Dec. 3, 1946. C. B. H. FELDMAN ET AL 2,411,872

MICROWAVE DIRECTIVE ANTENNA

Filed June 11, 1942

FIG. 1

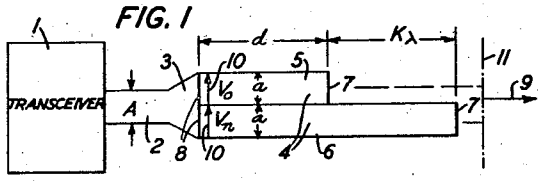


FIG. 2

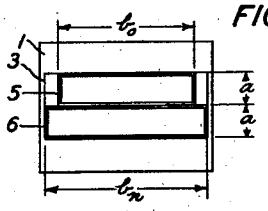


FIG. 3

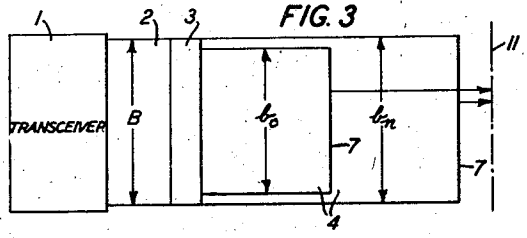


FIG. 4

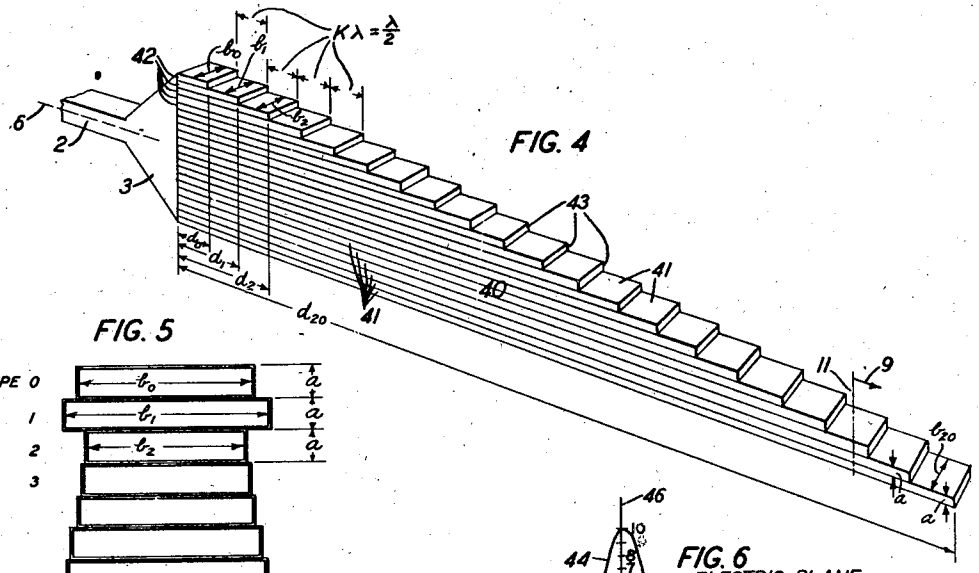


FIG. 5

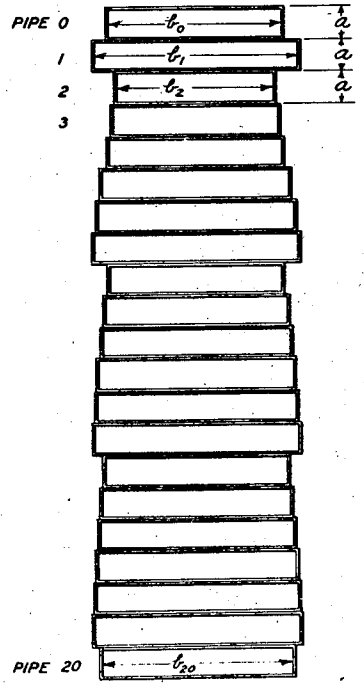


FIG. 6
ELECTRIC PLANE

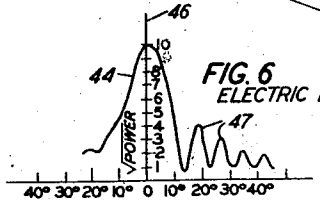
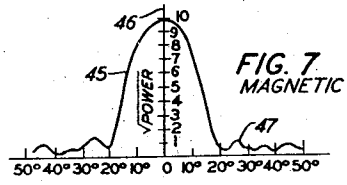


FIG. 7
MAGNETIC PLANE



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MICROWAVE DIRECTIVE ANTENNA

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16 Claims. (Cl. 250—11)

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This invention relates to antenna arrays and more particularly to microwave end-on antenna arrays.

