

March 10, 1964

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3,124,801

LINEAR ARRAY WITH ADJUSTABLE COUPLING NETWORK FOR BEAM STEERING

Filed Feb. 12, 1958

2 Sheets-Sheet 1

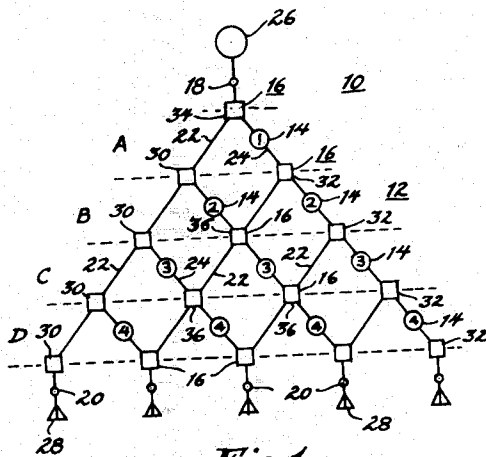


Fig. 1

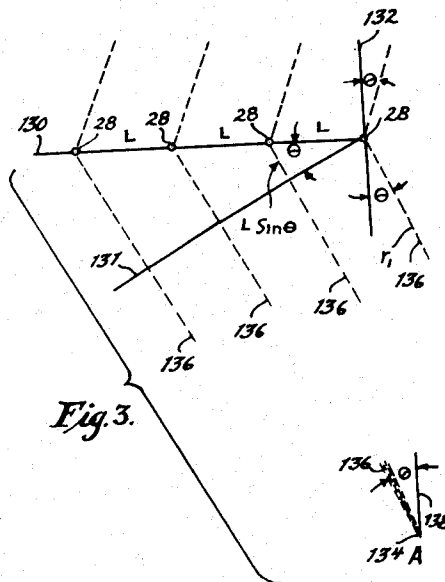


Fig. 3

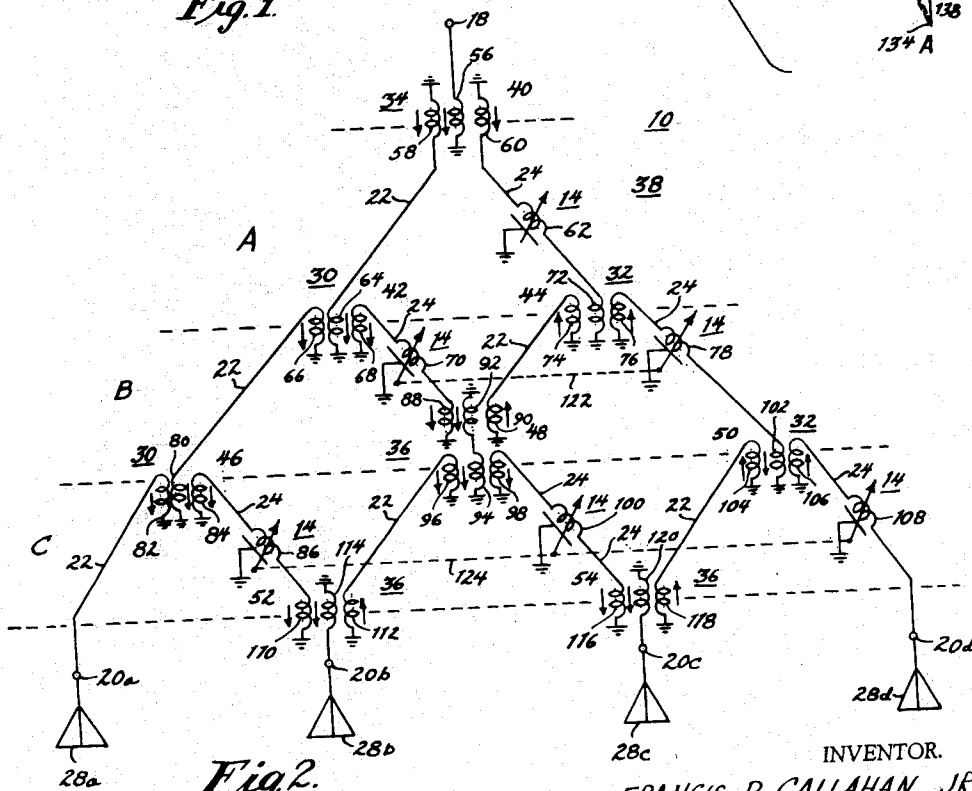


Fig. 2

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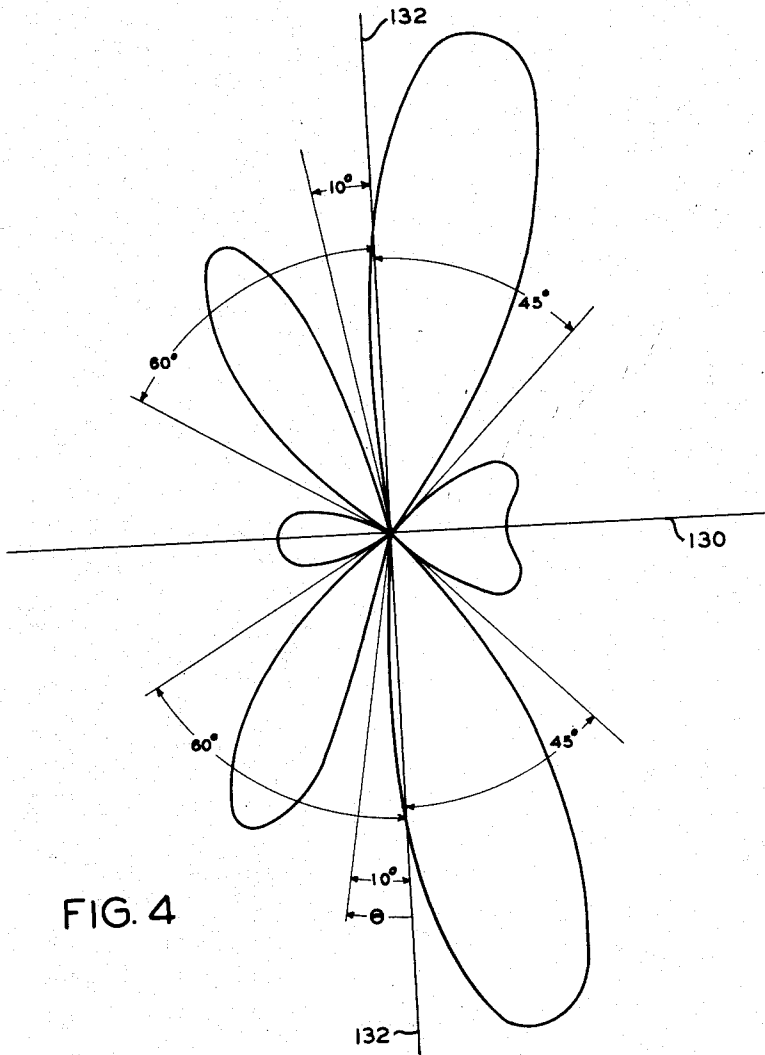


FIG. 4

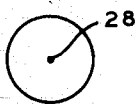


FIG. 5a



FIG. 5b

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3,124,801

LINEAR ARRAY WITH ADJUSTABLE COUPLING NETWORK FOR BEAM STEERING

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12 Claims. (Cl. 343—854)

The invention relates to an antenna device, and more particularly to an antenna device having a controlled field pattern.

Heretofore, antenna devices have provided a field pattern with lobes in predetermined directions. However, the prior art antenna devices have not provided a field pattern with a plurality of nulls in several controlled directions.

It is therefore a principal object of the invention to provide a new and improved antenna device having a field pattern with a plurality of nulls in several controlled directions.

Another object of the invention is to provide a new and improved antenna device which has a field pattern with a plurality of nulls in several controlled directions for either receiving or transmitting signals.

Another object of the invention is to provide a new and improved antenna device having a field pattern with a plurality of nulls in several controlled directions for a signal having one or a plurality of frequency components.

Another object of the invention is to provide a new and improved antenna device having a field pattern with a plurality of nulls in several controlled directions which directions differ for each frequency component of a received or transmitted signal.

Another object of the invention is to provide a new and improved antenna device having a field pattern with a plurality of nulls in several controlled directions, the directions of said nulls being identical for all of the frequency components of the signals received or transmitted.

Another object of the invention is to provide a new and improved antenna device having a field pattern with a plurality of nulls in several controlled directions, each of the nulls having its direction controlled independent of the directions of the other nulls.

Another object of the invention is to provide a new and improved antenna device with a field pattern having a plurality of nulls in several controlled directions, the number of independently controlled nulls being readily increased or decreased in accordance with design requirements.

