June 6, 1967 V. C. SUNDBERG ET AL 3,324,472

ANTENNA SYSTEM

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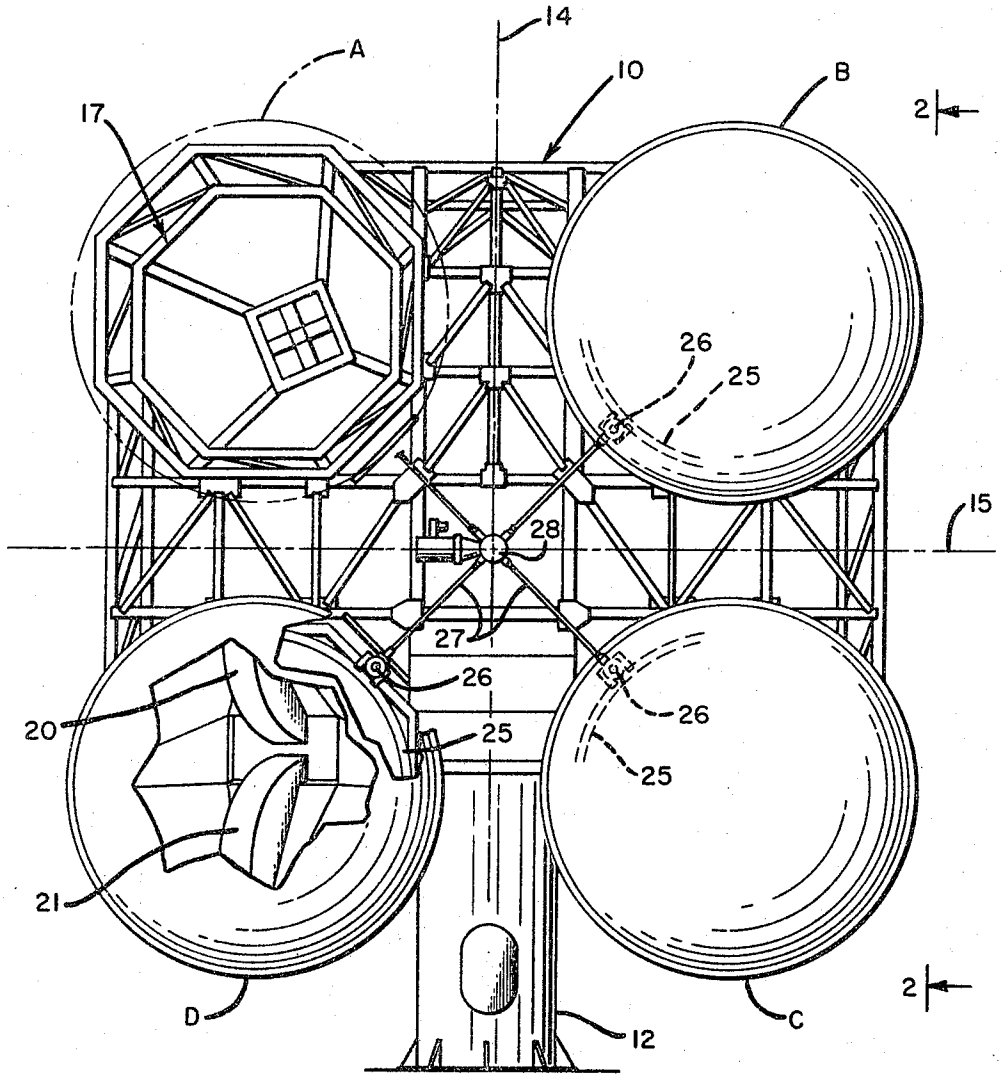


FIG-1

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ANTENNA SYSTEM

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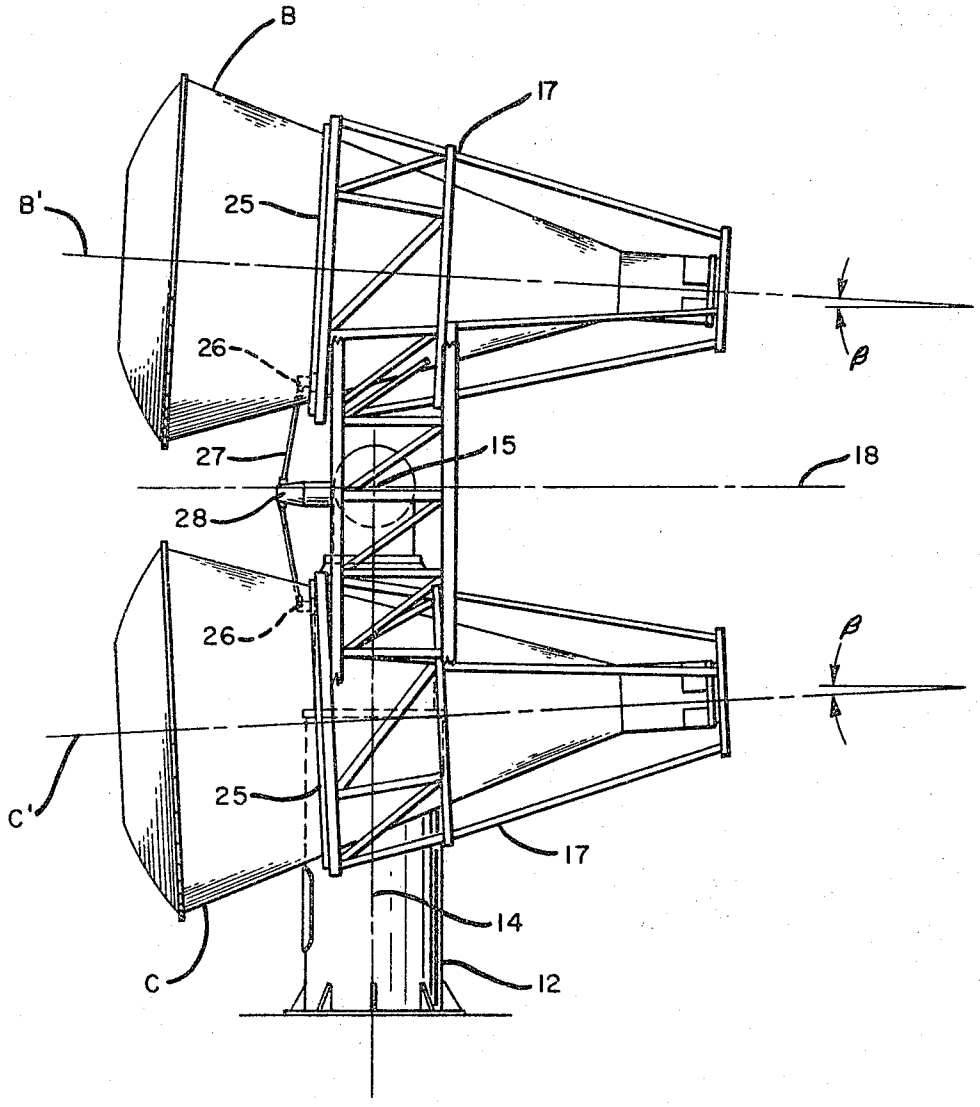


