forth, and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention, reference should be had to the following detailed description taken in connection with the accompanying drawings, in which:

FIG. **1** is a pictorial representation of the geometrical terms used in describing the invention;

FIG. **2** shows a side elevational view of a single tandem-V antenna;

FIG. **3** is a pictorial representation of an array of rhombic antennas embodying the invention; this Figure also illustrates features of a representative radiation pattern;

FIG. **4** is a plan view, partly in schematic form, of an array of inclined rhombic antennas incorporating the invention;

FIG. **5** is a side elevation view of the array of FIG. **4**;

FIGS. **6–9** are graphs illustrating the elevation plane performance of an antenna embodying the invention;

FIG. **10** is a plan view, partly in schematic form, of another array of rhombic antennas embodying the invention;

FIG. **11** is a side elevation view of the array of FIG. **10**;

FIG. **12** is a pictorial representation of an array of V antennas embodying the invention;

FIG. **13** is a plan view, partly in schematic form, of a rhombic antenna having a feed system embodying features of the invention;

FIG. **14** is a plan view, partly in schematic form, of a composite array comprising two arrays of the type shown in FIG. **10**;

FIG. **15** is a side elevation view of the composite array of FIG. **14**;

FIG. **16** is a perspective view of a high-low tandem rhomboid array embodying the invention and showing in schematic form a feed system for operation with it;

FIG. **17** is a plan view of the tandem rhomboid array of FIG. **16**;

FIG. **18** is a plan view of a parasol array embodying the invention;

FIG. **19** is a simplified vertical section of the parasol array taken along the lines **19—19** of FIG. **18**; and

FIG. **20** is a schematic representation of a multiple beam, multiple polarization feed system for the parasol array.

SUMMARY OF INVENTION

I have found that long wire antennas and systems of such antennas can be arranged to have remarkably directive patterns with high concentrations of power in single main lobes that are essentially free of nulls or minima. The antennas radiate a minimal amount of energy in side lobes. Moreover, their frequency ranges are generally much greater than that of prior long wire antennas. That is, the antennas embodying the invention maintain a low input VSWR and a high-gain directive pattern for frequency ranges generally extending at least over several octaves.

The spatial distribution or pattern of the energy radiated from an array of identical antennas is the product of the pattern of a single antenna and several array factors that are functions of the relative positions and the phasing of the antennas.

According to one feature of my invention, two nonresonant long wire antennas are overlapped and arranged with the main lobes of the individual antennas aligned in space to add. This results in a high-gain array main lobe. Further, the side lobe peaks and nulls of each individual antenna are arranged to coincide in space with the nulls and peaks, respectively, of the combined array factor for the two antennas.

That is, in the ideal case, the two antennas are arrayed with each side lobe peak of the individual antenna patterns coinciding with a null of the array factor and with each side lobe null of the individual antenna patterns coinciding with a peak of the array factor. The resultant array pattern then has maximum concentration of power in the main lobe with a minimum of energy diverted to side lobes. The amplitudes of each remaining side lobe is many times less than that of the main lobe.

The ground below the two arrayed long wire antennas reflects energy incident upon it. When the reflected energy coincides in space with energy radiated directly from the array, the two components subtract in directions where they have a relative phase difference equal to an odd number of half-wavelengths. Such directions, conventionally identified by elevation angles, are termed height-factor null positions. Nulls that develop in the primary lobe of the array due to such frequency-sensitive cancellation are effectively minimized according to the invention by inclining the main lobe axis of the arrayed antennas so that a minimal amount of energy is reflected to the position of the primary height-factor null.

Thus the directly radiated energy in the main lobe is, at most, only slightly diminished by the minimal amount of reflected energy that subtracts from it at the first height-factor null position.

Inclining the antennas generally diminishes also the energy reflected to other height-factor null positions. Moreover, the two arrayed antennas produce relatively small side lobes so that the reflected energy from such side lobes produces relatively negligible cancellation at the other height-factor null positions.

In this manner, the arrays of the invention attain remarkably high-gain directive patterns that remain relatively uniform over an extended frequency band.

Pairs of V and tandem-V antennas are advantageously arrayed in this manner. Thus, although the invention is described principally with reference to tandem-V antennas, it should be understood that it is applicable to other long wire antennas, such as the V configuration.

As also described more fully below, a single long wire antenna can be inclined with respect to ground, or other reflectors, to diminish nulls due to reflections, thereby improving the vertical characteristic of the antenna's radiation pattern.

The antenna systems of the invention are designed to provide patterns that represent selected solutions of the equations for the radiation pattern of a generalized long wire antenna structure. These equations are presented below.

The invention also provides a novel feed circuit for a long wire antenna, such as a V antenna, having at least two conductors. The feed system is capable of independently coupling two sources to the antenna. One source causes the antenna to radiate main lobe energy polarized parallel to the plane of the antenna's conductors. The feed applies the output from the other source to cause the antenna to radiate main lobe energy polarized transversely to the antenna's reflector. The feed system provids the same operation during reception, intercepting radio waves polarized in both planes and diverting them to separate receivers.

The feed system is advantageously used with an antenna whose conductors lie in a horizontal plane to detect signals regardless of their polarization, or, during transmission, radiate signals that can be detected by any antenna within range. This performance is particularly suited, for example, for passive reconnaissance stations and for radio beacons.

Alternatively, the feed system enables the antenna to be connected with two sources of different signals and to radiate the signals with different polarizations that have low interaction.

DESCRIPTION OF PREFERRED EMBODIMENTS

Considering the invention in greater detail, it can be shown that a wire extending above ground and energized at one end with a current I_o and terminated at the other end radiates a pattern whose electric field components at a point P located a great distance r from the wire are given by

$$E_\theta = E_\theta{}^d + E_\theta{}^r \exp\,[-j2Kh \cos\theta] \tag{1}$$

and

$$E_\phi = E_\phi{}^d + E_\phi{}^r \exp[-j2Kh\cos\theta] \tag{2}$$

where

E_θ is the total electric field strength polarized parallel to the plane of incidence and transverse to the wire,

the wire extends in the direction θ' and ϕ',

$E_\theta{}^d$ is the direct electric field component polarized parallel to the plane of incidence and transverse to the wire and is given by

$$E_\theta{}^d = -j\,(120)\,(\pi)\,(K)\,[A^d \sin\theta' \cos\theta \cos(\phi-\phi') - A^d \cos\theta' \sin\theta], \tag{3}$$

$E_\theta{}^r$ is the reflected electric field component polarized parallel to the plane of incidence and transverse to the wire and is given by

$$E_\theta{}^r = -j\,(120)\,(\pi)\,(K)\,[-A^r \sin\theta' \cos\theta \cos(\phi-\phi') - A^r \cos\phi' \sin\theta] \tag{4}$$

E_ϕ, $E_\phi{}^d$ and $E_\phi{}^r$ are the corresponding electric field components polarized perpendicular to the plane of incidence $E_\phi{}^d$ and $E_\phi{}^r$ are expressed as

$$E_\phi{}^d = -j\,(120)\,(\pi)\,(K)\,[(-)A^d \sin\theta' \sin(\phi-\phi')] \tag{5}$$

$$E_\phi{}^r = -j\,(120)\,(\pi)\,(K)\,[(-)A^r \sin\theta' \sin(\phi-\phi')] \tag{6}$$

where

$$A^d = \frac{\exp\,(-jKr_o)}{4\pi r_o}\, I_o \left[\frac{1-e)^{-V^d l}}{V^d}\right] \tag{7}$$

where

$$V^d = \alpha + JK\,(1-\cos\psi^d) \tag{8}$$

$$\cos\psi^d = \cos\theta' \cos\theta + \sin\theta' \sin\theta \cos(\phi-\phi') \tag{9}$$

and

$$A^r = \frac{\exp\,(-jKr_o)}{4\pi r_o}\, I_o \left[\frac{1-e^{-V^r l}}{V^r}\right] \tag{10}$$

where

$$V^r = \alpha = jK\,[1-\cos\psi^r] \tag{11}$$

$$\cos\psi^r = -\cos\theta' \cos\theta + \sin\theta' \sin\theta \cos(\phi-\phi') \tag{12}$$

Further,

$K = (2\pi/\lambda)$, where λ is the wavelength,

l is the length of the wire antenna,

α is the attenuation constant, and

h is the height of the wire at the point of phase reference, commonly the feed point.

FIG. 1 illustrates the geometrical quantities used in the above equations. A long wire antenna 9 lies along the vector A, with its feed point at the origin of the illustrated coordinate system.

When the wire is in free space, its radiation pattern components are as in Eqs. (1) and (2) with $E_\theta{}^r = E_\phi{}^r =$ zero.

The vertically polarized component of field strength of a tandem-V antenna at any point P (r,θ,ϕ), can be expressed in terms of its direct wave and its ground reflected wave as:

$$E_\theta = \frac{j60\pi I_o e^{-jKr}}{r\lambda}\Big\{[\text{direct wave}] \tag{40}$$

$$+R'' e^{j\phi''} e^{-j\frac{4\pi H_f}{\lambda}} \cos\theta\ [\text{indirect wave}]\Big\} - E_\theta{}^d + E_\theta{}^r \tag{41}$$

and the direct and indirect waves have opposite polarity.

Further,

I_o is the effective (RMS) current into the antenna, and

r is the distance from a reference point on the antenna, suitably its feed point, to the point P1 (r, θ, ϕ) in space and well beyond the induction field of the antenna.