Another object of the invention is to provide a new and improved antenna device which is readily constructed and maintained in operation, utilizes standard components, and is of great utility.

The above objects as well as many other objects of the invention are achieved by providing an antenna device having a plurality of antenna units and a network. The network has a first signal terminal and a plurality of second terminals respectively connected with said antenna units. A plurality of signal delaying elements and signal combining means connect the first terminal of the network with its second terminals for providing a di-

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rectional field pattern with a plurality of nulls in respective selected directions.

The delays of the elements are adjustable for independently controlling the direction of each of the nulls of the field pattern and are arranged in banks, each bank of elements corresponding to a respective one of the nulls of the field pattern. Each of the output signals delivered by the network to the antenna units has an amplitude and phase angle corresponding to the respective complex coefficients of a polynomial expression having at least two roots when the first signal terminal is energized by a sinusoidal signal. Adjustment of the elements of each bank controls the amplitudes and phase angles of the signals delivered by the network to the antenna units, thereby adjusting one of the plurality of roots of the corresponding polynomial expression. Each of the roots of the polynomial expression corresponds to a radial null of the field pattern, the directional orientation of the null being controlled by adjusting its corresponding root.

Because of the reciprocal action of the antenna device, it provides a field pattern which has a plurality of nulls in several controlled directions for either receiving or transmitting signals.

If the delay elements provide a signal delay which is independent of signal frequency, then, the direction of any particular null of the field pattern will be identical for the various frequency components of the signal which is being received or transmitted. However, if the delaying elements provide a signal delay which is a function of signal frequency, such as provided by signal phase shifters, the nulls of the field pattern will be dependent upon the signal frequency received or transmitted and, thus, will vary from one frequency component to another, providing a directional shift of the null depending upon frequency. The effect is similar to that achieved by a crystal in the diffraction or dispersion of light over the frequency spectrum. However, in this case, the null provides an absence of a particular frequency rather than its presence in a given direction.