FIG-2

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ANTENNA SYSTEM

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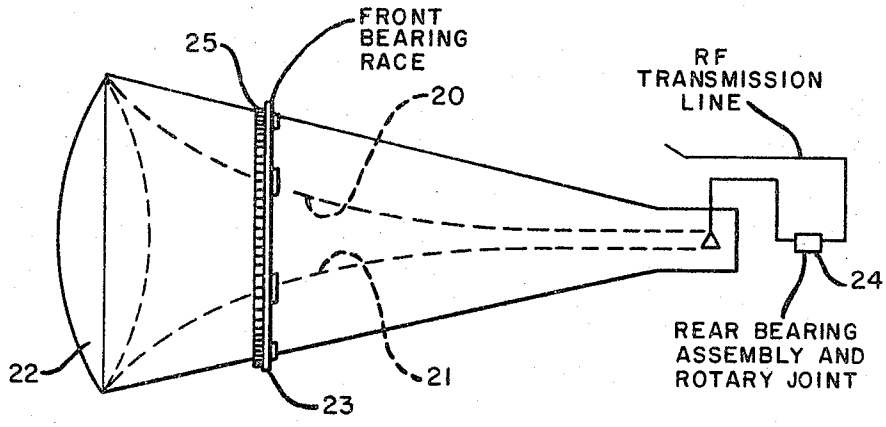