As is known, in the microwave or centimetric field open-ended metallic air-filled guides and horn antennas, and broadside arrays comprising simple pipe antenna units or horn units, have been suggested for emitting and collecting radio energy. Also, leaky air-filled pipe antennas of the longitudinal or transverse slot type have been suggested for securing broadside, oblique and end-on radiation. While, in general, the above arrangements have been used with success for broadside and oblique radio action, they have not functioned in an entirely satisfactory manner for securing pure end-on action. Since for certain purposes as, for example, for use in a scanning or radar single unit antenna system or in a multi-unit steerable array of the broadside MUSA type, end-on units or subarrays are advantageous, it now appears desirable to secure a highly efficient end-on unit or a sub-array of end-on unit antennas. A broadside antenna, an end-on antenna and an oblique antenna are here defined as antennas in which the angles between the maximum direction of radio action and the antenna axis are substantially 90 degrees, 0 degrees and acute, respectively.

It is one object of this invention to obtain highly directive end-on antenna radio action.

It is another object of this invention to obtain an end-on microwave array comprising a plurality of end-on elemental or unit antennas.

It is still another object of this invention to secure a small compact subarray of end-on units suitable for use as a broadside MUSA unit.

According to one embodiment of the invention, a plurality as, for example, twenty, of air-filled open-ended metallic rectangular wave guides or pipes are positioned parallel to each other and aligned with the path of desired end-on radiation or reception. As used herein the term "rectangular" denotes a quadrangular figure other than square, and the term "quadrangular" includes rectangular and square. The guides have equal a or narrow transverse widths and graded physical lengths differing a given amount as, for example, one-half wave-length, so that the remote open ends or apertures are uniformly spaced in the direction of desired radio action. The extremities or terminals are connected directly to a common dielectric channel and the associated translation device, which may be a transmitter or receiver, or to a scanning transceiver unit. The shortest guide has a given wide or b width,

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and therefore a given phase velocity at the operating frequency, and a given length. Each of the remaining guides has a b width and a phase velocity dependent upon its physical length, and a phase length or over-all phase angle shift dependent upon its b width and physical length. In the case of transmission, the energy or wavelet emitted by each of the remaining guides and propagated in the desired end-on direction, and the wavelet emitted by the shortest guide and having a similar propagation direction are in phase agreement and combine to produce an additive effect along the axis of the system. Consequently, the wavelets from all end-on pipe radiators combine to produce an extremely sharp, fixed, end-on maximum lobe analogous to the "comb" antenna lobe 39 or 40 illustrated in Fig. 5 of Patent 2,236,393, H. T. Friis and A. C. Beck, granted March 25, 1941. Conversely, when used for receiving, the differently phased wavelets absorbed at the two above-mentioned pipe apertures and having the aforementioned end-on direction have a cophasal relation at the receiver by reason of the difference in phase velocity and phase length of the two guides. While, as disclosed in the Proceedings of the I. R. E., December 1938, pages 1500 and 1501, various types of guided wave components may be used with rectangular pipe radiators or collectors, the invention will be explained in connection with the transverse electric component of the $H_{1,1}$ wave, which component is polarized parallel to the small transverse guide dimension a.

The invention will be more fully understood from a perusal of the following specification taken in conjunction with the drawing on which like reference characters denote elements of similar function and on which:

Figs. 1, 2 and 3 are side, end and top views, respectively, of a simple embodiment of the invention;

Figs. 4 and 5 are perspective and end views, respectively, of a preferred embodiment of the invention; and

Figs. 6 and 7 are measured directive characteristics of the embodiment illustrated by Figs. 4 and 5.