E is thus the vector sum of the direct and ground reflected waves at any point in space. It gives the magnitude and phase of the resultant wave, and its components can be expressed as

$$E_\theta{}^d = j\frac{60\pi I_0 e^{-jkr}}{r\lambda}\Bigg\{\left(\frac{1-e^{-[\alpha+jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi]}\right)[\cos m_1\cos T_1\sin\Delta\cos\phi-\sin m_1\sin\Delta\sin\phi+\cos m_1\sin T_1\cos\Delta]$$

$$\left(\frac{1-e^{-[\alpha+jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi]}\right)[\cos m_1\cos T_1\sin\Delta\cos\phi+\sin m_1\sin\Delta\sin\phi-\cos m_1\sin T_1\cos\Delta]$$

$$+\left(\frac{1-e^{-[\alpha+jk(1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi]}\right)(e^{-[\alpha+jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1})[\cos m_3\cos T_3\sin\Delta\cos\phi$$

$$+\sin m_3\sin\Delta\sin\phi-\cos m_3\sin T_3\cos\Delta]-\left(\frac{1-e^{-[\alpha+jk(1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi]}\right)$$

$$(e^{-[\alpha+jk\,1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1})[\cos m_3\cos T_3\sin\Delta\cos\phi-\sin m_3\sin\Delta\sin\phi-\cos m_3\sin T_3\cos\Delta]\Bigg\} \quad (42)$$

and

$$E\theta^r = -j\frac{60\pi I_o e^{-jkr}}{r\lambda}\left(R''e^{j\rho''}e^{-j\frac{4\pi h_t}{\lambda}\sin\Delta}\right)\Bigg\{\left(\frac{1-e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1+\cos m_1\sin T_1\sin]-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi]}\right)[\cos m_1\cos T_1\sin\Delta\cos\phi-\sin m_1\sin\Delta\sin\phi$$

$$+\cos m_1\sin T_1\cos\Delta]-\left(\frac{1-e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk\,[1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi]}\right)\cos m_1\cos T_1\sin\Delta\cos\phi+\sin m_1\sin\Delta\sin\phi+\cos m_1\sin T_1\cos\Delta]$$

$$+\left(\frac{1-e^{-[\alpha+jk(1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\cdot\Delta\sin\phi}\right)\left(\frac{e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1}}{[\cos m_3\cos T_3\sin\Delta\cos\phi+\sin m_3\sin\Delta\sin\phi+\cos m_3\sin T_3\cos\Delta]}\right)$$

$$-\left(\frac{1-e^{-[\alpha+jk(1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi]}\right)\left(\frac{e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}}{[\cos m_3\cos T_3\sin\Delta\cos\phi-\sin m_3\sin\Delta\sin\phi+\cos m_3\sin T_3\cos\Delta']}\right)\Bigg\} \quad (43)$$

An arrangement of a tandem-V antenna is illustrated in FIG. 2, showing the geometrical terms not shown in FIG. 1. The bisectors of the V's are inclined with respect to horizontal ground by angles T_1 and T_3. As shown, the legs of one V have the length l_1, and are angled with respect to their bisector by equal angles m_1. The other V has legs of length l_3 at equal angles m_3 with the bisector.

The total horizontally polarized component of the tandem-V antenna's field strength is

$$E_\phi = j\frac{60\pi I_o e^{-jKr}}{r\lambda}\Big\{[\text{direct wave}] + R\perp e^{j\rho\perp}e^{-j\left(\frac{4\pi H_t}{\lambda}\sin\Delta\right)}[\text{indirect wave}]\Big\} \quad (44)$$

$$= E_\phi{}^d + E_\phi{}^r \quad (45)$$

and the direct and indirect waves have the same polarity. The components of $E\,\phi$ can be expressed by

$$E_{\phi}^{d}=j\frac{60\pi I_0 e^{-jkr}}{r\lambda}\left\{\left(\frac{1-e^{-[\alpha-jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi]}\right)[\cos m_1\cos T_1\sin\phi-\sin m_1\cos\phi]\right.$$
$$-\left(\frac{1-e^{-[\alpha-jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi}\right)[\cos m_1\cos T_1\sin\phi+\sin m_1\cos\phi]$$
$$+\left(\frac{1-e^{-[\alpha+jk(1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi]l_3}}{\alpha+jk[1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi]}\right)\left(e^{-[\alpha\pm jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}\right)$$
$$[\cos m_3\cos T_3\sin\phi+\sin m_3\cos\phi]-\left(\frac{1-e^{-[\alpha+jk(1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1-\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi]}\right)$$
$$\left.\left(e^{-[\alpha+jk(1-\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\sin\phi)]l_1}\right)[\cos m_3\cos T_3\sin\phi-\sin m_3\cos\phi]\right\} \quad (46)$$

and

$$E_{\phi}^{r}=j\frac{60\pi I_0 e^{-jkr}}{r\lambda}\left(R^{\perp}e^{j\rho''}e^{-j\frac{4\pi h_f}{\lambda}\sin\Delta}\right)\left\{\left(\frac{1-e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi]}\right)\cos m_1\cos T_1\sin\phi-\sin m_1\cos\phi]\right.$$
$$-\left(\frac{1-e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1}}{\alpha+jk[1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi]}\right)[\cos m_1\cos T_1\sin\theta+\sin m_1\cos\theta]$$
$$+\left(\frac{1-e^{-[\alpha+jk(1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi+\sin m_3\cos\Delta\sin\phi]}\right)\left(e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi-\sin m_1\cos\Delta\sin\phi)]l_1}\right)[\cos m_3\cos T_3\sin\phi+\sin m_3\cos\phi]$$
$$\left.-\left(\frac{1-e^{-[\alpha+jk(1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi)]l_3}}{\alpha+jk[1+\cos m_3\sin T_3\sin\Delta-\cos m_3\cos T_3\cos\Delta\cos\phi-\sin m_3\cos\Delta\sin\phi]}\right)\left(e^{-[\alpha+jk(1+\cos m_1\sin T_1\sin\Delta-\cos m_1\cos T_1\cos\Delta\cos\phi+\sin m_1\cos\Delta\sin\phi)]l_1}\right)[\cos m_3\cos T_3\sin\phi-\sin m_3\cos\phi]\right\} \quad (47)$$

Further, the reflection coefficients R'' and R of Eqs. (40), (43), (44) and (47) are expressed as

$$R''=\frac{(\epsilon r-j\chi)\sin\Delta-\sqrt{(\epsilon r-j\chi)-\cos^2\Delta}}{(\epsilon r-j\chi)\sin\Delta+\sqrt{(\epsilon r-j\chi)-\cos^2\Delta}} \quad (48)$$

$$R^{\perp}=\frac{\sin\Delta-\sqrt{(\epsilon r-j\chi)-\cos^2\Delta}}{\sin\Delta+\sqrt{(\epsilon r-j\chi)-\cos^2\Delta}} \quad (49)$$

where

ϵ_r = dielectric constant relative to free space,

$\chi = (18\times10^3\sigma/f_{(megacycles)})$, and

σ = conductivity above ground.

I have determined several criteria for optimizing the directional characteristics of long wire antennas. These criteria represent certain solutions of the foregoing equations and will now be described first with reference to FIG. 3, showing a double tandem-V array. The array is formed with tandem-V antennas **10** and **12** overlapped with their individual main lobe axes **14** and **16** preferably in a single plane transverse to their transverse axes **18** and **20**. With this construction, the conductors of the antennas extend, in one direction, transverse to the plane of the main lobe axes **14** and **16**. The antennas are positioned with the directions of their principal radiation coinciding, and the array produces a radiation pattern having a fairly conical main lobe **22** directed along a beam axis **24** parallel to the plane of the axes **14** and **16**. Side lobes **26** extend in different directions from the beam axis **24** in a generally symmetrical pattern and separated by deep nulls **28**. It should be noted that FIG. **3** is very much out of scale, with the amplitudes of the side lobes **26** exaggerated with respect to that of the main lobe **22**.

The details of an antenna array **30** comprising planar tandem-V antennas **10** and **12** will now be discussed with reference to FIGS. **4** and **5.** The antenna **10** has conductors or legs **36** and **38** arranged in a V. The ends of the conductors **36** and **38** at the apex of the V form the feed point **40** of the antenna **10.** A conductor **42,** in series with the conductor **36** at its end **36***a*, is arranged in a V with a conductor **44** in series with the conductor **38.** A terminating resistor **46** is connected between the conductors **42** and **44** at their apex.

The tandem-V antenna **12** similarly comprises conductors **48** and **50** arranged in a V and conductors **52** and **54** arranged in a second V having a terminating resistor **56** connected at its apex. The feed point **49** of the antenna **12** is at the apex formed by the conductors **48** and **50.** The conductors **36, 38** and **48** and **50,** forming corresponding V's of the two antennas, are appropriately of the same length, as are the conductors **42, 44, 52** and **54.**

As seen in FIG. **5,** the conductors of the antennas **10** and **12** are suspended from towers **62** for elevation above ground, indicated at **64.** The conductors of the illustrated antennas lie in parallel planes spaced apart a distance S_V, measured transverse to the planes. Moreover, in accordance with the invention, the antennas **10** and **12** overlap each other in the array **30** with their main lobe axes **14** and **16** lying in the same plane. The beam axis **24** (FIG. **3**) lies in the plane of the axes **14** and **16;** this plane also bisects the main lobe **22,** which is directed in the forward direction, i.e. from the antenna feed points toward the terminations.