FIG-3

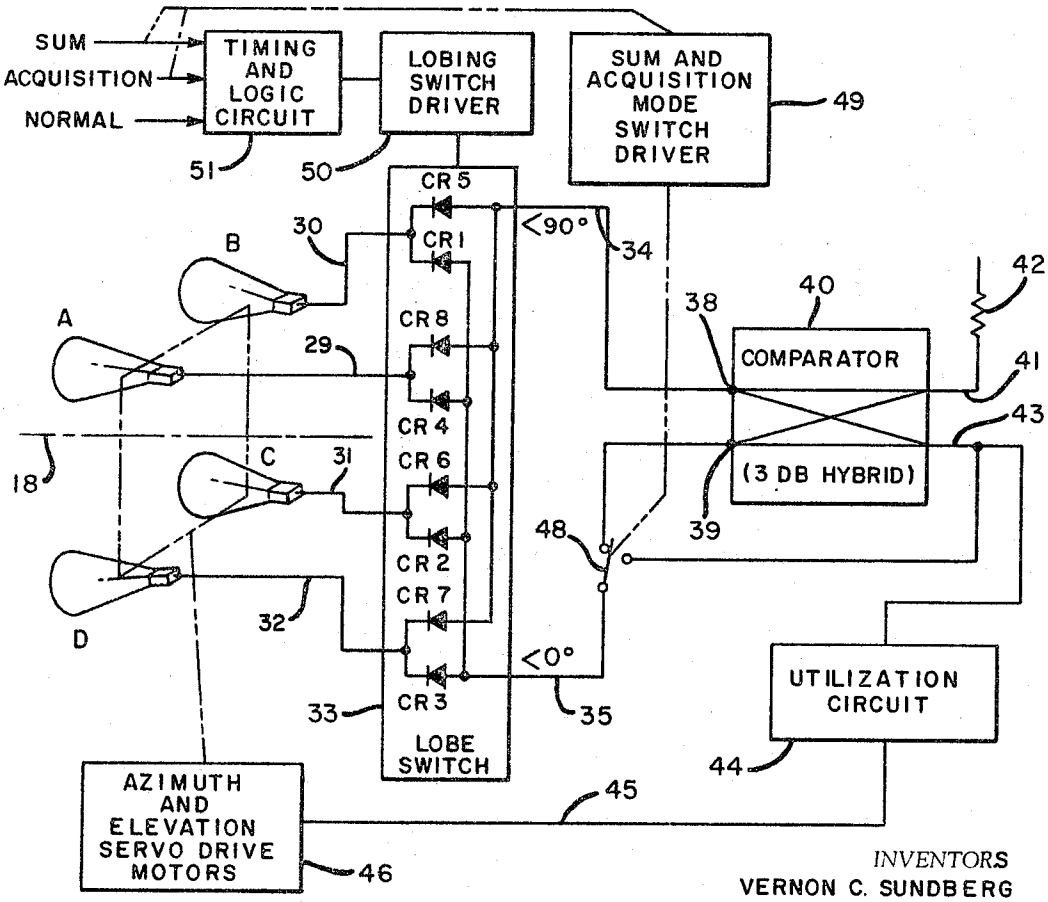


FIG-4

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ANTENNA SYSTEM

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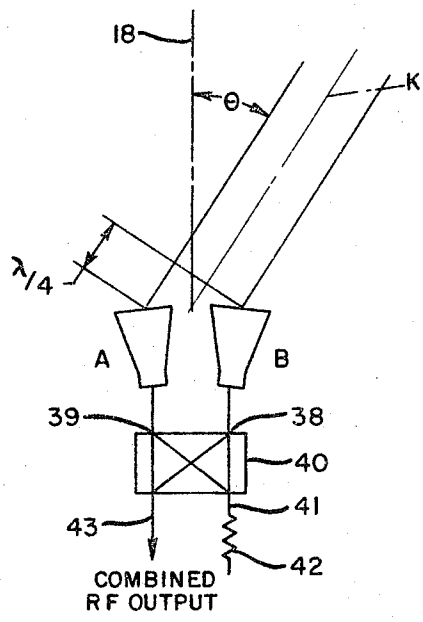


FIG-5(a)

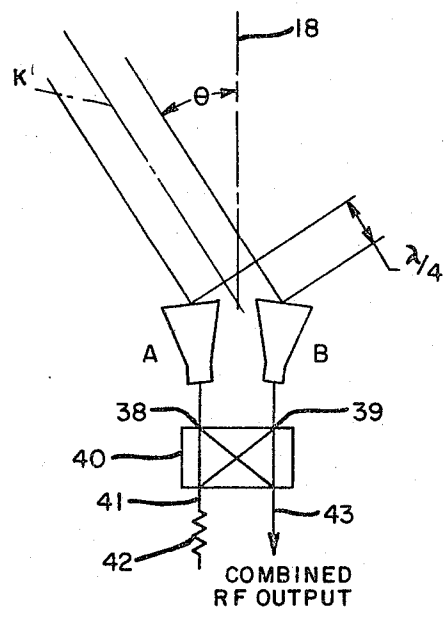


FIG-5(b)