The foregoing and other objects of the invention will become more apparent as the following detailed description of the invention is read in conjunction with the drawings, in which:

FIGURE 1 is a diagrammatic representation in block form of an antenna device embodying the invention,

FIGURE 2 is a schematic drawing showing in greater detail the antenna device of FIGURE 1,

FIGURE 3 is a diagrammatic representation of the antenna units of the device with respect to a distant point in space,

FIGURE 4 is a diagrammatic illustration of a field pattern with the three controllable nulls of the antenna device of FIGURE 1 having respective selected directions of 10°, 45° and 60° with respect to the normal direction to the line of antenna units, said representation being taken in the plane of FIGURE 3,

FIGURE 5a is a diagrammatic illustration of the horizontal cross-section of the field pattern of a single isolated dipole antenna unit, a plurality of which may be used in the antenna device of FIGURE 1, and

FIGURE 5b is a diagrammatic illustration of the vertical cross-section of the field pattern of said isolated dipole antenna unit.

Like reference numerals designate like parts throughout the several views.

Refer now to FIGURE 1 which discloses diagrammatically in block form an antenna device 10 embodying the invention.

The antenna device 10 includes a network 12 comprising a plurality of delaying elements 14 illustrated by circles and signal combining means 16 shown as squares and arranged in triangular or pyramiding form. The network 12 is provided with a signal terminal 18 at its apex and a plurality of signal terminals 20 at its base. The delaying elements 14 are arranged in a plurality of banks, A, B, C and D which are intermediate and connect the apex terminal 18 with the base terminals 20. The first bank A is connected with the apex terminal 18 and includes one delaying element 14, while the second bank B includes two elements 14 shown by the two circles including the numeral 2 representing the second bank. Similarly, the third bank has three delaying elements 14, and the fourth (or last bank illustrated) has four delaying elements 14 with the numeral 4 within the circles indicating the fourth bank.

The bank A is connected with the following bank B by two signal combining means 16 represented by squares, while the bank B is connected with the following bank C by three signal combining means 16. Similarly, bank C is connected with the following bank D by four connecting means 16, while the bank D is connected with the five base terminals 20 by five respective signal combining means 16.

It is noted that the first bank is in the form of a triangle having right and left arms, with the right arm containing the delaying element 14. Similarly, the second bank B comprises two triangular forms each with a signal combining means 16 at its vertex and a delaying element 14 in its right arm. Likewise, the third bank has the form of three triangles delimited by the signal combining means 16 with the delaying elements 14 in the right arm of each triangle, while the last bank D has the form of four triangles each having a signal combining means 16 at its vertex and a delaying element 14 in its right arm.

In forming the pyramid or triangular configurations, each combining means 16 has a pair of upper and lower leads 22, 24 providing left and right triangular arms with the right lower arm 24 containing a delaying element 14. Thus, a pair of arms 22, 24 provide the top or upper leads of a signal combining means 16, while a second pair of lower leads 22, 24 extend from its bottom forming its lower arms. In this manner, the network 12 is built up of a plurality of banks which contain one or more delaying elements 14 and are interconnected by signal combining means 16. Each succeeding bank contains an additional delaying element 14, while the number of connecting means 16 increases by one as the number of banks progressively increase, thereby, forming the pyramiding or triangular form of the network 12.

It is noted that each signal combining means 16 has a minimum of three leads or arms and a maximum of four leads, two being received at the top and two at the bottom. Each signal combining means 16 has the property of subtracting the signal received on its upper left lead 24 from the signal received on its upper right lead 22 and delivering the identical output signal to its lower leads 22 and 24. If signals are delivered to the lower leads of a signal combining means 16, the means 16 adds the signal received on its lower lead 22 to the signal received on its lower lead 24 and delivers signals of equal value to its upper arms 22 and 24 with one being inverted or negative with respect to the other.

The terminal 18 at the apex of the network 12 may be connected with an input output means 26 which may selectively deliver signals to the terminal 18 or detect signals delivered to the terminal 18.

The terminals 20 of the network 12 are respectively connected with antenna units 28 for radiating or detect-

ing electromagnetic signals. For example only, the units 28 may each be a simple dipole antenna having a field pattern shown by FIGURES 5a and 5b, but need not be limited to such antenna or field pattern. For this purpose, the antenna units 28 may be linearly aligned and equally spaced along a straight line which may be vertical, horizontal or have any other such orientation in space. It is also noted that two such linear arrays may be arranged to form a cross or other such configurations. Permissible orientations of antenna units will become evident when considered in connection with the description and mathematical analysis of the operation of the antenna device 10 which is given in connection with the FIGURES 2 and 3.

When the antenna device 10 is to radiate an electromagnetic signal, an electrical signal is delivered to the terminal 18 by the means 26. The signal delivered to the terminal 18 is received by the network 12 which delivers output signals to the terminals 20 respectively connected with the antenna units 28. As already noted, each signal combining means 16 subtracts the signal received by its upper left lead or arm 24 from the signal received by its upper right lead or arm 22, while delivering its output signal equally to its lower leads 22 and 24.