The overlapping antennas **10** and **12** are spaced with respect to each other along the axes **14** and **16** by a distance S_H, indicated in FIG. **4.** The spacings S_H and S_V of the antennas **10** and **12** are so selected, as detailed hereinafter, that nulls of the individual radiation patterns coincide in space with peaks of the array factor of the two antennas. Similarly, with preferred spacings, the side lobe peaks of the individual radiation patterns coincide in space with nulls of the array factor. Since the intensity of the energy radiated from an antenna approaches zero in a deep null, in each direction about the array **30** where a null of the antennas **10** and **12** coincides with a peak of the array factor, and vice versa, the resultant energy intensity is small. The array **30** thus diverts little energy to side lobes, and hence concentrates its radiated energy in the main lobe, producing a correspondingly high directive gain.

Moreover, the main lobe of the array **30** is thinner than the main lobes of its constituent tandem-V antennas. More specifically, as one moves away from the beam axis **24** (FIG. **3**), the amplitude of the main lobe diminishes according to a cosine function of the direction angle with respect to the beam axis.

To radiate energy from the double tandem-V array **30,** a feed system indicated generally at **58,** FIGS. **4** and **5,** and illustrated as a two-conductor transmission line having an input port **59,** applies radio frequency voltage from a transmitter **60** across the feed point **40** and, preferably with equal amplitude, across the feed point **49.** As the energy from the transmitter **60** travels along the antenna conductors toward the terminating resistors, a substantial amount radiates into space. The balance of the energy arrives at the terminating resistors **46** and **56,** which are matched to the characteristic impedance of the conductors so as to reflect substantially no energy back toward the feed system **58.**

The feed system **58** is constructed according to conventional techniques, with a phase delay from the port **59** to the feed point **49** of antenna **12** which is $(2\pi S_H/\tau)$ radians greater than the delay from the port **59** to the feed point **40** of antenna **10.** As a result, the main lobes of the two antennas **10** and **12** are in phase and reinforce each other.

In addition to adjusting the spacings S_H and S_V to minimize the amplitude of the side lobes in the pattern of the array **30,** the conductor length, the elevation of the conductors, and the tilt angles can be adjusted to enhance the concentration of the power in the array's main lobe. The tilt angles are the angles between each conductor **36, 42, 38** and **44** and the transverse axis **18,** and between the conductors **48, 52, 50** and **54** and the transverse axis **20.** The relation between leg length and tilt angle is discussed, for example, on page 881 of "Electronic and Radio Engineering," F. E. Terman, 4th Ed., McGraw-Hill, 1955. This text and the references cited therein dicuss conventional techniques for calculating the dimensions of a single rhombic antenna.

Considering again the double tandem-V array **30** shown in FIGS. **4** and **5,** the resultant field strength, F_R, for one polarization component is

$$F_R = F_I \, F_H \, F_V \, F_G \tag{50}$$

where

F_I is the corresponding polarization component of the pattern for one of the arrayed antennas, as given by Eqs. (40) or (44),

F_G is the ground reflection factor, and

F_H and F_V are the array factors accounting for the spacings S_H and S_V, respectively, between the arrayed antennas. Except where otherwise indicated, the array factor equations used herein are derived for arrayed antennas fed in phase.

Further, for antennas in parallel planes,

$$F_H = \sqrt{2} \left| \cos \left[\left(\frac{\pi(n-1)S_H}{\lambda} \right) (\cos \psi) \right] \right| \tag{51}$$

where

n is the number of tandem-V antennas in the array and is 22 in the illustrated case,

S_H is the spacing along the main lobe axis **24** between antennas, as in FIG. **4,** and

ψ is the angle, in polar coordinates, between the axis **24** and a line extending to the point for which the field is being computed. (See FIG. **1**) The angle ψ is defined by

$$\psi^2 = \Delta^2 + \phi^2 \tag{52}$$

where

Δ is the elevation angle of the direction in interest and ϕ is the azimuth angle of the direction in interest.

Also,

$$F_V = \sqrt{2} \left| \cos \left[\left(\frac{N(n-1)S_V}{\lambda} \right) (\sin \Delta) \right] \right| \tag{53}$$

The array factor F_H is thus seen to be a cosine function of (S_H/λ) times the cosine of the angle to the point of interest. The factor F_V is a cosine function of (S_V/λ) times the sine of the elevation angle.

The use of the array factors F_H and F_V in arraying antennas according to the invention is indicated in Table I wherein Eqs. (50) and (52) are evaluated:

1. in the forward direction along the axis **24** (FIG. 3), i.e. $\psi = \Delta = \phi = 0$
2. in the lateral direction, along a plane trans-verse to the axis **24**, i.e. $\Delta = 90°$ and ϕ varies between 0° and 90°, and
3. in the backward direction along the axis **24**, i.e. $\psi = \Delta = 180°, \phi = 0$

TABLE I

	Forward direction	Lateral direction		Backward direction
	$\psi=\Delta=0$	$\psi=90°$		$\psi=\Delta=180°$
		$\Delta=0$	$\Delta=90°$	
Array factor F_H	$\sqrt{2}\cos\left\|\left(\frac{\pi S_H}{\lambda}\right)\right\|$	$\sqrt{2}$	$\sqrt{2}$	$\sqrt{2}\left\|\cos\left(\frac{\pi S_H}{\lambda}\right)\right\|$
Array factor F_V	$\sqrt{2}$	$\sqrt{2}$	$\sqrt{2}\left\|\cos\left(\frac{\pi S_V}{\lambda}\right)\right\|$	$\sqrt{2}$

For antennas fed in phase with each other, Table I indicates that factor F_H has a frequency invariant peak in the lateral direction and the factor F_V has frequency invariant peaks in the forward and backward directions. However, as mentioned above, the feed system **58** (FIGS. **4** and **5**) energizes the antennas with a relative phase difference such that the energy from the two antennas adds in the front direction along the axis **24** (FIG. 3).

It has also been found that the spacing S_H can advantageously be selected to bring together, in space, a null of the array factor F_H with the antenna pattern (F_I) side lobe peak closest to the axis **24** in the forward direction. As a result, the array factor null effectively cancels the antenna side lobe peak so that the pattern of the array has only a small side lobe, if any, in the direction of the former unwanted peak.

More generally, the spacing S_H is adjusted to minimize side lobes that would otherwise appear in the forward direction at small angles with respect to the main lobe axis **24**, and to minimize side lobes in the backward direction.

With the antennas **10** and **12** fed with a selected phase difference corresponding to the spacing S_H, the spacing S_V (FIG. **5**) is adjusted to cancel remaining peaks of the antenna pattern F_I by means of nulls in the array factor F_V. Judicious control of the spacing S_V has been found particularly suitable for cancelling single-antenna side lobe peaks in directions oriented at between 20° and 90° with respect to the forward direction on axis **24**.

When the tandem-V antennas **10** and **12** are energized with a radio frequency voltage applied across the conductors **36** and **38** and across the conductors **48** and **50**, the radiation from each antenna is principally polarized parallel to the plane of its conductors, referred to hereinafter as lateral polarization. However, only in the plane of each antenna in its radiation entirely free of components polarized transverse to the plane containing the conductors. The magnitude of the transversely polarized component increases in the direction away from the plane of each antenna.

The side lobe cancellation and main lobe concentration made possible with the present invention is equally effective on polarization components parallel to and transverse to the plane of each antenna. Thus, when, for example, the array is designed according to the invention to optimize the pattern of the laterally polarized radiation component, it has been found that the pattern of the transversely polarized radiation component also has minimal side lobe levels and a correspondingly high-gain main lobe.

Still considering FIGS. **4** and **5**, a reflector such as ground in the field of array **30** reflects energy incident upon it. The reflected and direct waves coinciding in space subtract from each other when the phase difference between them is equal to an odd number of half wavelengths. The resultant pattern then has a minimum value, termed a height factor minimum. The direct and reflected waves add, producing a height factor maximum, when the phase difference is equal to an integral number of wavelengths.

The resultant pattern of an antenna system above ground accordingly varies with the elevation angle to the point of interest and also with frequency. This is demonstrated by the information in Table II, showing, for a rhombic antenna, the elevation angles at which the first height factor minimum and maximum occur at different frequencies.

TABLE II

Frequency	Elevation Angle First Maximum	First Minimum
5 mc.	32°	More than 50°
16.5 mc.	9.5°	19°
30 mc.	5°	10.5°

In order to maintain a frequency invariant main lobe, reflections from ground must not substantially interfere with the main lobe. For this reason, the antennas **10** and **12** are spaced as described above to minimize, so far as practical, side lobes directed toward ground "underneath" the main lobe. Such a side lobe is indicated in FIG. 3 at **26a** and its reflections would coincide with the main lobe **22** and hence interfere with it.

It is generally not feasible to eliminate fully side lobes whose reflections interfere with the main lobe. Accordingly, the main lobe axes of the rhombic antennas **10** and **12** are inclined with respect ground, with the termination of each antenna at a greater elevation than its feed point, as shown in FIG. **5**. This inclination of the antennas elevates the axis **24** of the main lobe **22** and changes the angles with which side lobes are incident upon and reflected from ground. The conductors of each inclined tandem-V antenna shown in FIGS. **4** and **5** thus lie in a plane that extends, in the direction of the antenna's transverse axis, parallel to ground. The plane of each antenna's conductors is inclined by an acute angle with respect to ground along the antenna's main lobe axis.