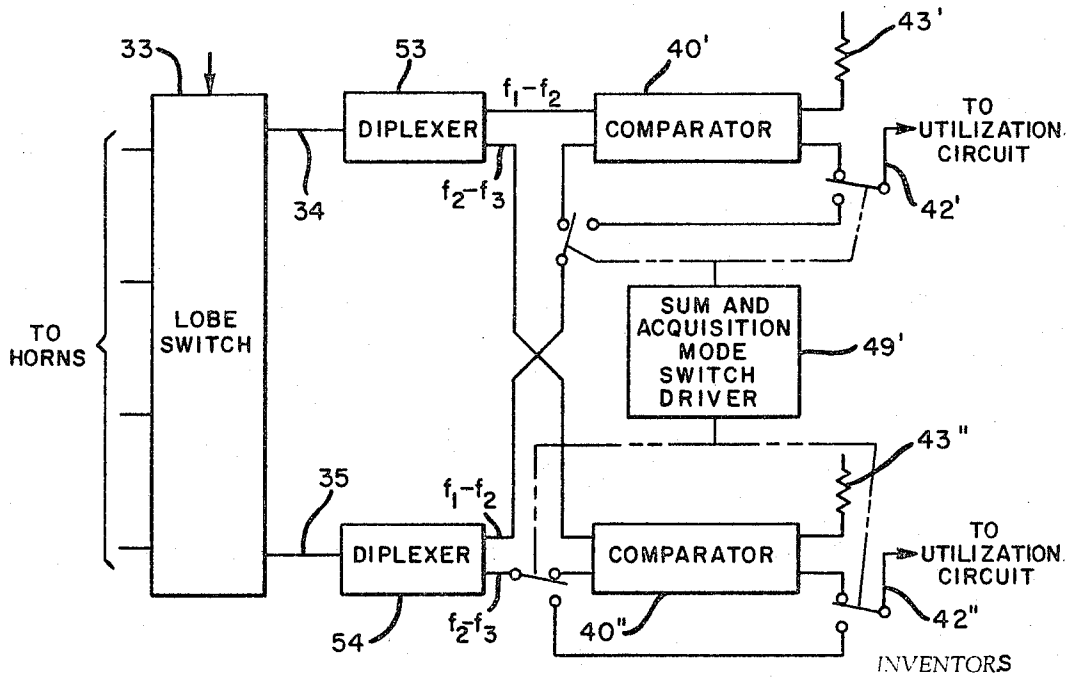


FIG-6

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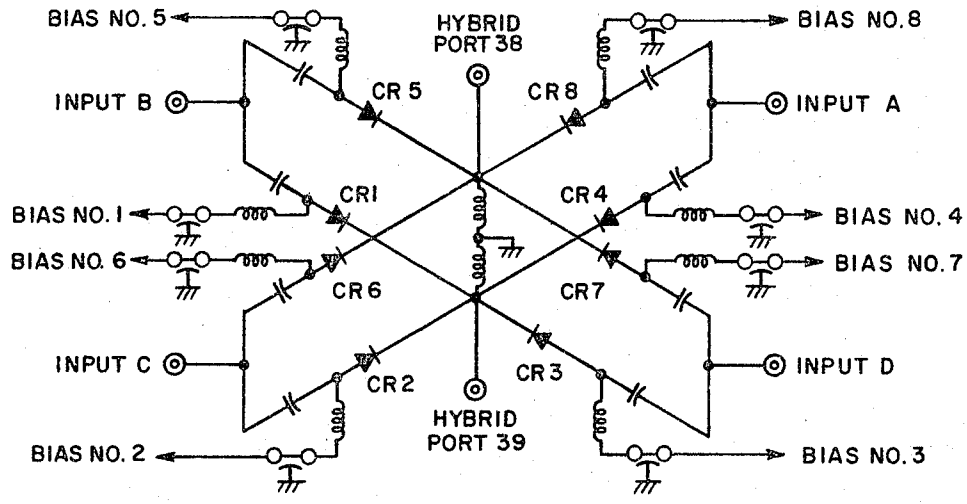
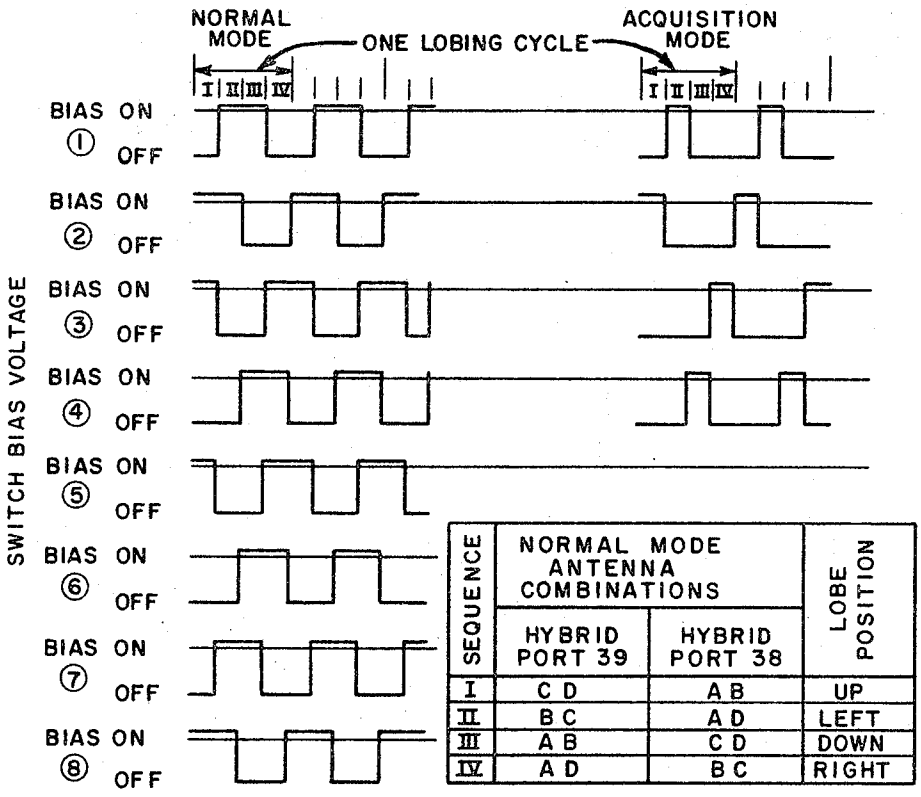


FIG-7-A



SEQUENCE	NORMAL MODE ANTENNA COMBINATIONS		LOBE POSITION
	HYBRID PORT 39	HYBRID PORT 38	
I	C D	A B	UP
II	B C	A D	LEFT
III	A B	C D	DOWN
IV	A D	B C	RIGHT

FIG-7-B

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ANTENNA SYSTEM

Filed Oct. 23, 1964 7 Sheets-Sheet 6

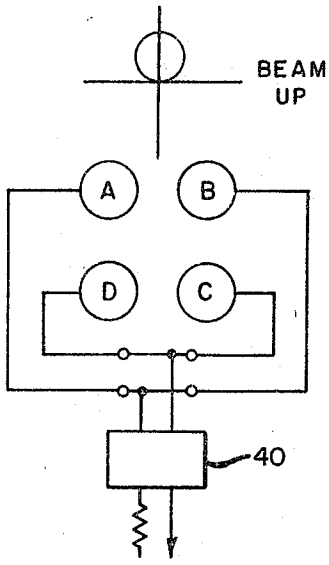


FIG-8(a) I

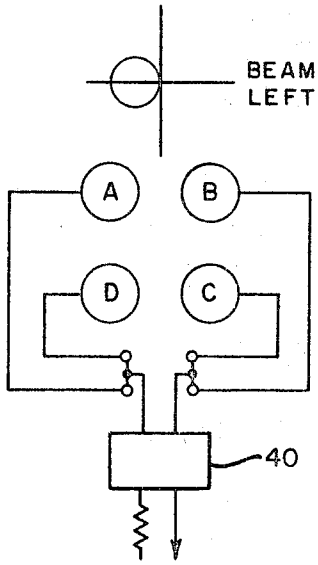


FIG-8(b) II

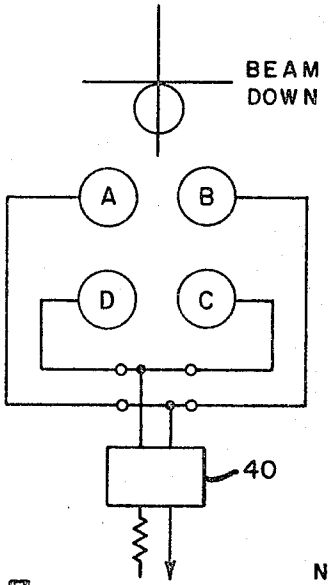
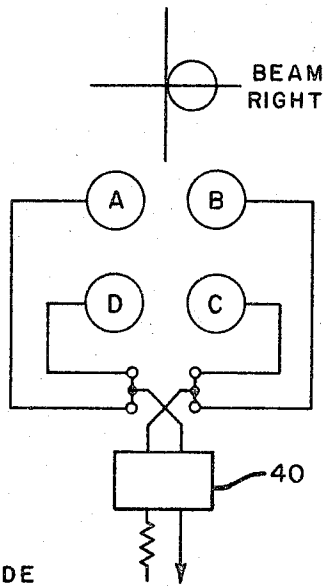