Referring to Figs. 1, 2 and 3, reference numeral 1 designates a transceiver (TR) which is connected by the main air-filled guide or dielectric channel 2 and coupling guide section 3 to an end-on array 4 constructed in accordance with the invention. The transceiver device is of the type conventionally used in radio scanning systems and includes a pulse transmitter, cathode

ray indicator, receiver and a circuit for alternately connecting the transmitter and receiver to the main guide 2. If desired, an ordinary translation device, such as a transmitter or receiver, may be used in place of the transceiver 2. Array 4 comprises a rectangular air-filled metallic guide or pipe 5, hereinafter designated pipe o, and another rectangular air-filled metallic pipe 6, hereinafter designated pipe n, the far ends 7 of the pipes o and n being open-ended and constituting aperture-type elemental antennas and the near ends 8 being immediately adjacent to each other and directly coupled to the coupling section 3. The longitudinal paths included in guides 2 and 3 and extending between the device 1 and the near ends 8 are equal in electrical length. Pipes o and n are positioned parallel to each other and their longitudinal axes are aligned with the desired end-on direction or path 9 of radio action. Pipe o has a given wide transverse dimension b_0 and therefore at the operating frequency a given phase velocity v_0. Also, it has a given physical length d_0 and therefore a given "phase time" $t_0=d_0/v_0$. Pipe n has a given physical length d_n greater by a predetermined amount $K\lambda$ than d_0, as explained more fully below, where λ is the operating wave-length measured in free space and K is constant. Also, pipe n has a wide transverse dimension b_n which, as also explained below, may or may not differ from b_0. The narrow transverse a dimensions of the pipes o and n are equal. Since, as stated above and as shown by arrow 10, the transverse electric component utilized is parallel to the short pipe wall or side, the dimension a is the electric plane dimension, dimension b being the transverse magnetic plane dimension.

In operation, assuming the array 4 is used for transmitting, energy is supplied by device 1 to the connecting wave guide 2 and through coupling wave guide 3 to the input or near-end terminals 8 of pipe o and pipe n. The wavelets entering pipes o and n have the same polarity and phase angle since the paths connecting the input apertures to device 1 are equal in length. As radiated, the wavelets differ in phase angle an amount corresponding to the physical separation between the apertures 7 and dependent upon the b dimension of pipe n. More accurately, the phase angle of the wavelet emitted by aperture 7 of tube n is retarded relative to that emanating from aperture 7 of tube o by an amount t corresponding to the time interval in which the wavelet from pipe o travels in the ether medium along path 9 to a point opposite aperture 7 of pipe n, whereby the wavelets are propagated in direction 9 in phase agreement and in other directions in phase disagreement, and maximum radiation occurs end-on. The terms "phase agreement" and "cophasal" as used herein signify that the energies have the same phase angle values and similar instantaneous polarities or have angles differing by 360 degrees or a multiple thereof and similar polarities. Conversely, when used for the collection of energy, the wavelets incoming in a direction opposite to direction 9 have at any given instance a phase angle difference related to the spacing $K\lambda$, and by reason of the phase velocity characteristics and phase lengths of pipes o and n these wavelets have, upon arrival at the transceiver 1, a cophasal relation whereby maximum reception occurs end-on. As explained below in connection with Figs. 4 and 5, additional pipe radiators may be employed to enhance the end-on action.

Considering the operation of the array 4 from a mathematical standpoint, if b_0, d_0, v_0, t_0 and d_n ($=d_0+nK\lambda$) of pipe n are given, the phase velocity v_n and therefore the dimension b_n of pipe n are selected so as to obtain for pipe n a phase time t_n which renders, in the case of transmission, the wavelets or out-of-phase energies propagated from the apertures 7 to the desired wave front plane 11, which is perpendicular to direction 9, in phase agreement at plane 11. Conversely, the out-of-phase energies absorbed at apertures 7 from a wave having its front in plane 11 arrive in phase agreement at device 1. The method of ascertaining the values for the phase velocity v_n, the width b_n and the phase time t_n ($=d_n/v_n$) of pipe n will now be explained.