Thus, each of the signal combining means 30 which are positioned along the left side of the network 12 only receive signals on their upper right leads 22 since their left leads 24 are absent, and deliver the same signal to their lower output leads 22, 24. On the other hand, the signal combining means 16, such as the means 32 which are along the right side of the network 10 receive a signal only on their upper left arms or leads 24 and receive no other signals since their upper right leads 22 are absent. The combining means 32 deliver identical output signals on their lower leads 22, 24 which signals are inverted or negative with respect to the input signal.

The signal combining means 34 at the apex of the network 12 delivers at its lower leads 22, 24, the identical signal delivered at the terminal 18 or a signal which is inverted with respect thereto. The signal combining means 16, such as the means 36 which are internally positioned within the network 12 are provided with both upper and lower pairs of leads 22, 24. Since means 36 receives signals on both of its upper leads, it subtracts the signal received on its upper left lead 24 from the signal received by its upper right lead 22, and delivers the difference signal equally to both of its lower leads 22, 24.

Thus, the signal impressed on terminal 18 will be acted upon by the network 12 and delivered over the terminals 20 to the respective antenna units 28. The signals respectively delivered to the antenna units 28 will be such as to provide a radiation field pattern having a plurality of nulls in several controlled directions. This is achieved by the particular relationships between the signals impressed upon the several antenna units 28 of the antenna device 10. Each frequency component of the respective signals impressed upon the several antenna units 28 may be represented by a complex coefficient of a polynomial expression of five terms. This polynomial expression has four roots each of which characterizes a particular direction of a null in the radiation field pattern of the antenna device 10. If all of the roots have the same value or coincide, then, the several nulls coincide into one position in space. However, if each of the roots is different from the others, then, they correspond to four different radial directions of nulls in the field pattern.

The network 10 provides for varying the roots of the polynomial expression, thereby, allowing control of the radial directions of the several nulls in the field pattern of the antenna device 10. Each of the banks A, B, C and D corresponds to and provides for the adjustment of one of the roots of the polynomial expression which represents the signals of a particular frequency on the respective antenna units 28. Each of the roots and, there-

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by, each of the nulls in the field pattern is adjusted by varying the delay provided by the delaying element 14 of the banks A, B, C and D. Thus if the delaying element 14 of bank A represented by the 1 enclosed by the circle is varied, the root of the polynomial expression to which it corresponds is accordingly adjusted. Whereas, if the delaying elements 14 represented by the circles with the numeral 2 therein of the bank B has its delay varied, it accordingly varies and adjusts its corresponding root, thereby, controlling the direction of its null in the radiation field pattern. Similarly, the delays of the delaying elements 14 of the banks C and D can be varied and adjusted to control the direction of their respective nulls in the field pattern. It is noted, that an adjustment of the delaying elements 14 of one bank adjusts the direction of its respective null of the field pattern and is independent of the adjustment of the delaying elements 14 of the other associated banks. This means that each of the banks independently adjust the value of one of the roots of the characteristic polynomial expression without affecting any of the other roots. Of course, it is evident that with the adjustment of one of the roots, the values of the signals (for the frequency component considered) will be affected and changed at each of the antenna units 28.

The signal source of the means 26 may deliver a signal having one or more frequency components. In the case where the means 26 delivers a signal having one frequency component to the terminal 18, the signals delivered to the antenna units 28 in the illustrated embodiment, will have the same frequency but will have various amplitudes and phase angles corresponding to the complex coefficient of the polynomial expression corresponding to the roots determined by the banks A, B, C and D.

In the case where the means 26 delivers a signal having a plurality of frequency components, the several antenna units 28 will receive signals comprised of these signal components and each having various amplitudes and phase angles. Of course, if the amplitude for a particular frequency component at a given antenna is zero as required by the polynomial expression, then, such frequency component will be absent. It will be shown that when the delaying elements 14 provide a pure delay, that is a signal delay which is not a function of the signal frequency, but is independent of signal frequency, then, each of the frequency components of the signal will provide a radiation field pattern with a plurality of nulls in selected directions which is identical to the field patterns of the other frequency components. This means that the radiated signals may comprise modulated signals which include a plurality of frequency components without disturbing the directions of the nulls in the field pattern provided by any one of the frequencies, since the directions of the nulls of the field patterns for all of the frequencies are identical.

On the other hand, if the delaying elements 14 provide a signal delay which is a function of frequency, such as provided by a signal phase shifter, then the directions of the nulls for each frequency component will differ from one frequency component to another depending upon the relative phase shift. Thus, the nulls for a band of frequencies will not coincide but will be spread over space, analogous to the frequency spread effected by the diffraction of light.

Although the antenna device 10 has been diagrammatically illustrated with four banks for providing a field pattern with four independently controlled nulls in several directions, the number of nulls in the field pattern may readily be increased or decreased according to requirements by adding or subtracting banks in accordance with the pattern and scheme disclosed in connection with the FIGURE 1.

Because of the reciprocity in the operation of the antenna device 10, the means 26 may receive at the terminal 18 signals detected by the several antenna units 28 of

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the antenna device 10, so that the signal detection field pattern has a plurality of nulls in several controlled directions as explained in connection with the transmission of radiant energy. Thus, if a signal originates in space in a particular direction, which is in the direction of one of the nulls for the particular frequency of the signal under consideration, then, this frequency component will not be delivered at the terminal 18 for detection by the means 26. However, signals originating in space in a direction from the antenna units 28 which does not coincide with any of the nulls of the field pattern for the frequency of the signal, will be delivered at the terminal 18 for detection by the means 26. Thus, the antenna device 10 may be utilized for selectively or alternately delivering and receiving signals with a controlled field pattern of the type described in detail above.