More specifically, the minimum and maximum values of the direct and the reflected waves from a single horizontal tandem-V antenna disposed over horizontal ground occur at the same elevation angles. Thus, as seen in curves **66** and **68** of FIG. **6**, which are graphs of signal strength as a function of elevation angle above ground, both the direct and reflected waves of the horizontal antenna (i.e. having both the main lobe and the transverse axes horizontal) have minimum values at 19.5° and at 34°, and maximum values at 27° and at 39.5°.

The strengths of the direct and reflected waves thus vary in phase with each other and combine to produce strong peaks at the positions of height-factor maximums and subtract to produce sharp nulls at the positions of height-factor minimums. (The height-factor null positions are marked in FIG. **6** as N-HF and the maximums as M-HF, with a number prefix.) As a result, the combined (direct plus reflected) radiation shown in curve **70** of FIG. **7** varies widely with elevation angle. This variation also changes substantially with frequency, as indicated above in Table II.

Inclining the main lobe axis of the antenna by an angle of T° increases by T° the elevation angles at which the direct wave has maximum and minimum values but decreases by T° the angles of the reflected wave peaks and nulls. This is shown in FIG. **8** where the curves **72** and **74** correspond to the curves **66** and **68**, respectively. More specifically, the curves **72** and **74** are plotted at the same frequency and for the same antenna whose performance is shown in curves **66, 68** and **70**, but inclined 8° (i.e. T = 8°). The overall effect of thus separating by 2T° the positions of corresponding direct and reflected wave peaks and nulls is to diminish the height-factor peaks and nulls, so that the combined radiation has less variation in the elevation direction. This is shown by curve **76** in FIG. **9**.

With one preferred construction according to the invention, the inclination of the single tandem-V antenna, whose performance is shown in FIGS. **6–9**, is selected to make the first null of the reflected wave (curve **68** in FIG. **6**) substantially coincide with the first height-factor null. Thus, as shown in curve **74** of FIG. **8**, the reflected wave has its first null at 10.5°, within 1° of the first height-factor null. As a result, the reflected wave is substantially zero at the first height-factor null and hence does not noticeably diminish the direct wave. The antenna's resultant pattern, curve **76**, FIG. **9**, has effectively no variation at the position of the first height-factor null.

The elevation characteristics of FIGS. **6–9** illustrate the operation of a rhombic antenna having all four conductors **301** feet long and arranged in two V's, each having half-apex angles *m* (the angles *m* are indicated in FIG. 2) of 19°. The average elevation of the antenna is 90 feet and the graphs show its operation at 30 mc. The antenna provides similar operation at frequencies extending to below 5 mc.

Referring again to FIG. **6**, it will be noted that the nulls and peaks of each of the curves **66** and **68** occur at elevation angle intervals of about 8°. This same angle was found desirable for the inclining angle T.

Whereas the antenna whose performance is plotted in FIGS. **6–9** is designed for operation primarily between 5 mc. to 30 mc., it has been found that a tandem-V antenna designed for operation at lower frequencies may advantageously be inclined by one-half the angular interval between successive nulls and peaks of its direct and reflected waves. For example, a rhombic antenna similar to the ones shown in FIGS. **4** and **5** and operating principally between 2 mc. to 12 mc., is advantageously inclined according to the invention by an angle T of slightly less than 5°. This is one-half of the 10° elevation angle intervals between peaks and nulls of its direct and reflected waves. By way of illustration, the other dimensions of the 2–12 mc. antenna are

$$m = 24°;\ l = 470 \text{ ft; and } H_{av} = 123 \text{ ft},$$

where H_{av} is the antenna's average elevation.

Cancelling side lobes and reflected waves, and adding main lobes, to attain high directive gain would appear to result in narrow-band, frequency sensitive operation, However, the array and other factors combined according to the present invention provide high gain antennas that retain these characteristics over a wide band of frequencies. This is because the factors that are combined in designing antenna systems according to the invention vary with frequency at corresponding rates.

For example, referring to FIG. **6**, the peaks and nulls of the reflected waves and the height-factor nulls and maximums occur at correspondingly larger elevation angles at lower frequencies. That is, the elevation characteristic of the reflected wave and of the height-factor vary similarly with frequency. As a result, the first null of the reflected wave and the first peak of the direct wave occur at the first height-factor null (as shown in FIG. **8**) over 10:1 frequency range of the inclined antenna.

It will thus be seen that inclining the main lobe axis of a single long wire antenna in the form of a tandem-V, by the proper angle, greatly improves the elevation characteristic of its radiation pattern. It broadens the elevation plane main lobe pattern and diminishes the effect of an otherwise strong frequency variation on the antenna pattern.

Consider again an array of two tandem-V antennas arranged as in FIGS. **4** and **5**, to strengthen the main lobe and diminish the side lobe level. The effect of ground reflections on the array is considerably less than on a single tandem-V antenna, due to the smaller amplitude of the side lobes whose reflections interfere with the main lobe.

Moreover, inclining the arrayed antennas in the manner shown in FIG. **5** separates the positions of the array's direct wave peaks and nulls from those reflected from remaining side lobes. The pattern of the resultant inclined array hence has no substantial variation due to ground reflections.

Corresponding to the case of a single tandem-V antenna disposed over ground, the main lobe axes of the arrayed antennas are preferably inclined to make the first height-factor null coincide with a sharp null of the array's free space pattern. The resultant radiation pattern of antennas arrayed according to the invention has, at the most, small side lobes whose ground reflections interfere only slightly with the main lobe. As a result, the array's main lobe can have a low elevation angle and a wide vertical beam width and still remain relatively free of nulls due to ground reflections. Such a wide frequency-band, low elevation angle and wide vertical beam width system are desirable, for example, in many long-range communication antennas and in antennas for air to ground or ground to air communication or radar systems.

One antenna array constructed in accordance with the invention has two identical rhombic antennas as shown in FIGS. 4 and 5 with each conductor being 400 feet long, the tilt angle m being approximately 66°, and each main lobe axis being inclined 8° with respect to ground. The feed points were about 90 feet above ground and the spacings S_H and S_V were 90 feet and 18 feet, respectively. The array's main lobe has vertical coverage from 2 degrees to 30 degrees. It exhibits relatively small change over a 10:1 frequency range extending from 3 to 30 mc. The directive gain of the array is around 20 db over this frequency range and the amplitudes of the largest side lobes are 15 db below the main lobe, with the maximum side lobe occurring at the upper frequency. The input SWR of the antenna is under 2:1 over the frequency range.

The high gain, wide band, double tandem-V antenna array **30** described with reference to FIGS. **4** and **5** requires only approximately 25 percent more land space than a conventional single rhombic antenna. However, the double tandem-V antenna array **82** shown in FIGS. **10** and **11** requires no more land space than a conventional single rhombic antenna and yet provides high gain wide band operation substantially equivalent to the array **30.** Moreover, the array **82** requires only two more support towers than a conventional single rhombic.

More specifically, the array **82** comprises two tandem-V antennas **84** and **86** disposed one above the other with common feed apexes **88** and common terminating apexes **90.** Conductors **92** and **94** are arranged in a V in the antenna **84** and form its feed apex **88.** Conductors **96** and **98** in the antenna **86** are appropriately of the same length as the conductors **92** and **94** and arranged in an identical V that forms the terminating apex **90** of the antenna **86.** Similarly, the V-arranged conductors **100** and **102,** of equal length and forming the terminating apex **90** of antenna **84,** are longer than the conductors **92** and **94** and equal in length to the conducotrs **104** and **106** that form the feed apex for the antenna **86.** Thus, the tandem-V antennas **84** and **86** are identical but are disposed with opposite apexes coinciding in space. The spacing S_H between the transverse axes is measured along the main lobe axes as shown. The spacing S_V is measured as shown in FIG. **11,** between the lines **109** and **111** joining the midpoints of the conductors **94** and **100,** and conductors **106** and **98,** respectively.

The two tandem-V antennas **84** and **86** forming the array **82** can appropriately be supported from six towers: a lower **108** at the feed apex **88;** a tower **110** at the terminating apex **90,** and towers **112, 113, 114** and **115** at the sides. Where needed, support cables **116** extend a short distance from each of the towers to the conductors secured thereto. It should be noted that FIGS. **10** and **11** are not to scale. For example, the distance between the conductor ends **88***a* and **88***b*, at the feed point apex **88,** is highly exaggerated, as in the spacing between the conductor ends **90***a* and **90***b*. Hence, the distances from the towers **108** and **110** to the conductors attached thereto are actually very short.

In some instances, the antennas **84** and **86** can be constructed with a single tower on each side, one replacing the two towers **112** and **114** and another replacing the towers **113** and **115.** The array then has the same number of support towers as a single antenna.

Further, this array can also be constructed with the corresponding apexes vertically spaced apart, along a common vertical line rather than coinciding as shown in FIG. **11.**

One array conforming to FIGS. **10** and **11** for optimum operation between 4 MHz and 20 MHz has conductors **92, 94, 96** and **98** each approximately 127 meters long and conductors **100, 102, 104** and **106,** each approximately 176 meters long. The feed apex angle for antenna **86** and the terminating apex angle for antenna **84** are each approximately 14°, and the other terminating and feed apex angles are 20°. The spacing S_H is approximately 52 meters and S_V is approximately 2 meters. The first order side lobes of the array are more then 10 db down over the 5:1 frequency range and the lower order side lobes are at least 15 db down from the directive main lobe.