FIG-8(c) III



NORMAL MODE

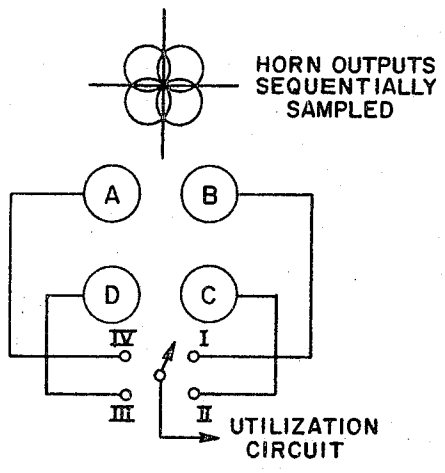
FIG-8(d) IV

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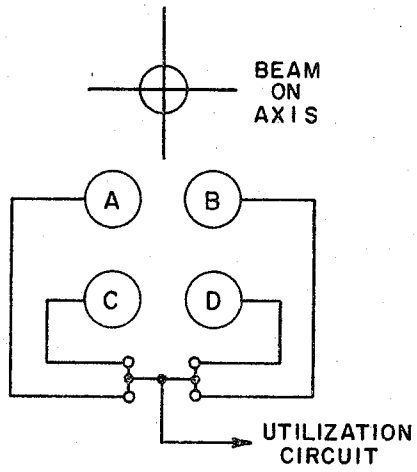
ANTENNA SYSTEM

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AQUISITION MODE

FIG-9



SUM MODE

FIG-10

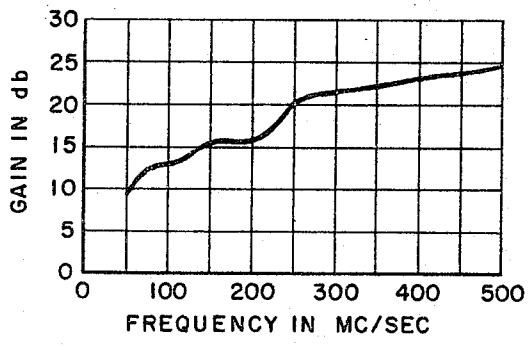


FIG-11

FOUR-HORN ARRAY GAIN AS A FUNCTION OF FREQUENCY ON BORESIGHT AXIS.

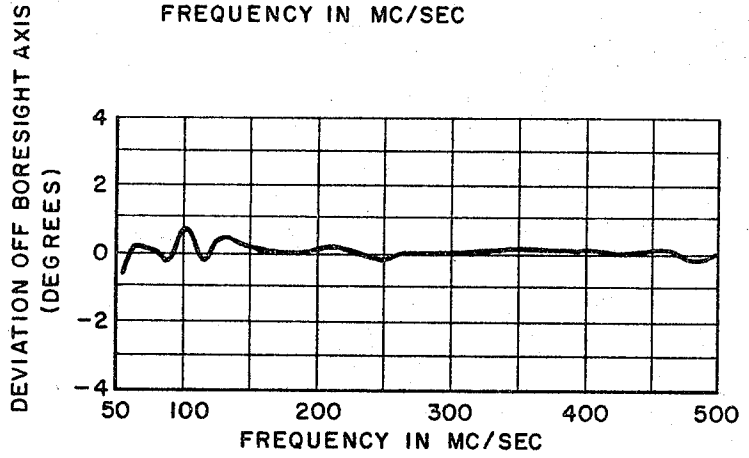


FIG-12

BORESIGHT SHIFT AS A FUNCTION OF FREQUENCY

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United States Patent Office

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3,324,472

ANTENNA SYSTEM

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Filed Oct. 23, 1964, Ser. No. 406,106
10 Claims. (Cl. 343—117)

This invention relates to antennas and more particularly to a broadband automatic tracking antenna system.

Ground waves and skywaves in the very high frequency (VHF) region, i.e., 50 to 500 mc./sec., are affected to a considerably lesser degree by ionospheric conditions and disturbances than at higher frequencies. Accordingly, this frequency band is especially favorable for aerospace communications and navigational control which often require automatic tracking features. The difficulty in providing VHF automatic tracking systems is the large size of the antenna structure required, especially at the lower end of the band. This problem is also complicated by the need for two or more separate antenna systems or arrays to operate over the band due to bandwidth limitations of present arrays. Furthermore, multi-element arrays in the past have been generally unsatisfactory because of deterioration of patterns due to mutual coupling of adjacent elements.

A general object of the invention is the provision of an improved electromechanical automatic tracking VHF antenna system.

A more specific object is the provision of an automatic tracking antenna system capable of operating over greater than a 10:1 band in the VHF range.

Another object is the provision of a four-element VHF antenna array which is capable of operating in a plurality of tracking modes with a minimum of undesired mutual coupling between the elements.

A more specific object is the provision of a broadband automatic tracking system with a plurality of double-ridged lens-corrected VHF horns as antenna elements.