A careful distinction should be made between v_0, the velocity of phase propagation or the phase velocity, which is an apparent rather than an actual velocity, and the actual velocity of energy propagation of the wave within the air-filled guide. As explained in the two articles "Rectangular hollow pipe radiators" by W. L. Barrow and F. M. Greene and "Waves in hollow tubes of rectangular cross section" by L. J. Chu and W. L. Barrow, both published in the Proceedings of the I. R. E., December 1938, the phase velocity in an air-filled rectangular guide and the propagation velocity depend upon the ratio of the operating frequency to the guide cut-off frequency, the width b and the dielectric constant of the material constituting the channel. See especially pages 1532 and 1540, I. R. E. Proceedings, December 1938, and see also Patent 2,106,768, G. C. Southworth, February 1, 1938; "Wireless Engineering," March 1942, page 93 and two articles "Hyper-frequency wave guides—mathematical theory" by S. A. Schelkunoff et al., and "Hyper-frequency wave guides—general considerations" by G. C. Southworth, both published in the Bell System Technical Journal, April 1936. As the b width approaches the cut-off dimension, the operating frequency being constant, the propagation velocity becomes a fraction of the free space propagation velocity while the phase velocity becomes a multiple of the free space propagation velocity. In an air-filled guide the phase velocity is always greater than the free space velocity. Hence, while the two guides may have the same physical length, their phase lengths may be different, depending upon the relation of their b dimensions and the phase velocities.

In order to secure phase agreement between the wavelets emitted at the apertures 7 of the two pipes o and n, the spacing $K\lambda$ between apertures being a constant, the phase time t_n of pipe n must have the value given by the following equation:

$$t_n=\frac{d_n}{v_n}=\frac{d_0}{v_0}+\frac{K\lambda}{c}\pm\frac{N\lambda}{c} \qquad (1)$$

where

d_n=the given physical length of pipe n

c=the free space velocity

λ=the operating wave-length as measured in air

N=an integer having a value such that the waves from pipe o and pipe n add in the same manner as if the velocity in pipe n has any one of a number of values which make the phase time correct to within any number of complete periods

K=a constant as, for example, ½ representing in the two element system of Fig. 1 the spacing between apertures. In a system comprising more than two elements, K represents the uniform spacing between adjacent apertures and nK the separation between the apertures of

pipes o and n. For the two-element system $n=1$.

Hence we have the general case

$$t_n=\frac{d_0}{v_0}+\frac{nK\lambda}{c}\pm\frac{N\lambda}{c} \quad (2)$$

Equation 2 equates the phase time for pipe n with the phase time for pipe o to which has been added the phase time of the spacing. The phase time for pipe n, in terms of its own velocity is:

$$t_n=\frac{d_0+nK\lambda}{v_n} \quad (3)$$

and by substituting in Equation 2 the value of t_n as given by Equation 3 we get

$$\frac{d_0+nK\lambda}{v_n}=\frac{d_0}{v_0}+\frac{nK\lambda}{c}\pm N\frac{\lambda}{c} \quad (4)$$

$$=\frac{d_0}{v_0}+\frac{\lambda}{c}(nK\pm N) \quad (5)$$

Multiplying both sides of Equation 5 by c we have

$$\frac{d_0+nK\lambda}{\frac{v_n}{c}}=\frac{cd_0}{v_0}+\lambda(nK\pm N) \quad (6)$$

$$\frac{v_n}{c}=\frac{\frac{d_0}{\lambda}+nK}{\frac{d_0}{\lambda}\frac{c}{v_0}+nK\pm N} \quad (7)$$

From the teaching on page 1532, Proceedings I. R. E., December 1932 of the Chu and Barrow article, we have

$$v_n=\frac{c}{\sqrt{1-\left(\frac{\lambda}{2b_n}\right)^2}} \quad (8)$$

and

$$b_n=\frac{\lambda}{2\sqrt{1-\left(\frac{c}{v_n}\right)^2}} \quad (9)$$

provided

$$\frac{\lambda}{2}<b_n<\lambda$$

Referring now to Figs. 4 and 5, the array **40**, hereinafter denoted "organ pipe array" comprises twenty-one air-filled metallic rectangular pipes **41** designated for convenience, **0**, **1**, **2** . . . **20** as indicated by the subscripts for the b dimensions. The near end apertures **42** of pipes **41** are adjacent each other and directly connected to the coupling section **3**. The twenty-one pipes are aligned with the desired direction **9** of radio action and have uniformly graded lengths d_0, d_1, d_2 . . . d_{20}, as shown in Fig. 4, so that the spacing between the far end apertures **43** of each pair of adjacent pipes is $K\lambda$, and the spacing between the aperture **43** of pipe o and aperture **43** of any other pipe is $nK\lambda$, where n corresponds to the pipe designation. The a or electric plane widths are the same for all pipes. The b_0, b_1, b_2 . . . b_{20} or magnetic plane widths vary as shown in the enlarged end-view, Fig. 5, since the b widths of pipes **0**, **1**, **2** . . . **20** are critically dimensioned as explained above in connection with Figs. 1, 2 and 3. The b width variations are not shown in Fig. 4 inasmuch as the scale employed does not permit detail illustration of these widths.