The antenna array of FIG. **12** illustrates the application of the present invention to V antennas, each of which can generally be considered as comprising a tandem-V antenna in which a pair of conductors has zero length. Accordingly, the illustrated array comprises two overlapping V antennas **118** and **120,** fed at their apexes **122** and **124** out of phase according to the spacing S_H between their feed points. Conductors **126** and **128** form the antenna **118** and conductors **130** and **132,** generally of the same length as the conductors **126** and **128,** form the antenna **120.** The illustrated antennas **118** and **120** are above a ground reflector, preferably of substantially unity reflection coefficient, and are inclined with their apexes at a higher elevation than the remote ends **126***a*, **128***a*, **130***a*, and **142***a* of their conductors. Terminating resistors **134** are connected to ground from the remote ends of the conductors **126–132.** The spacings S_H and S_V between the V antennas are selected on the bases discussed above with reference to the tandem-V antennas.

In the same manner as discussed above with reference to the graphs of FIGS. **6–9,** the main lobe of the resultant pattern that the downwardly inclined V antennas **118** and **120** radiate is relatively free of strong variations with elevation angle when the angle T at which the antennas are inclined is such that peaks and nulls in the reflected wave coincide with nulls and peaks, respectively, in the direct wave. More specifically with an efficient reflector, which can conventionally be achieved by providing a crisscross of conductors on the ground, a downwardly inclined antennas as shown in FIG. **12** has the same radiation pattern as an antenna inclined upwardly at the same angle.

The conductors forming each tandem-V antenna in the above-described arrays embodying the invention may also be disposed in different planes, and the conductors in the V and tandem-V antennas may have unsymmetrical lengths, as in FIG. **2.** However, calculations are simplified with the co-planar and symmetrical length constructions illustrated above.

Although the illustrated antennas have only a single conductor in each leg, they may be constructed with a plurality of parallel-connected wires in each leg. For example, each conductor **36, 38, 42, 44** and **48–54** of the array **30,** FIGS. **4** and **5,** may be constructed with several wires in parallel.

Moreover, the antennas forming the arrays may be constructed without terminating resistors. Reflections from the unterminated ends of the antenna conductors then travel back along the conductors toward the feed point, causing the antenna to radiate energy in the backward direction, opposite to the direction of the main lobe 22 shown in FIG. 3. However, at certain frequencies, the back radiation caused by the reflected energy on the antenna conductors cancels, and the array does not radiate energy in the back direction at these frequencies. The array pattern is then substantially as shown in FIG. 3 and has the high gain as provided by the invention. However, in this instance, the radiation pattern is more frequency sensitive.

Antenna arrays may be constructed according to the invention with more than two V or tandem-V antennas. As an example, such arrays may comprise multiples of two antennas, with each pair being arrayed as described herein and then considered as a single antenna. Two arrays, of two antennas each, can then be arrayed in the manner detailed above for further enhancement of operating characteristics.

More specifically, FIGS. 14 and 15 show a composite array 170 constructed with two sub-arrays 172 and 174, each of which may be identical to the array 82 shown in FIGS. 10 and 11. For clarity, the conductors of the sub-array 174 are shown with dashed lines.

To combine the sub-arrays 172 and 174, the field that each one radiates may be determined as discussed hereinabove. Thereafter, the arrays are considered as single rhombic antennas and arrayed in the same manner as are the rhombic antennas 10 and 12 in the array 30 of FIGS. 4 and 5. Accordingly, the subarrays 172 and 174 of FIGS. 14 and 15 overlap each other and are spaced apart in the horizontal and the vertical directions. Also, they are preferably identically inclined with respect to ground.

Towers 176 and 178 support the apexes of the sub-array 172, and towers 180 and 182 support the apexes of the sub-array 174. The sides of one rhombic antenna 172*a* in the sub-arry 172 are supported with towers 184 and 186, and towers 188 and 190 support the sides of the rhombic antenna 174*b* in the sub-array 174. The sides of the other antennas 172*b* and 174*a* in the sub-arrays 172 and 174, however, may be supported with a single pair of towers 192 and 194. Thus, the composite array 170 provides further construction economies in that it requires only two towers more than the single array 82 of FIGS. 10 and 11.

When a transmitter, or alternatively a receiver, is connected between the conductors forming the feed apex of a conventional rhombic antenna, the antenna is primarily responsive to energy polarized in the plane of the conductors. This particularly so in the main lobe.

When, on the other hand, the two antenna conductors forming the feed apex are connected together, and energized in parallel by a transmitter connected between them and ground, the energy radiated along the main lobe axis is vertically polarized.

A feed arrangement for energizing long wire antennas for both vertical and horizontal polarization sensitive is shown in FIG. 13 connected with a tandem-V antenna 136. The antenna has electrically symmetrical branches 135 and 137 extending between the feed point and the termination, with at least portions of the branches horizontally spaced apart, i.e. in the direction of a ground relfector. The feed circuit comprises a transformer 138 having a primary winding 140 and a secondary winding 142 provided with a center tap 144. The secondary winding 142 is connected between the antenna feed terminals 146 and 148. A communication device, illustrated as a transmitter 150, connected across the transformer primary winding 140 then energizes the antenna to radiate energy polarized parallel to the antenna's transverse axis 152. A transmitter 154 connected between ground and the center tap 144 energizes the antenna to radiate energy that is vertically polarized.

More specifically, the transformer 138 applies the radio frequency voltage from transmitter 150 across the feed terminals 146 and 148. This voltage between the antenna's branches and 137 travels to the termination 156, and, in response, the antenna radiates energy whose electric field is parallel to the traverse axis 152 extending between the branches.

Simultaneously, the transformer winding 142 applies the radio frequency voltage from transmitter 154 to between ground and the feed terminals 146 and 148, with the terminals being excited in phase. This voltage difference between the antenna and ground travels along the two branches to the termination, resulting in energy being radiated with a vertical electric field.

Substantially no voltage from the transmitter 150 appears between the transformer center tap 144 and ground and hence the transmitter 154 is isolcated from the transmitter 150. Similarly, there is no net flux in the primary winding 140 from the transmitter 154 connected to the secondary winding center tap 144. Accordingly, substantially no voltage from the transmitter 154 appears across the transmitter 150. Grounding one side the transmitter 150, as shown, does not change this isolation between the transmitters.

Alternatively, during reception, the communication devices 150 and 154 are receivers. The antenna 136 delivers the intercepted energy polarized parallel to its transverse axis 152 to the receiver connected to the winding 140. The receiver connected between ground and the center tap 144 receives the intercepted energy that is vertically polarized.

Although two communication devices are shown in FIG. 13, a single transmitter or single receiver may be connected to both the primary winding and between ground and the center tap.

FIGS. 16 17 show a high-low tandem rhomboid array 200 in which two tandem rhomboid sub-arrays 202 and 204 operate over consecutive frequency bands to provide continuous, highly directive operation over an extended frequency range. The upper sub-array 202 operates over the lower portion of the desired frequency range and the lower sub-array 204 operates over the upper portion of the frequency range.

The sub-array 202 is similar to the array 82 of FIGS. 10 and 11 and comprises two tandem-V antennas 206 and 208 that correspond to the antennas 84 and 86 of FIGS. 10 and 11. The antennas 206 and 208 are inclined above the ground reflector by an angle determined in the same manner as discussed above, i.e. to place the first height factor null for the combined antennas at the same elevation angle as the primary null in their free space pattern.

The sub-array 204, likewise comprising two tandem-V antennas 210 and 212, is spaced below the sub-array 202.

The feed apex 214 common to the antennas 206 and 208 of the sub-array 202 is vertically in-line with the common feed apex 218 of the antennas 210 and 212 of the other sub-array. Similarly, the common terminating apex **216** in the sub-array **202** is vertically in-line with the common terminating apex **220** in the sub-array **204.** However, as discussed below, the apex angles of the upper sub-array **202** are larger than the corresponding angles of the lower sub-array **204.** The tandem rhomboid antennas have resistive terminations connected to their legs at the terminating apexes.

With this arrangement of the two sub-arrays **202** and **204,** the high-low array **200** can be supported with only six towers, two end towers **222** and four side towers **223.** This is the same number of towers required to support the array **82** of FIGS. **10** and **11,** which operates over a smaller frequency range than the high-low array. Moreover, the array **200** occupies the same land area as the array **82.** These two items, the towers and the land area, constitute principal costs in constructing long wire antennas of the present type. Hence, the high-low array provides uniform, highly directional characteristics over an unusually wide frequency range at a comparatively low cost.

With further reference to FIG. **16,** the sub-array **202** has a feed port **224** and the sub-array **204** is fed at a port **226.** A bidirectional crossover network **228** has branch terminals **228*b*** and **228*c*** connected to these feed ports **224** and **226;** its common terminal **228*a*** is connected to a switch **230.** The switch connects either a transmitter or a receiver to the array, depending on whether transmission or reception is to be carried out. Also, for horizontal polarization, baluns **232–232** are connected between the feed ports **224** and **226** and the crossover network **288** to transform the unbalanced transmission line of the crossover network to the balanced mode.

The crossover network **228,** constructed with well-known techniques, provides a signal path from its common terminal **228*a*** to only the branch terminal **228*b*** over the lower portion of the array operating frequency range. Over the upper portion of this frequency range the cross network provides a signal path between its common terminal **228*a*** and only its other branch terminal **228*c*.** Thus, the uppermost sub-array **202** is active only in the lower part of the operating frequency range and the lower sub-array **204** is active only in the upper part of this frequency range.