Still another object is the provision of a broadband sequential lobing tracking antenna system with an array of antenna elements arranged to minimize boresight shift over the operating frequency range.

A further object is the provision of such an antenna system with the lobe control switch connected between the horns and the beam-forming network including associated multiplexing circuitry for minimizing boresight shift over the operating frequency range.

Still another object is the provision of a broadband VHF antenna array that is sufficiently light and compact to permit rapid tracking response.

These objects and other advantages of this invention are accomplished with an antenna system comprising four lightweight double-ridged lens-corrected waveguide horns. These horns are spaced apart and symmetrically disposed about the central or boresight axis of the array on a two-axis pedestal such that the horns are positioned at the corners of a "square" which has adjacent sides parallel to the azimuth and elevation directions, respectively. The plane of this "square" extends in a direction perpendicular to the axis of the array. The horns, therefore, may be directed toward any target in the hemisphere above the pedestal axis. The outputs of the horns are coupled to a utilization circuit through switches which control operation of the system in one of three modes: a NORMAL mode in which the horns are electrically combine in quadrature by pairs into an array that is sequentially switched to create beam lobing; an ACQUISITION mode in which a receiver or utilization circuit is electrically switched from horn to horn to provide less accurate tracking information suitable for searching; and a SUM mode in which RF energy is received from all four horns in phase to form an on-axis high-gain beam for manual tracking of low level signals. Each horn is mounted with its axis inclined outwardly from the boresight axis in order to resolve tracking ambiguities when operated in the ACQUISITION mode.

The above and other objects of this invention will be understood from the following description of a preferred embodiment thereof reference being had to the accompanying drawings in which:

FIGURE 1 is a front view of the antenna array embodying this invention with portions of the structure broken away or removed to show details of construction;

FIGURE 2 is a side view of the array as viewed on line 2—2 of FIGURE 1;

FIGURE 3 is a schematic elevation of a lens-corrected ridged waveguide horn which comprises an element of the array;

FIGURE 4 is a schematic and block diagram of the antenna system and associated circuitry;

FIGURES *5a*, *5b*, are simplified diagrams (plan view) of the horn array illustrating the relationship of the phase delay in the comparator to the angle between the principal lobe and the boresight axis;

FIGURE 6 is a block diagram of a comparator circuit modified to operate over two frequency bands;

FIGURE *7a* is a schematic diagram of the lobing switch and FIGURE *7b* is a timing diagram for its operation;

FIGURES *8a*, *8b*, *8c*, *8d*, 9 and 10 are block diagrams showing the switch connections of the four horns (viewed from the rear) for the three operating modes; and

FIGURES 11 and 12 are performance curves for the four-horn system.

Referring now to the drawings, an antenna system embodying the invention is illustrated in FIGURES 1 and 2 and comprises four ridged waveguide horns A, B, C and D supported by a truss **10** on a pedestal **12** for rotation about an azimuth axis **14** and about an elevation axis **15**. Each horn is supported in a basket frame **17** rigidly connected to the truss **10**. The four horns are symmetrically disposed about the boresight axis **18** at the corners of a "square" having a plane normal to the boresight axis. The horns are supported in the basket frame **17** for rotation about the longitudinal axes A', B', C' and D' of the horns. The horn axes are inclined outwardly in both azimuth and elevation planes (i.e., along the diagonals of the "square") at an angle β (about 5 degrees) from the boresight axis to eliminate tracking ambiguities.

Each horn has a pair of inwardly projecting radial ridges **20** and **21**, see FIGURE 3, and has an outer shell that is tapered to provide the proper impedance match between the feed line and free space. The ridges serve to extend the bandwidth of the tapered horn by lowering the normal cutoff frequency of the horn. An electromagnetic lens **22** in the horn aperture reduces the physical length required for the horn while maintaining minimum phase

variation in the plane of the aperture. The lens preferably is made of a lightweight composition and may, for example, be constructed of metal-sprayed polystyrene foam blocks nested together and varying in depth as described in the copending application of Donald L. Anderson, Ser. No. 374,521, filed June 11, 1964.

The horn preferably is made in two half-sections and comprises a fiberglass laminated structure that has a high strength-to-weight ratio. The two ridges **20** and **21** are molded integrally with the sections and extend the full length of the shell. Brackets bonded to the horn body support the front bearing race **23** and the rear thrust bearing **24**. Suitable bearings, not shown, on the basket frame **17** engage the horn races and permit angular displacement of the entire horn structure about its axis within basket frame **17** to change the polarization direction of the horn. In one embodiment of the invention, a horn 18 feet long with a 1-inch thick cone-shaped shell and a 12 foot diameter circular aperture was constructed in accordance with the procedure described in the copending application of Donald L. Anderson, Kenneth L. Walton and Richard F. Huelskamp, Ser. No. 359,684, filed Apr. 15, 1964.

In order to provide selected adjustment of the polarization of the four horns A, B, C and D simultaneously, each horn has a chain or toothed ring **25** secured to its outer surface adjacent the front bearing race **23**. Four pinions **26** driven by shafts **27** from a common four-way drive unit **28** simultaneously effects equal angular displacement of the four horns. The drive unit **28** is remotely controlled and is energized sufficiently to adjust the polarization as desired.

Horns A, B, C and D are electrically connected by transmission lines **29**, **30**, **31** and **32**, respectively (see FIGURE 4) to a lobe switch circuit **33** which couples each horn to two switch output lines **34** and **35**. When the array is operated in the NORMAL mode, output lines **34** and **35** are connected to input ports **38** and **39**, respectively, of a comparator **40**, which compares the outputs of each pair of horns to determine the position of a target or signal source with respect to the boresight axis as explained below.