It is noted that although the antenna device 10 has been described with delaying elements 14 in one of the arms of each of the triangular forms of the network, the delaying elements 14 may be distributed to provide delays in the other arms of the device while still providing the described function and producing the results of the antenna device 10. It is also noted that other variations in the described antenna device 10 will be evident to those skilled in the art, for producing the desired signals at the antennas 28 to provide the described field pattern with a plurality of several nulls in controlled directions for transmitting or receiving signals.

For a description in greater detail of an antenna device 38 conforming with the device 10 shown in FIGURE 1, but schematically illustrating the use of three banks A, B, and C, refer now to FIGURE 2.

The terminal 18 of the network 38 is connected with the first bank A by the signal combining means 34 in a form of a signal transformer 49, while the bank A is connected with the bank B by the signal combining means 30 and 32 respectively in the form of transformers 42 and 44. The bank B is connected with the bank C by the signal combining means 30, 36 and 32 which respectively comprise signal transformers 46, 48 and 50. The bank C connects directly with the left and right end antenna units 28a and 28d, and respectively by the signal combining means 36 in the form of signal transformers 52 and 54 with the intermediate antenna units 28b and 28c.

The terminal 18 is connected to ground potential through the winding 56 of the transformer 40, while the winding 58 connects between ground potential and the line 22 of the bank A, and winding 60 has one end grounded and the other end joined with the signal delaying element 62 by the line 24. The windings 56, 58 and 60 of the transformer 40 are arranged so that a signal on the winding 56 will produce equal signals of the same polarity in the windings 58 and 60.

The signal on line 22 is delivered to the winding 64 of the transformer 42 which is returned to ground potential. The winding 66 of the transformer 42 is connected between ground potential and a line 22 of the bank B, while the winding 68 is returned to ground potential and series connected with the signal delaying element 70 by a line 24. A signal delivered to the winding 64 of the transformer 42 also results in the delivery of equal output signals by the windings 66 and 68 having the same polarity.

The output signal from the signal delaying element 62 of bank A is returned to ground potential through the winding 72 of the transformer 44. The winding 74 of transformer 44 is connected between ground potential and a line 22 of bank B, while the winding 76 has one end grounded and the other end series connected to the signal delaying element 78 by line 24. The delivery of a signal to the winding 72 of the transformer 44 results in the delivery of identical output signals by the windings 74 and 76 which have a polarity opposite to that of the input signal.

The signal from the transformer 42 is delivered over line 22 to the winding 80 of the transformer 46 which is

returned to ground potential. The winding 82 of transformer 46 has one end grounded and the other end directly joined to the terminal 20a by a line 22 of bank C, while the winding 84 is connected between ground potential and linked to the signal delaying element 86 by a line 24. The signal delivered to the winding 80 of the transformer 46 is also delivered by the windings 82 and 84, each of these output signals being of the same polarity as the input signal to the winding 80.

The signal delaying element 70 is connected to ground potential through the winding 88 of the transformer 48, while the winding 90 returns the lead 22 from the transformer 44 to ground potential. The windings 88 and 90 are wound in opposite directions and magnetically coupled with a winding 92. The winding 92 is connected to ground potential at one end and joined at the other end with the winding 94 which is also returned to ground potential. The winding 96 of the transformer 48 has one end returned to ground potential, while the other end connects with a line 22 of the bank C; and the winding 98 is series connected with the signal delaying element 100 by a line 24. The windings 96 and 98 are magnetically coupled with the winding 94 to produce an output signal having the same polarity as a signal delivered to the winding 94.

Due to the opposite directions of the windings 88 and 90, the delivery of signals to these windings results in the difference of these signals being delivered by the winding 92 to the winding 94. This results in the delivery of this different signal by the output lines 22, 24 of the transformer 48.

The signal from the delaying element 78 of bank B is delivered to the end of winding 102 which has its other end returned to ground potential. The winding 104 of transformer 50 is connected to a line 22 of bank C, while the winding 106 is connected in series with the signal delaying element 108 by a line 24. The delivery of a signal to the winding 102 of the transformer 50 produces output signals of the same polarity at the windings 104 and 106.

The signal from the delay element 86 of bank C is delivered to a winding 110 of the transformer 52 which is returned to ground potential, while the signal from winding 96 of transformer 48 is delivered to the winding 112 which also has one end grounded. The windings 110 and 112 of the transformer 52 are magnetically coupled with a winding 114 which has one end returned to ground potential and the other end connected to the terminal 20b. The windings 110, 112 and 114 of the transformer 52 are arranged to provide an output signal to the terminal 20b which is the difference of the signals delivered to the windings 110, and 112.

Similarly, the signal from the signal delaying element 100 of bank C is delivered to a winding 116 of the transformer 54 which is returned to ground potential, while the signal from the winding 104 of transformer 50 is delivered over a line 22 to one end of the winding 118 which also has its second end returned to ground potential. The windings 116 and 118 are magnetically coupled with the winding 120 which has one end connected to ground potential and the other end connected to the terminal 20c. The windings 116, 118 and 120 are arranged so that the signal delivered by winding 120 to the terminal 20c is the difference of the signals delivered to the windings 116 and 118.