As also shown in FIGS. **16** and **17,** the apex angles at the feed and terminating apexes of the sub-array **202** are larger than the corresponding angles of the sub-array **204.** This enables the two sub-arrays to radiate energy at essentially the same elevation angle even though they operate at different frequencies and have the same inclination above the horizon. (The apex angle as defined above with reference to FIG. **2,** is measured between each leg and the bisector of the V it forms.) Further, the antenna legs of the sub-array **202** are directed closer to the side towers **223** than are the antenna legs of the sub-array **204.** Accordingly, the latter sub-array has larger tilt angles (defined above with reference to FIG. **14**) than the sub-array **202.**

The optimum values for these apex and tilt angles of each sub-array, their elevations above ground, and the spacings S_V and S_H (measured as indicated in FIGS. **10** and **11**), are determined in the manner discussed above using the equations provided.

By way of example, a high-low array as shown in FIGS. **16** and **17** designed for operation between 3 MHz and 30 MHz in accordance with these equations has the following dimensions for a cross over frequency of 10 MHz.

I. Sub-array **202**		
A.	Angle of inclination relative to ground:	
	(1) for legs connected to feed apex	3.1°
	(2) for legs connected to terminating apex	2.6°
B.	Elevation of feed apex	100 ft.
C.	S_H	170 ft.
D.	S_V	negligible
D.	Length of legs forming feed apex 214 in antenna 206 and of legs forming termination apex 216 in antenna 208	492 ft.
F.	Length of legs forming terminating apex 216 in antenna 206 and of legs forming feed apex 214 in antenna 208	578 ft.
G.	Feed apex angle in antenna 206 and terminating apex angle in antenna 208	19°
H.	Terminating apex angle in antenna 206 and feed apex angle in antenna 208	13.5°
II. Sub-array 204		
A.	Angle of inclination relation to ground	
	(1) for legs connected to feed apex	6.6°
	(2) for legs connected to terminating apex	4.6°
B.	Elevation of feed apex	75 ft.
C.	S_V	negligible
D.	S_H	170 ft.
E.	Length of legs forming feed apex **218** in antenna 210 and of legs forming terminating apex 220 in antenna 212	408 ft.
F.	Length of legs forming terminating apex 220 in antenna 210 and of legs forming feed apex 218 in antenna 212	573 ft.
G.	Feed apex angle in antenna 210 and terminating apex angle in antenna 212	16.5°
H.	Terminating apex angle in antenna 210 and feed apex angle in antenna 212	11.6°

This array has a main lobe 3 db beamwidth ranging about from 20 to 7 degrees in elevation and about from 20 to 6 degrees in azimuth over the 3–30 MHz range. All side lobes are at least 12 db down from the main lobe over this range.

Where land is at a premium, the high-low array **200** can be constructed with V antennas, rather than with four tandem-V antennas as shown. That is, the V portion of each tandem-V antenna **206, 208, 210** and **212** between the side towers **223** and the terminating end tower **222** can be eliminated. The resulting four-V high-low array occupies only a little more than half the land area of the full aray **200.** A further saving can then be realized in the cost of the remaining towers by inclining the antennas "downhill" from the feed apexes, rather than "uphill" as in FIG. **16.** With this arrangement, only a single tall tower, the tower **222** supporting the feed apexes **214** and **216,** is required. The four side towers **223** can be considerably shorter than in the FIG. **16** structure.

Such an array of V antennas produces radiation patterns in which side lobes are cancelled to the same extent as with tandem-V antennas arrayed in the manner described above. That is, arrays of V antennas designed in accordance with the invention provide the same main lobe reinforcement and side lobe cancellation as do arrays of tandem-V antennas.

Referring back to FIGS. **4** and **5,** another high-low array analogous to the quardruple tandem-V array **200** of FIGS. **16** and **17** can be constructed with two vertically spaced sub-arrays, each similar to the double tandem-V array **30** of FIG. **4.** The feed and terminating apexes of corresponding antennas in the sub-arrays are vertically in-line, as in the FIG. **16** array **200.** Also, the low band upper array has larger apex angles and smaller tilt angles than the high band lower sub-array.

The V and tandem-V antennas and arrays described above are illustrated as having only one conductor per leg. However, in general, each leg may enploy (n) coextensive conductors vertically in register with each other and connected in parallel at the feed apexes and at the terminating resistors. The elevation angle of the multiple-conductor leg is the average of the angles all the conductors make with the horizon.

Such a curtain arrangement of several conductors in each leg is used primarily for impedance considerations. In particular, a relatively low input impedance at the antenna feed apex is generally desired to facilitate matching the antenna to its associated transmission line feed system and the transmitting receiving terminal equipment. A high radiation impedance, on the other hand, is requisite to realize high radiation efficiency, i.e. to radiate a large portion of the transmitter energy applied to the antenna.

The use of a pair of conductors, and sometimes more in each antenna leg reduces frequency-dependent changes in the input impedance and in the radiation impedance. This often facilitates maintaining a high ratio of radiation impedance to input impedance over the entire 10:1 or other multiple-octave operating frequency range of long wire antennas and arrays designed with the foregoing equations. Such a high impedance ratio enables the antenna structure to operate with high efficiency.

The long wire antenna structures now to be described with reference to FIGS. **18** and **19** are illustrated as employing plural conductors in each leg. These figures show a parasol antenna array **240** formed by a circular pattern of travelling wave, long wire antenna legs **242** radially extending from a common central tower **244.** Each leg consists of two conductors **246** and **248,** each of which has a section **250** inclined downward from the central tower to one of two end posts **252** and **254** supporting each leg. From its end post, the conductor extends, with a section **256,** to a terminating resistor **258.**

The feed port **260** (FIG. **19**) for each leg of the parasol array is located at its radially innermost end and the two conductors of the leg are connected to it in parallel with each other. The inner ends of the leg conductors are preferably brought as close as practical to the central tower **244**; in a typical installation the radial distance between the central tower **244** and the feed ports is around 3.5 meters. A matching transformer can be used to feed each leg **242** from a coaxial feed tranmission line.

As shown in FIG. **19,** the end posts **254** supporting the lower conductors **248** are closer to the central tower **244** than the other end posts **252,** but the two end posts, and hence the two conductors, for each leg are on the same radial path.

Further, there is a uniform included angle **262,** FIG. **18,** between adjacent legs of the array. This angle controls the azimuthal shape of the pattern, i.e. the shape in planes parallel to FIG. **18.** It also controls the elevation angle of the pattern main lobe above ground, since the lobe elevation angle decreases as the apex angle is increased.

As indicated in FIG. **19,** the inclination angle **267** of each leg **242** in the parasol array is the angle between the horizontal plane and the bisector of the angle between the sections **250** of its two conductors **246** and **248.** This angle, the same for each leg of the array, is determined in the manner set forth above for V and tandem-V antennas. That is, it is determined to make the primary height factor null coincide in space with the first null in the free-space pattern of the excited sector.

The parasol array **240** is operated by energizing selected legs **242** to form an array that illuminates the desired radiation pattern. For example, operating a sector **263** (FIG. **18**) of the array constituting four V antennas formed by the eight circumferentially consecutive legs **242*a*–242*h*** in FIG. **18** forms a directional pattern having a main lobe **264,** shown drastically reduced relative to the scale of the array. The inner V antenna in the sector **263** is formed by the legs **242*d*** and **242*e*,** and next to it is a second V antenna formed by legs **242*c*** and **242*f*.** A third V antenna in the sector **263** is formed by the two legs **242*b*** and **242*g*** and the legs **242*a*** and **242*h*** form the outer V antenna of the sector. These V antennas have a substantially common center and the same leg length, and are symmetrically arranged about a boresight axis **266** about which the main lobe **264** of the pattern they produce is symmetrical. The sector **263** can thus be designed using the equations set forth above separately for each such V antenna and summing the individual patterns to obtain the overall sector pattern.

The array spacing S_H between the V antennas of a sector of the parasol array is produced by operating them at different relative phases so as to separate their phase centers by the desired S_H distance. In the sector **263,** for example, the first, center, V antenna, i.e. the V antenna formed by legs **242*d*** and **242*e*,** can be fed without a phase shift. The next V antenna, formed by legs **242*c*** and **242*f*,** is then fed with a delay of (B1) radians relative to the first V antenna. Similarly, the succeeding two V antennas in the sector **263** are fed with delays of (B2) radians and (B3) radians respectively relative to the phase of the first V antenna.

However, this relative phasing can be omitted where somewhat larger side lobes, e.g. only 15 db or so down from the main lobe, are acceptable.

When the two legs of each V antenna noted above in the sector **263** are operated in phase, and the only phase difference between the four V-antennas of the sector is that which provides the desired spacing S_H of their phase centers, the resultant pattern of the array is vertically polarized. The eight legs can be energized with a cosine-like amplitude distribution such that the legs at the center of the sector receive the largest signal components and the legs at the two ends of the sector receive the smallest signal components.

Alternatively, the sector has a horizontally polarized pattern when each of the four legs on the right side of the FIG. **18** axis **266** is operated out of phase from the leg on the other side of the axis with which it forms a V antenna. The feed system described below with reference to FIG. **20** is well suited for operating the parasol array in either or both polarizations.

The pattern of the parasol array can be moved, or steered, by exciting circumferentially adjacent sectors of the array in a time succession. Further, overlapping sectors, even those sharing some of the same legs, can be energized concurrently to produce multiple simultaneous patterns in different azimuthal directions. The modulation and/or frequency of the signal in each pattern can be different from that in the other patterns.

By way of example, in a parasol antenna designed for operation from 3 MHz to 30 MHz, the radial distances from the central tower **244** to the posts **252** and **254** are approximately 600 feet. The included angle **262** is 4.5° and the elevation angle **267** is about 7°. The central tower is 160 feet high, so that each end post **252** and **254** is 80 feet high. Although this array is designed for operation over a 10:1 frequency range, by the use of the high-low band techniques discussed with reference to FIGS. **16** and **17**, it is possible to use the antenna array efficiently up to 150 MHz; that is, over a 50:1 frequency range.