Output port **41** of the comparator **40** is terminated in a resistive load **42**, and output port **43** is connected to a utilization circuit **44** which processes the compared signals for displaying, recording and/or analyzing purposes. In addition, utilization circuit **44** derives error signals proportional to the target position deviations from bore-sight in azimuth and elevation and transmits these signals by line **45** to servo drive motors **46** for moving the horn array in the proper direction for tracking the target.

Comparator **40** preferably is a 3 db hybrid coupler which provides a $-90°$ phase shift of signals passing between ports **38** and **43** and between ports **39** and **41** relative to a 0° phase shift; and 0° phase shift of signals passing between ports **39** and **43** and between ports **38** and **41**. Bypass switch **48** connects line **35** directly to output **43** to bypass the comparator during operation of the system in the ACQUISITION and SUM modes. Switch **48** is actuated by a driver **49** which is energized when the timing and logic circuit **51** operates in the ACQUISITION and SUM modes.

Lobe switch circuit **33** comprises four pairs of individually controlled switches connected to the outputs of the four antenna horns A, B, C and D, respectively. Each horn output is connected to two switches. Preferably the switches are the single-pole single-throw type and comprise microwave diodes identified on the drawings as CR1 to CR8, inclusive. Each diode is switched between a forward-biased conducting state ("on") and a reverse-biased nonconducting state ("off") by control voltages generated by a lobing switch driver circuit **50**. The individual diodes are biased between operating states in one of several selected sequences by the circuit **50** as controlled by a time and logic circuit **51**. One switch in each pair of diode switches is connected to lobe switch output line **34** and the other switch in each pair is connected to output line **35**.

The selected sequences of lobe switch actuation available in this system provide for the operation of the horn array in a NORMAL mode, an ACQUISITION mode and a SUM mode. In the NORMAL tracking mode one pair of horns (e.g., AD in FIGURE 5(*a*)) is fed in parallel to one input of the comparator while the remaining pair (e.g., BC) is fed in parallel to the other input. The comparator then combines the signals from the four horns after subjecting signals from one input (e.g. signals from horns BC) to a 90° phase delay. Because of this 90° delay, the electrical axis K of the array is angularly displaced from the boresight axis to the right as indicated in FIGURE 5(*a*). When these connections are reversed as shown in FIGURE 5(*b*), e.g., horns AD to port **38** and horns BC to port **39**, the electrical axis K′ of the array is displaced to the left (as viewed) from boresight. The array axis is sequentially shifted to four equally spaced positions about the boresight axis by sequentially switching each of the horns between the comparator inputs. Thus, horns are combined as $AB+jCD$, $BC+jAD$, $CD+jAB$, and $DA+jBC$ (where the (j) indicates a $-90°$ phase shift) in that order to cause clockwise sequential lobing of the array. In the ACQUISITION mode, the outputs of the individual horns are sampled sequentially and separately, i.e., horns A, B, C and D in that order, to provide a lobe that shifts sequentially to four positions around the boresight axis. This provides tracking data that is sufficiently accurate to be useful in searching for targets or signal sources. When the array is operated in the SUM mode, the outputs of all four horns are combined simultaneously and in phase to form an on-axis high-gain beam useful in manually tracking low-level signals. Each of these modes of operation of the antenna system will be discussed in detail below.

Comparator **40** uniquely compares the outputs of one pair of horns with the outputs of the remaining pair of horns at any one time and is connected in the antenna system only during the NORMAL mode of operation. Each pair of horns is connected together and their outputs are combined at the comparator **40** so that the patterns of the four horns essentially form a single lobe at a predetermined angle from boresight axis **18**. In other words, the four horns function as a single antenna to produce a lobe with a phase front directed at a predetermined angle from boresight. The position of a target in space with respect to this lobe is determined by comparator **40**, the output of which is a signal having a magnitude which varies in accordance with target position. The lobe formed by combining the next group of horns in the lobing sequence similarly produces an output from the comparator **40**, the magnitude of which varies with the target position relative to that lobe. As the subsequent groups or combinations of horns are sampled, the utilization circuit demodulates the resultant amplitude modulated output of the comparator and generates an error signal of the proper sense to move the horn array until the target is on the boresight axis. In the latter position, the target produces comparator output signals of equal amplitude and hence unmodulated.

Comparator **40** may be any well-known four-port 3 db hybrid coupler such as that manufactured by The Narda Microwave Corporation, Plainview, N.Y. In practice, bandwidth limitations of conventional hybrid couplers have necessitated the provision in this system of more than one comparator to accommodate the operating bandwidth of the antenna horns. The connections for such a system in which the array bandwidth is covered in two steps are shown in the block diagram of FIGURE 6. The outputs of lobe switch **33** on lines **34** and **35** are connected to two identical diplexers **53** and **54**, respectively, which divide the input signals into outputs in the frequency bands f_1 to f_2 (50 to 250 mc.) and f_2 to $_3f$ (250 to 500 mc.). The output signals from the diplexers in the f_1

to f_2 band are connected to comparator **40'** and the outputs in the range f_2 to f_3 are similarly connected to comparator **40''**. These comparators function in the manner described above to combine the outputs of successive pairs of horns. The outputs from the comparators on lines **42'** and **42''** may then be combined or may be further subdivided as required for processing in the utilization circuit.