The operation of the system of Figs. 4 and 5 is believed to be apparent in view of the explanation given above relative to the two-element system. In the case of transmission, the radiations from the twenty pipes add in phase for direction **9** and in the case of receiving maximum reception occurs in a direction opposite to that represented by arrow **9**. In a system actually constructed in accordance with Figs. 4 and 5 highly efficient end-on action was obtained. The dimensions of the system actually constructed are given in the table below.

Pipe No. (n)	Pipe length d in λ	$\frac{v_n}{c}$	$\pm N$	Pipe b width in cm.
0	d_0 1	2	0	b_0 5.6580
1	d_1 1.5	3/2	0	b_1 6.5740
2	d_2 2.0	4	−1	b_2 5.0606
3	d_3 2.5	5/2	−1	b_3 5.3463
4	d_4 3.0	2	−1	b_4 5.6580
5	d_5 3.5	7/4	−1	b_5 5.9708
6	d_6 4.0	8/5	−1	b_6 6.2770
7	d_7 4.5	3/2	−1	b_7 6.5740
8	d_8 5.0	2	−2	b_8 5.6580
9	d_9 5.5	11/6	−2	b_9 5.8463
10	d_{10} 6.0	12/7	−2	b_{10} 6.0328
11	d_{11} 6.5	13/8	−2	b_{11} 6.2165
12	d_{12} 7.0	14/9	−2	b_{12} 6.3970
13	d_{13} 7.5	3/2	−2	b_{13} 6.5740
14	d_{14} 8.0	16/9	−3	b_{14} 5.9265
15	d_{15} 8.5	17/10	−3	b_{15} 6.0592
16	d_{16} 9.0	18/11	−3	b_{16} 6.1904
17	d_{17} 9.5	19/12	−3	b_{17} 6.3200
18	d_{18} 10.0	20/13	−3	b_{18} 6.4479
19	d_{19} 10.5	3/2	−3	b_{19} 6.5740
20	d_{20} 11	22/13	−4	b_{20} 6.0738

In the system tested

K was chosen to be ½;

d_0 was chosen to be one wave-length, that is, λ, and the velocity v_0 in pipe o was chosen to be $2c$. Substituting these values in (7) gives

$$\frac{v_n}{c}=\frac{1+\frac{n}{2}}{\frac{1}{2}+\frac{n}{2}\pm N}$$

If the arbitrary constant N were not utilized and if n were regarded zero we would have for pipe $n=10$ a value of

$$\frac{v_n}{c}=\frac{6}{5.5}$$

which would make $b_n>\lambda$ and this would permit higher order waves. In the above table the minus values of $\pm N$ are used to keep b_n within the limits.

Figs. 6 and 7 illustrate, respectively, the measured a or electric plane and the b or magnetic plane characteristics of the end-on array actually constructed and having dimensions as given in the above table. As shown by these curves, the maximum electric plane lobe **44** and the maximum magnetic plane lobe **45** are aligned substantially with the axis **46** and the desired direction **9**, the angle "zero degrees" being coincident with axis **46**. More accurately, in the magnetic plane, the principal axis of lobe **45** is exactly aligned with the zero degree direction but in the electric plane the largest axis of lobe **44** is at a slight angle to the zero degree direction, the slight deviation resulting, it is believed, from the coupling between the apertures **43**. Also, as shown by the curves of Figs. 6 and 7, the maximum lobe in both planes has a relatively narrow width and negligible secondary lobes **47**.

Although the invention has been explained in connection with specific embodiments, it is not to be limited to the structures illustrated since other apparatus may be utilized in successfully practicing the invention. Obviously air-filled pipes of square or circular cross section or dielectrically loaded pipes may be used in place of the rectangular air-filled pipes. Also, any practical number of pipes may be used and, instead

of uniformly graded pipe lengths d_0, d_1, d_2 . . . d_{20}, the physical lengths of the pipes may obviously be non-uniformly graded, provided that the phase velocities of the pipe are properly proportioned in accordance with the lengths.