The signal from the delaying element 108 is directly connected to the terminal 20d. The terminals 20a, 20b, 20c and 20d are respectively connected to antenna units 28a, 28b, 28c and 28d.

The signal delaying elements 62, 70, 78, 86, 100 and 108 are preferably provided with means for adjusting the signal delays which they produce for the purpose of varying the directions of their respective nulls in the signal field pattern. It is noted that the element 62 is the only one present in bank A, while the elements 70 and 78 are in bank B, and elements 86, 100 and 108 are in bank C. The

dashed line 122 in bank B indicates that the signal delaying elements 70 and 78 are ganged for simultaneously adjustment of their signal delays. Similarly, the dashed line 124 in bank C indicates that the signal delaying elements 86, 100 and 108 are ganged for simultaneously adjustment of their signal delaying properties. The ganged elements of the banks B, C may respectively have equal delays, which delays are maintained equal when the elements are adjusted by means of their ganged relationships.

The signal delaying elements 14 may be of the type providing a signal delay which is independent of signal frequency, that is a so called pure signal delay, or they may be of the type providing a signal delay which is a function of signal frequency (in the nature of phase shifting elements) as previously described in connection with FIGURE 1.

As already noted in connection with FIGURE 1, a signal is delivered to the terminal 18 when the antenna device 10 is to be used for transmitting a signal having a radiation field pattern with a plurality of nulls in several selected directions. The signal is acted upon by the network 38 to deliver respective signals to the antenna units 28 which correspond to the complex amplitude of a polynomial expression, which expression in the case of network 38 has three roots corresponding to the three banks A, B and C. Adjustment of the signal delays produced by the elements 14 of the respective banks A, B and C controls their corresponding roots of the polynomial expression. Since each of the roots corresponds to a direction of a null in the field pattern, the signal delays produced by the delaying elements of the respective banks and their adjustment, correspondingly control and adjust the position of the nulls in the field pattern.

In a similar manner, if a signal detector of means 26 is connected with the terminal 18, the signals delivered to the terminal 18 responsive to the signals received by the antenna units 28 provide a field pattern with the several described directional nulls, which nulls are likewise directionally controlled by the delaying elements 14. As previously explained, the character of the field pattern for different signal frequencies will depend upon whether the signal delaying elements 14 have a signal delay which is independent of the signal frequency or whether their delay is a function of the signal frequency.

Refer now to FIGURE 3 which discloses a plurality of antenna units 28 which are equally spaced along a straight line 130 with a distance L between adjacently positioned antenna units 28. The direction of each of the nulls produced in the field pattern is designated by the angle coordinate measured with respect to the line 132 which is perpendicular to the line 130 as shown in FIGURE 4. It is noted, that because of the symmetry of the arrangement, a null produced in the direction θ about the line 130 takes the form of a surface of a right cone with the line 130 passing through its apex in the direction perpendicular to its base. Thus, if the front direction of the antenna units 28, is to be considered in the direction toward the distant point 134 at A, and if the field provided by the back radiations is not desired or required, reflectors may be placed behind each of the antenna units 28 eliminating back radiation and increasing the power of the radiation in the forward direction.

It is also noted that the lines 136 from the antenna units 28 to a far distant point 134 at A, may be considered substantially parallel to each other. This fact will be utilized in the mathematical analysis of the field pattern to be presented herein. It is noted that from geometrical considerations the lines 136 may be considered to form the angle θ with the line 138 which is projected parallel to the line 132.

In order to analyze the field pattern provided by the antenna device 10, consider the device 10 operating to transmit a signal by its antenna units 28 with a field pattern having a plurality of nulls in several selected directions as illustrated by FIGURE 4. For this purpose, the signal

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generator of means 26 delivers a sinusoidal signal of one frequency to the terminal 18 of the network 10. The analysis will be broadened later to indicate that the signal terminal 18 may have many frequency components and that an antenna device 10 is operative in the inverse manner for receiving a detecting signal.

Since a signal having one frequency is delivered to the terminal 18, the delay elements 14 may be considered to produce a phase shift in the signal passing therethrough which will be designated by the phase angle θ_k . The phase angle θ_k on a given bank A, B or C is related to the direction of the null in space (see FIGURE 3) by the equation:

$$\phi_k = \frac{2\pi L}{\lambda} \sin \theta_k$$

where L is the distance between emitters in the array, λ is the wavelength of the radiation, and θ_k is the angle between the direction of the null and the normal 132 to the line 130 of the antenna units 28.

With respect to the field pattern of the antenna device 10, it will be shown that:

$$P(\theta) = \left| \sum_0^N Z_n \xi^n \right|^2$$

where $P(\theta)$ is a factor proportional to the power emitted in direction θ , and θ has been defined as the angle between the normal 132 to the line 130 of the array and the direction of the null indicated by the dashed lines 136 of FIGURE 3.