Over the 10:1 range, the 15-leg sector described above provides a vertically polarized pattern directed within 1° of the design azimuth, and having an azimuthal main lobe 3 db beam-width ranging from 10 to 30 degrees. The directive gain is in excess of 10 db. All side lobes are at least 10 db down from the main lobe. The patterns sensitive to horizontal polarization are generally identical except that the main lobe 3 db azimuthal beam-width is between 6 and 30 degrees.

By way of a further example, another parasol array such as is shown in FIGS. **18** and **19** has an included angle of 3° between adjacent legs. For vertical polarization, a sector of three legs is employed; a central leg, along which the radiation pattern is centered, and the two legs next to it on either side.

Horizontally polarized coverage in the upper frequency band of this parasol array is obtained by using six consecutive legs. The resultant beam is directed along an axis extending midway between the two central legs. The horizontally polarized radiation pattern at the lower frequency band of the array extends in essentially the same direction. It also is produced with a sector of six legs, but not the same six used at the upper band. Specifically, the low-band six-leg sector consists of the second, fourth and sixth legs on each side of the resultant pattern axis. Thus, the extreme outer legs of this six-leg, low-band sector have a 33° included angle between them.

The parasol array has several advantages over the prior art Wullenweber, which is an array of vertical antennas symmetrically disposed outside a vertical cylindrical reflector. The feed line to each Wullenweber element usually extends from the center of the array to the periphery, similar to the radial extension of the section **250** of each leg in the parasol array. However, in the Wullenweber, this relatively lengthy transmission line contributes nothing to the ability of the array to capture energy on reception or to radiate energy during transmission. In the parasol array, of course, the radial conductors constitute principal ports of the antenna elements. Moreover, the Wullenweber is limited primarily to vertical polarization, whereas the parasol array is capable of simultaneous dual polarization.

FIG. **20** shows a fragment of a multiple beam-forming network for operating a parasol array with either or both vertical and horizontal polarization. The network energizes sector of eight consecutive legs, such as the FIG. **18** sector **263** of legs **242*a*–242*h***, and it provides successive beams that overlap substantially three-fourths of the two adjacent beams. For simplicity, the drawing shows only a complete circuit for two beams arbitrarily designated as numbers 3 and **4**. The drawing represents each leg **242** of the array with a single antenna.

The input port **268** for producing the number 3 beam with vertical polarization is the common port of a **2**:**1** input hybrid **270** that functions as a broadband radio frequency directional coupler. The hybrid has branch ports **272** and **274** and a fourth hybrid port, not shown, that is internally terminated receives only a small unbalance signal. The branch ports of the hybrid **270** are connected to branch ports of **2**:**1** hybrids **271** and **273** having, respectively, common ports **275** and **277**.

The antenna legs **242*a–d*** on the left side of the boresight axis **266–3**, i.e. the axis for beam number **3**, are energized equally from the hybrid port **275** and the four legs **242*e–h*** on the right side of the axis are energized from the hybrid port **277**. The connection to the left legs is made through a **4**:**1** hybrid **276** having a common port connected to the hybrid common port **275**. Each of the four branch ports **278–278** of the hybrid **276** is connected to one of four branch ports **280** on a **4**:**1** cross-coupling hybrid **282** whose common port is connected to one leg **242** of the array. Each hybrid **282** couples energy from any branch port to its common port with little energy appearing at the other branch ports; a signal applied to the common port, on the other hand, uniformly energizes each branch port.

Similarly, the common port of a **4**:**1** hybrid **283** is connected to the hybrid port **277** energized from the branch port **274** of the input hybrid **270**. Each branch port of the hybrid **283** is connected to one branch port **280** of the cross-coupling hybrids **282** whose common ports are connected to the four array legs **242** disposed immediately on the right side of the axis **266–3**.

The transmission lines **279** forming these connections between the input hybrid **270** and the hybrids **271** and **273** have the same electrical lengths, as do the two lines between hybrids **271** and **276** and between hybrids **273** and **283**. This is true also for the lines from the cross-coupling hybrids to the antenna legs **242**.

Also, the input hybrid **270** has the same phase shift between its common port **268** and each of its branch ports **272** and **274**, and both **2**:**1** hybrids **271** and **273** have the same phase shift between their common ports and their branch ports. Further, each **4**:**1** hybrid **276** and **283** has the same phase shift between its common port and each of its branch ports.

However, the transmission lines connecting the hybrids **276** and **283** with the cross-coupling hybrids **282** generally have different lengths selected so that energy radiated from the antennas **242*a*–242*h*** is in phase along a common wave front parallel to the path along which the antennas are disposed. Thus, these transmission lines introduce selected different time delays to the signals that propagate therealong.

The hybrids **270, 271, 273, 276** and **284** thus provide a bidirectional broadband **8**:**1** power-dividing circuit betweenthe beam **3** vertical polarization port **268** and the eight legs **242** centered on the axis **266–3.** Vertically polarized radiation, incident on these eight antenna elements produces signals that are combined in phase in the **4**:**1** hybrids **276** and **283** and again at the input hybrid **270** to produce a single resultant signal at the beam port **268.** Similarly, a signal applied to the beam port **268** energizes the eight antenna elements centered in the axis **266–3** to radiate a vertically polarized wave.

The beam-forming network of FIG. **20** can also produce beam **3** with horizontal polarization simultaneous with the vertically polarized beam. The common port of a **2:1** hybrid **284** is the beam **3** horizontal polarization input port **286.** Additional transmission lines **279** connect the two branch ports of this hybrid to the other branch ports of the **2:1** hybrids **271** and **273.** The hybrid **284** is constructed to delay the signal component applied to one branch port from its common port by 180° relative to the signal component applied to its other branch terminal. Each leg **242***e, f, g* and *h* on one side of the beam **3** axis **266–3** is then energized from the port **286** with energy 180° out of phase from the leg **242***d, c, b, a*, respectively, with which it forms a V antenna.

Where only vertical polarization is required in beam **3,** the hybrids **284, 271** and **273** can be omitted and the branch ports **272** and **274** connected directly to the common ports of the **4:1** hybrids **276** and **283.** Similarly, for only a horizontally polarized beam **3,** the hybrids **270, 271** and **273** can be omitted.

With further reference to FIG. **20,** the stage of cross-coupling hybrids **282** enables the same legs **242** that form beam **3** to be energized with other groups of legs to illuminate beams on either side of the number **3** beam. For example, as will now be described, six of the eight legs that form the number **3** beam also form the number **4** beam.

Specifically, the beam number **4** vertical polarization input port **288** is the common port of a **2:1** input hybrid **290.** The branch ports **292** and **294** of this hybrid are connected through **2:1** hybrids **296** and **298** to common ports of **4:1** hybrids **300** and **302.** The branch ports of the hybrids **300** and **302** are connected through phase shifters **285** as indicated and through cross-coupling hybrids **282** to the six rightmost legs **242** that form the number **3** beam and to the next two legs **242** to the right.

A beam **4** horizontal polarization input port **306** is the common port of a **2:1** hybrid **308** whose branch ports connect to the remaining branch ports of the hybrids **296** and **298.** The relative phase relations of the foregoing hybrids and interconnecting transmission lines associated with beam **4** are identical to those associated with beam **3.**

The complete beam-forming network of FIG. **20** has additional hybrid circuits identical to those described for beams **3** and **4** for each beam the network is to produce from the parasol array to which it is connected. Accordingly, the remaining branch ports of the cross-coupling hybrids **282** shown in FIG. **20** are fed from the input ports for beam number **0, 1, 2** and **5, 6** and **7,** as indicated.

Each beam input port such as the four shown in FIG. **20** can be operated independently from and simultaneously with the other beam input ports. That is, each beam input port can be connected with a different transmitting/receiving terminal device operating independently of the other terminal devices. Thus, the parasol array can be used for simultaneous communication in several different directions. And, since a horizontally polarized pattern and a vertically polarized pattern can be produced in each direction at the same time, the parasol array is capable of concurrent communication in each polarization in any azimuthal direction.

With further reference to the parasol array of FIGS. **18** and **19,** a sector of the array with less than 360° coverage can be built where communication in only a restricted number of directions is required. Moreover, for operation in a single direction, a sector of the full array having at least eight legs usually provides more than the needed performance. By way of example, a one-directional sector of the FIG. **18** array having the 4.5° included angle would extend over 36° with eight legs. The other sector noted above with eleven legs separated by 3° included angles covers only 33°.

The long wire travelling wave antennas and arrays described above and constructed in accordance with the invention exhibit relatively little interaction with other, independently operated like arrays located close by. This makes it possible for complexes of the long wire antenna systems to be constructed at a single site for diverse communication and surveillance objectives.

The antenna arrays described above thus comprise long wire antennas arrayed in overlapping, spaced configurations wherein the main lobes of the individual antennas coincide in phase in only one direction. The principal side lobes of each antenna coincide with nulls of another antenna in the array.

The resultant pattern of each array has major lobes that are of substantially greater amplitude than the major lobes of the individual antennas. The side lobes of the array are diminished far below the side lobes of the individual antennas so that there is relatively negligible side lobe radiation and, conversely, sensitivity. The arrays maintain this concentration of radiated energy in a single directive main lobe over remarkably wide frequency ranges.