What is claimed is:

1. An end-on antenna array comprising a plurality of open-ended dielectric channels having different phase velocity characteristics.

2. An antenna array comprising a plurality of open-ended dielectric channels having different lengths.

3. An end-on antenna array comprising a plurality of open-ended dielectric channels having different cross-sectional areas.

4. An antenna array comprising a pair of parallel dielectric end-on antenna members having different physical lengths and different phase velocity characteristics, the velocity difference being a function of the length difference.

5. In combination, a pair of parallel end-fire dielectric radiators having different lengths and different widths, the difference in width being a function of the length difference.

6. An antenna array comprising a plurality of parallel rectangular open-ended wave guides having different wide transverse dimensions, the open ends of said guides being spaced on the desired wave path an amount dependent upon the difference in said dimensions.

7. In combination, a radio device, a pair of open-ended parallel metallic wave guides connected thereto for conveying transverse electric components, said guides having different physical lengths and each guide having a physical length differing from its phase length, the phase length of one guide being equal to the phase length of the other guide plus said length difference.

8. A dielectric antenna array comprising a pair of dielectric channels connected to a translation device and having apertures at their remote ends, said apertures being spaced on the path of desired radio action, said channels having for a given frequency different phase velocities, the phase velocity difference being a function of the aperture spacing.

9. An end-on dielectric antenna array comprising a pair of open-ended parallel dielectric channels having different lengths and connected to a translation device, said channels having different physical lengths and phase velocities differing by an amount related to the physical length difference and such that the difference in phase length of said channels equals the difference in physical length or equals the last-mentioned difference plus or minus a multiple, including one, of a wave-length as measured in the ether.

10. An antenna array comprising a plurality of open-ended, air-filled, metallic rectangular wave guides having a given difference in physical length as measured in wave-lengths in the ether medium and a difference in phase length as measured in wave-lengths in the guides, said guides having a difference in their wide transverse dimensions related to the physical length difference and selected so as to render the phase length difference equal to the physical length difference or equal to the physical length difference plus a multiple, including one, of a wave-length as measured in the ether.

11. In combination, a radio transceiver, a plurality of air-filled parallel rectangular metallic wave guides connected thereto and having apertures at their remote ends, said guides having different physical lengths and different wide transverse dimensions, the wide transverse dimension of the longer guide being a function of the physical length of said guide and the phase length of the shorter guide.

12. In combination, a radio translation device, a first open-ended, metallic wave guide connected thereto and having a given phase velocity and a given phase length differing from its physical length, a second open-ended metallic wave guide connected to said device and having a greater physical length, said guides being parallel and aligned with a desired direction of action, said second guide having a phase velocity differing from that of the first guide by an amount such that the difference in phase length of said guides is equal to the difference between the physical length of said guides.

13. A dielectric antenna array comprising a pair of parallel open-ended metallic wave guides aligned substantially with a desired direction of action and having different physical lengths, said guides having a difference in phase velocities proportioned to secure a difference in phase lengths equal to the difference in their physical lengths.

14. In combination, a translation device, a plurality of dielectric channels connected thereto and having antenna apertures spaced on the path of desired radio action substantially, the adjacent channels having at least one dimensional difference related to the spacing between the associated apertures whereby the relative phase velocities in said adjacent channels are such that the wave-lengths as received at said device from a wave traveling on said path are cophasal and the wavelets emitted along said path are cophasal and form a wave front perpendicular to said direction.

15. An end-on dielectric antenna array comprising a plurality of end-on dielectric antenna members, each member comprising an air-filled open-ended rectangular metallic wave guide having a narrow transverse dimension and a wide transverse dimension and connected to a transceiver for utilizing waves polarized parallel to the narrow transverse dimension, said members having graded lengths and graded transverse wide dimensions, the transverse wide dimension of any intermediate member being a function of the sum of the length of the shortest member and the difference in length between said intermediate member and said shortest member.

16. In combination, a translation device, a pair of dielectric channels connected thereto and each having an end antenna aperture, said channels having different longitudinal dimensions and different phase velocity characteristics for a given frequency, the difference in length and the difference in phase velocity characteristic being related to the spacing on the path of desired direction between said apertures.

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