The number ξ is a complex number of unit magnitude defined by:

$$\xi = e^{\frac{2\pi i L}{\lambda} \sin \theta}$$

where L is again the spacing between antennas and λ is the wavelength of the radiation. Z_n is the complex amplitude at the n th emitter or antenna unit 28 the emitters being numbered from right to left in FIGURE 3, the first one being numbered 0. Although the above formula is reasonably well known, it can be derived, in view of FIGURE 3, by considering that the signal provided by the n th antenna unit 28 is $f_n(t)$, so that the total signal received at A is given by:

$$f(t) = \frac{\sum_0^N f_n \left(t - \frac{r_n}{c} \right)}{r_n}$$

where r_n is the distance from A to the n th emitter and c is the velocity of light. The signal reception point A is sufficiently far from the antenna array or units 28, so that r_n in the denominator may be replaced by r_0 , the distance between the far right antenna unit 28 and the point A at 134, while the r_n in the function f_n in the numerator may be replaced by:

$$r_n = r_0 - nL \sin \theta$$

This relationship follows from FIGURE 3 by the fact that the lines 136 from the antenna units 28 to the distant point A at 134 are very nearly parallel. Thus, if r_n is considered to be the distance from the second antenna unit 28 from the right to the point A, this value will be given by the above formula if 1 is substituted for n . If r_n is the distance between the third antenna unit 28 from the right, then, the number 2 should be substituted for n . In this case r_n is equal to r_1 minus $2L \sin \theta$ which is also readily evident from the FIGURE 3.

Since the n th antenna unit 28 is emitting a sinusoidal signal, this signal may be represented by:

$$f_n = A_n \cos(\omega t + \phi_n)$$

A_n is the amplitude, ϕ_n is the phase lead at the n th emitter or antenna unit 28, and ω is the angular frequency meas-

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ured in radians per unit time. Thus, for the signal received at A, at the relatively distant location 134

$$f(t) = \frac{1}{r_0} \left[\sum_0^N A_n \cos \left[\omega \left(t - \frac{r}{c} + \frac{nL \sin \theta}{c} \right) + \phi_n \right] \right]$$

Now, noting that the $\cos \theta$ is the real part of $e^{i\theta}$ it is found that:

$$f(t) = \frac{1}{r_0} \text{Re} \left[\sum_0^N Z_n e^{\frac{n i \omega L \sin \theta}{c}} \right] e^{i \omega \left(t - \frac{r_0}{c} \right)}$$

where the complex amplitude Z_n is defined by:

$$Z_n = A_n e^{i \phi_n}$$

and "Re" means "Real part of".

Also,

$$e^{\frac{i \omega L \sin \theta}{c}} = e^{\frac{i 2 \pi L \sin \theta}{\lambda}}$$

To obtain the above equations use has been made of the relationship between the wavelength and angular frequency, namely:

$$\omega = \frac{2 \pi c}{\lambda}$$

Finally, it is noted that the power transmitted to A at 134 must be proportional to the average of the square of $f(t)$ taken over one period, so that upon averaging the following is obtained:

$$P(\theta) = \left| \sum_0^N Z_n \xi^n \right|^2$$

The proportionally factor has been omitted above as irrelevant.

In order to establish the condition for nulls it is noted that from the equation above it follows that for the field pattern to have a null in the direction θ_k , the following relation must obtain:

$$\sum_0^N Z_n (\xi_k)^n = 0$$

where

$$\xi_k = e^{\frac{2 \pi i L}{\lambda} \sin \theta_k}$$

That is, ξ_k must be a root of the polynomial. For this to be so, it follows from a well known theorem, that $(\xi - \xi_k)$ must be a factor of the polynomial. Thus, if the antenna device 10 is to have N nulls at angles $\theta_1, \theta_2, \dots, \theta_N$, the following must be true:

$$\sum_0^N Z_n \xi^n = Z_N (\xi - \xi_1) (\xi - \xi_2) \dots (\xi - \xi_N)$$

where ξ_k is defined by

$$\xi_k = e^{\frac{2 \pi i L}{\lambda} \sin \theta_k}$$

That is, the complex amplitudes $Z_1, Z_2, \dots, Z_N$ at the emitters or antenna units 28 must be the coefficients of that polynomial having roots $\xi_1, \xi_2, \dots, \xi_N$ in order that the field pattern have nulls at $\theta_1, \theta_2, \dots, \theta_N$.

In order to demonstrate that the network 12 of FIGURE 1 produces such nulls, it is necessary to show that the network 12 does in fact produce signals corresponding to complex signals at the antenna units 28 having complex amplitudes which are the coefficients of the polynomial expression having the specified roots. This may be shown by mathematical induction:

Theorem.—If the complex amplitudes of the signals delivered by the n th bank to the $(n+1)$ th bank of the network 12 of the antenna device 10, are the coefficients of the polynomial $(\xi - \xi_1) (\xi - \xi_2) \dots (\xi - \xi_m)$, then

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those signals delivered by the m th plus 1st bank and the m th plus 2nd bank are the coefficients of the polynomial $(\xi - \xi_1)(\xi - \xi_2) \dots (\xi - \xi_m)(\xi - \xi_{m+1})$.