This efficient performance can readily be extended over even wider frequency ranges with the high-low arrays and the crossover feed systems provided by the invention.

Further, a novel feed system that provides long wire antenna operation in two mutually orthogonal polarization planes is also described. The feed system is suited for operating a single antenna or an array of antennas.

The parasol and sector arrays described above are capable of simultaneously projecting multiple steerable beams of high directive gain over extended frequency range. These long wire arrays can simultaneously produce horizontally polarized beams and vertically polarized beams in each direction.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

Having described the invention, what I claim as new and secure by Letters Patent is:

1. An antenna array comprising

A. first and second tandem-V antennas

1. each of which has a feed apex spaced along its main lobe axis from a terminating apex,
2. each of which has first and second conductors connected to its feed apex and third and fourth conductors connected to its terminating apex

with said first and third conductors being connected together and said second and fourth conductors being connected together,

3. said antennas being disposed

a. with the feed apexes thereof along a first common vertical line and the terminating apexes thereof along a second common vertical line,

b. with the interconnections in said first antenna of said first and third conductors, and of said second and fourth conductors spaced along said main lobe axis from the corresponding interconnections of said second antenna.

2. The antenna array defined in claim 1 in which said conductors of said first and second antennas are so spaced apart in the vertical direction that side lobe peaks and nulls of each antenna coincide with nulls and peaks, respectively, of the array factor for said array.

3. The antenna array defined in claim 1 in which said antennas are inclined with respect to the ground below them with the feed apex of each antenna being at a lower elevation than its terminating apex, the inclination of each antenna being such as to direct substantially a null of a radiated wave of said array in the direction of the first height-factor null of said array.

4. An antenna array comprising

A. a first sub-array of two tandem-V antennas,

B. a second sub-array of two tandem-V antennas,

C. each antenna in each sub-array

1. having a feed apex spaced along its main lobe axis from a terminating apex,

2. having first and second conductors connected to its feed apex and third and fourth conductors connected to its terminating apex with said first and third conductors being connected together and said second and fourth conductors being connected together,

D. said two antennas in each sub-array being disposed with corresponding apexes being positioned along common vertical lines, the junctions of said first and third conductors being out of register and the junctions of said second and fourth conductors being out of register,

E. said sub-arrays being disposed with

1. the feed apexes of said second sub-array being intermediate the feed and terminating apexes of said first sub-array,

2. the terminating apexes of said first sub-array being intermediate the feed and terminating apexes of said second sub-array, and

3. the junction of said first and third conductors and the junction of said second and fourth conductors of a first antenna in said first sub-array being

a. in register, respectively, with the junction of said first and third conductors and with the junctions of said second and fourth conductors of a second antenna in said second sub-array, and

b. intermediate the junctions of the other antenna in said first sub-array and the junctions of the other antenna in said second sub-array.

5. The antenna array defined in claim 4 in which said conductors of said antennas of each sub-array are so spaced apart in the vertical direction that side lobe peaks and nulls of each antenna coincide with nulls and peaks, respectively, of the array factor for its sub-array, and in which said sub-arrays are so spaced apart in the vertical direction that side lobe peaks and nulls of each sub-array coincide with nulls and peaks, respectively, of the array factor for said array.

6. The antenna array defined in claim 4 in which said antennas are inclined with respect to the ground below them with the feed apex of each antenna being at a lower elevation than its terminating apex, the inclination of each antenna being such as to direct substantially a null of reflected radiation of said array in the direction of the first height-factor null of said array.

7. A long wire travelling wave antenna array comprising

A. a first sub-array

1. having a feed port and designed for operation over a first range of frequencies, and

2. comprising at least a first V antenna formed by a first pair of long wire legs converging together at a feed apex,

B. a second sub-array

1. having a feed port and designed for operation over a second range of frequencies at least partially lower than said first range of frequencies,

2. comprising at least a second V antenna formed by a second pair of long wire legs converging together at a feed apex,

3. overlying said first sub-array with the corresponding feed apexes of said sub-arrays being vertically in line with each other, and

4. arranged and oriented to produce a radiation pattern whose main lobe over said second range of frequencies is substantially spatially coincident with the main lobe of the pattern said first sub-array produces over said first range of frequencies,

C. a common port, and

D. means coupling radio frequency signals from said common port substantially only to said feed port of said first sub-array at said first range of frequencies and coupling radio frequency signals from said common port substantially only to said feed port of said second sub-array at said second range of frequencies.

8. An antenna array according to claim 7 in which said second V antenna has a larger feed apex angle than said first V antenna.

9. An antenna array according to claim 7 wherein each of said antenna legs comprises at least two substantially coextensive conductors connected in parallel with each other at said feed apex of the V antenna and uniformly vertically spaced apart.

10. A long wire travelling wave antenna array comprising

A. a first sub-array

1. having a feed port and designed for operation over a first range of frequencies, and

2. comprising at least a first tandem-V antenna formed by a first pair of long wire legs converging together at a feed apex and a second pair of long wire legs converging together at a terminating apex,

B. a second sub-array

1. having a feed port and designed for operation over a second range of frequencies at least partially lower than said first range of frequencies,

2. comprising at least a second tandem-V antenna formed by a third pair of long wire legs converging together at a feed apex and a fourth pair of

long wire legs con-verging together at a terminating apex,

3. overlying said first sub-array with the corresponding feed apexes of said subarrays being vertically in line with each other.

C. a common port, and

D. means coupling radio frequency signals from said common port substantially only to said feed port of said first sub-array at said first range of frequencies and coupling radio frequency signals from said common port substantially only to said feed port of said second sub-array at said second range of frequencies.

11. An antenna array according to claim **10** wherein said terminating apexes of said first and second tandem-V antennas are vertically in line with each other.

12. An antenna array according to claim **10** wherein said first tandem-V antenna has larger tilt angles than said second tandem-V antenna.

13. An antenna array according to claim **10** in which

A. said first sub-array comprises a first pair of tandem-V antennas arranged to be fed in parallel from said first sub-array feed port and each of which has a feed apex and a terminating apex,

B. said second sub-array comprises a second pair of tandem-V antennas arranged to be fed in parallel from said second sub-array feed port and each of which has a feed apex and a terminating apex, and

C. each tandem-V antenna of said second sub-array

1. is associated with one tandem-V antenna of said first sub-array, and

2. has the feed and terminating apexes thereof vertically in line with the feed and terminating apexes respectively of the associated tandem-V antenna of said first sub-array.

14. A long wire travelling wave antenna array comprising

A. a first antenna sub-array

1. having a first feed port and providing a directional radiation pattern over a first range of frequencies, and

2. comprising first and second tandem-V antennas

a. uniformly inclined relative to the horizon by a first elevation angle, and

b. connected with said first feed port to be energized in parallel therefrom,

B. a second antenna sub-array

1. having a second feed port and providing a directional radiation pattern over a second range of frequencies different from said first range of frequencies, and

2. comprising third and fourth tandem-V antennas

a. associated respectively with said first and second tandem-V antennas,

b. uniformly inclined realtive to the horizon by said first elevation angle, and

c. connected with said second feed port to be energized in parallel therefrom,

3. disposed with said third tandem-V antenna overlying said first tandem-V antenna and with said fourth tandem-v antenna overlying said second tandem-V antenna,

4. arranged and oriented to produce a radiation pattern whose main lobe over said second range of frequencies is substantially spatially coincident with the main lobe of the pattern said first sub-array produces over said first range of frequencies, and

C. a feed network

1. having a common terminal and first and second branch terminals connected respectively to said first and second feed ports,

2. coupling energy

a. substantially exclusively between said common terminal and said first branch terminal in said first range of frequencies and

b. substantially exclusively between said common terminal and said second branch terminal in said second range of frequencies.

15. An antenna array according to claim **14** in which each tandem-V antenna has a feed apex and a terminating apex and further characterized in that

A. each pair of said associated tandem-V antennas is disposed with the feed apexes thereof vertically in line and with the terminating apexes thereof vertically in line,

B. said first tandem-V antenna has smaller feed and terminating apex angles and larger tilt angles than said third tandem-V antenna, and

C. said second tandem-V antenna has smaller feed and terminating apex angles and larger tilt angles than said fourth tandem-V antenna.

16. An antenna array according to claim **14** wherein

A. each tandem-V antenna

1. comprises two legs forming a feed apex thereof and two further legs forming a terminating apex thereof, and

2. has a first interconnection between one feed-apex-forming leg thereof and one terminating-apex-forming leg thereof and has a second interconnection between the other two legs thereof,

B. said first and second sub-arrays are so further arranged that

1. one tandem-V antenna in said first sub-array has said two interconnections therein coplanar with said two interconnections of one tandem-V antenna in said second sub-array,

2. the other tandem-V antenna in said second sub-array has said two interconnections therein coplanar with said two interconnections of the other tandem-V antenna in said second sub-array.

17. An antenna array according to claim **16** further comprising a plurality of towers supporting said four tandem-V antennas above ground and consisting of

A. support towers supporting said tandem-V antennas at said feed and terminating apexes thereof, and

B. only four further towers supporting said tandem-V antennas at said interconnections.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,757,341 Dated September 4, 1973

Inventor(s) Arnold W. Gilbo

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6 Line 59	Change "Pl" to --P--
Column 6 Line 62	Change "E" to --E_{θ}--
Column 10 Line 1	Change "R(second occur.) to --R^1--
Column 20 line 13	After "branches" insert --135--
Column 22 line 42	before "V antennas"insert --four--

Signed and sealed this 2nd day of April 1974.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents

PO-1050
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