Proof.—Consider the polynomial expression

$$(\xi - \xi_1)(\xi - \xi_2) \dots (\xi - \xi_m) = P_0 + P_1\xi + P_2\xi^2 + \dots + P_m\xi^m$$

Then, multiplying both sides of the equation by $(\xi - \xi_{m+1})$, there results:

$$\begin{aligned} (\xi - \xi_1)(\xi - \xi_2) \dots (\xi - \xi_m)(\xi - \xi_{m+1}) \\ = (-\xi_{m+1}P_0) + (P_0 - \xi_{m+1}P_1)\xi + \dots \\ + (P_{m+1} - \xi_{m+1}P_m)\xi^m + P_m\xi^{m+1} \end{aligned}$$

That is, the numbers

$$(-\xi_{m+1}P_0), (P_0 - \xi_{m+1}P_1); \dots (P_{m-1} - \xi_{m+1}P_m), P_m$$

should be the complex amplitudes of the signals delivered by the $m+1$ st bank. Noting that the transfer function for a phase shifter is $e^{i\theta}$, it is seen from a consideration of the network 12 and 38, respectively shown in FIGURES 1 and 2, that these networks are arranged so as to transform the complex amplitudes at the m th row into those at the $m+1$ st row exactly according to the scheme illustrated above. This completes the proof.

It is noted that from the equation:

$$\xi_k = \exp\left\{\frac{i\omega L \sin \theta_k}{c}\right\}$$

that the desired nulls will be produced over a band of frequencies, if the delays produced by the signal delaying elements 14 are not functions of frequency, but are independent of the particular frequencies of the components of the signal being transmitted. Thus, it is seen that the transfer function is that for a pure time delay having delay

$$\frac{L \sin \theta_k}{c}$$

It is also evident that if the transfer function produced by the signal delaying elements 14 are functions of frequency, then the direction of the nulls for different frequency components is a function of the frequency of each of the frequency components of the signal being transmitted.

By the reciprocal action of the network the antenna device 10 may be utilized for receiving signals with a field pattern having a plurality of several nulls in selected and adjustable directions.

That the antenna device 10 has many and varied uses and that combinations of such antenna device 10 may be utilized for providing different field patterns, will be readily evident to those skilled in the art.

For example, the antenna device may be used to deliver information to predetermined regions while preventing or excluding the radiation of energy in several controlled directions. As a detecting means, the antenna device can be used to receive and detect radiant signals from space, while eliminating signals from several controlled directions which directions may provide a source of interference or jamming signals. The device may be utilized for detecting the positions of bodies by using a null direction and thereby preventing the constant receipt of radiant energy from the antenna device by the detected object. The antenna device may be used alone or in combination with other such devices for tracking of bodies and many other purposes.

It will be obvious to those skilled in the art that the invention may find wide application with appropriate modification to meet the individual design circumstances, but without departure from the essence of the invention.

What is claimed is:

1. An antenna device comprising a plurality of at least three antenna units, and a network having a signal ter-

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minal and a plurality of signal delaying elements and signal combining means connecting said terminal with said antenna units to provide a directional field pattern with a plurality of nulls in respective selected directions, said delay elements being arranged in banks, each said bank corresponding to a respective one of said nulls of said pattern, the delays of the elements of each said bank being adjustable for independently controlling the direction of its corresponding null of said pattern.

2. The antenna device of claim 1 in which each bank has its delaying elements coupled for simultaneously varying their delays to control the direction of its corresponding null of said pattern.

3. The antenna device of claim 2 in which each of said banks has at least one delay element, said banks with a plurality of delaying elements respectively having their elements coupled for simultaneously adjusting their delays to control the direction of the corresponding null of said pattern.

4. The antenna device of claim 3 in which the first bank has at least one delay element and each succeeding bank has an additional delaying element, and in which the number of said antenna units exceeds the number of said banks by one.

5. The antenna device of claim 4 in which the antenna units are equally spaced.

6. The antenna device of claim 1 including a source of signals having one or more frequency components connected with said signal terminal of said network, the radiation field pattern provided by said antenna units having a plurality of independently controlled nulls for each frequency component of said signal.

7. The antenna device of claim 1 including a signal detecting means connected with said signal terminal of said network, the signal detecting field pattern provided by said antenna units for each signal frequency having a plurality of independently controlled nulls.

8. An antenna device comprising an array of at least three antenna units, and means connecting said units with each other and with a common signal terminal, said means comprising a plurality of signal delay elements and signal combining means forming series signal paths between said terminal and said antenna units, the number of said elements included in that series signal path between said common terminal and any given antenna unit which comprises the least number of said combining means differing by one from the number of said elements included in that series path between said common terminal and an adjacent unit of said array which comprises the least number of said combining means.

9. The device of claim 8 further characterized in that said number increases in one direction along said array.

10. An antenna device comprising a plurality of at least three antenna units, and a network interconnecting said units and a signal terminal, said network including a plurality of banks of signal paths, the bank nearest the terminal consisting of a pair of paths branching out from said terminal toward said antenna units, and each succeeding one of said banks comprising pairs of signal paths, different ones of said paths branching out toward said antenna units from different ends of the signal paths of the preceding bank, one path in each said pair of signal paths including a signal delay element, and each said bank other than said bank nearest said terminal means being provided with means for joining the path in each said pair which includes a delay element to the path in a different pair in the same bank which is without a delay element.

11. The device of claim 10 characterized in that each said joining means is a signal combining device.

12. The device of claim 1 characterized in that different ones of said antenna units are coupled to the ends of different ones of said signal paths in the bank nearest said antenna units.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,124,801

March 10, 1964

Francis P. Callahan, Jr.

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

Column 2, lines 10, 16 and 17, for "polynominal", each occurrence, read -- polynomial --; column 12, line 5, for "delay" read -- delaying --; line 70, for the claim reference numeral "1" read -- 11 --.

Signed and sealed this 4th day of August 1964.

(SEAL)

Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents

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