The sequence in which the diode switches **CR1** to **CR8** are biased between the conducting and non-conducting states for the NORMAL and ACQUISITION modes is shown in FIGURE 7(*b*). Lobing switch driver **50** generates D.C. bias voltages for the eight diodes in a sequence and timing pattern controlled by timing circuit **51**. Each diode is biased on or off in a predetermined time relationship with respect to the other diodes as shown in FIGURE 7(*b*) to accomplish the desired lobing pattern. For example, in the NORMAL mode, Sequences I, II, III and IV (in that order) represent counter-clockwise rotation of the combined beam about the boresight axis as viewed from the rear of the horns. Referring to the table in FIGURE 7(*b*), the connection of horns C and D to hybrid port **39** and horns A and B to hybrid port **38** results in a combined beam that is directed above the boresight axis (see FIGURE 8(*a*)). To effect these connections, diodes **CR1–4–6–7** are reversed-biased and diodes **CR 2–3–5–8** are forward-biased. By changing bias voltages to the diodes in accordance with the timing diagram, connections of the four horns are completed to provide counter-clockwise sequential lobing of the array in the NORMAL mode.

During the ACQUISITION mode of operation, switch **48** (FIGURE 4) is actuated so as to cause the lobe switch output on line **35** to bypass comparator **40**. This prevents loss of one-half of the signal in load **42** for a single horn input. One horn at a time is switched to line **35**. Thus, as shown in FIGURE 7(*b*) for Sequence I of the ACQUISITION mode, diode **CR2** is forward-biased and horn C is connected to line **35** while the other horns are disconnected.

During the SUM mode of operation, switch **48** is moved to the comparator bypass position and diodes **CR1**, **CR2**, **CR3** and **CR4** are forward-biased to connect the four horns directly to utilization circuit **44**. The other diodes are reverse-biased and cut off.

FIGURES 8*a*, 8*b*, 8*c*, 8*d* 9 and 10 illustrate the connection of the horns A, B, C, and D to the utilization circuit for the NORMAL, ACQUISITION and SUM modes and in the sequences described in FIGURE 7(*b*). The horns are represented as viewed from their waveguide ends.

Adjacent horns are equally spaced apart and all horns are equally spaced from the boresight axis. The purpose of mounting each antenna horn in truss **10** with the horn axis inclined with respect to the boresight axis is to provide a sufficiently low level crossover of adjacent lobes (i.e., 3 db down or less) to delineate the direction of signals detected by the horns when operating in the ACQUISITION mode. This tilt angle does not affect the operation of the system in the NORMAL or SUM modes. Mutual coupling effects between horns are minimized because each horn effectively confines the field of the propagated energy within it and is inherently shielded from adjacent horns.

A four-horn array embodying the invention has been built and tested, and has performed satisfactorily over a frequency range of 50 mc. to 500 mc. in the three modes described above. The gain and boresight shift (deviation of electrical boresight axis from true boresight axis) during the NORMAL mode is illustrated in FIGURES 11 and 12 for an antenna system having the following dimensions and characteristics:

Four-horn array:

Operative frequency range	50 to 500 mc.
Bandwidth	13:1 (45 to 575 mc.).
Physical properties:	
Length	18 feet.
Diameter of aperture	12 feet.
Weight (includes horn, lens and bearing-race)	1,400 lbs.
Weight of corresponding aluminum horn	2,000 lbs.
Spacing between adjacent horns (aperture centers)	16 feet.
Boresight accuracy	Less than 1° boresight shift at all frequencies from 55 to 500 mc.
Polarization	Linear; adjustable.
VSWR	2.5:1 average; 5:1 maximum.
Cross-coupling	−30 to −50 db from any one horn to any other horn in the array.

Lobing switch and driver:

Acquisition and normal mode—	
Switching rate	0–2,000 c.p.s.
Insertion loss	1.5 db maximum.
VSWR	2.5:1 maximum.

What is claimed is:

1. An antenna system comprising

an array of antenna elements having a boresight axis,

means for supporting said array for movement about elevation and azimuth axes perpendicular to said boresight axis,

each of said elements comprising a ridged waveguide horn supported with its longitudinal axis inclined outwardly from the boresight axis,

a switch circuit having first and second outputs and comprising a plurality of switches,

means for connecting said elements to pairs, respectively, of said switches,

means for connecting one switch of each pair of switches to the first output of the switch circuit,

means for connecting the other switch of each pair to the second output of the switch circuit,

comparator means having at least two input ports and two output ports and providing a 90 degree phase shift of signals passing between diagonally opposite input and output ports,

means for connecting the first and second outputs of the switch circuit to the input ports, respectively, of the comparator means,

means for controlling the operating state of each switch for selectively electrically connecting and disconnecting said horns to and from the first and second outputs of the switch circuit,

a termination load connected to one of the output ports of said comparator means,

a utilization circuit connected to the other output port of said comparator means,

bypass switch means for changing the connection of one of the switch circuit outputs between the comparator means and the utilization circuit, and

means responsive to an output of said utilization circuit to move said array of elements about said azimuth and elevation axes.

2. An antenna system comprising

an array of four antenna horns supported for movement about elevation and azimuth axes,

a switch circuit having first and second outputs and comprising eight switches,

means for connecting said horns to pairs, respectively, of said switches,
means for connecting one switch of each pair of switches to the first output of the switch circuit,
means for connecting the other switch of each pair to the second output of the switch circuit,
a hybrid coupler having two input ports and two output ports,
means for connecting the first and second outputs of the switch circuit to the input ports, respectively, of the coupler,
means for controlling the operating state of each switch for selectively electrically connecting and disconnecting said horns to and from the first and second outputs of the switch circuit,
a utilization circuit connected to one of the output ports of said coupler, and
means responsive to an output of said utilization circuit to move said array of elements about said azimuth and elevation axes.

3. An antenna system comprising
an array of antenna elements having a boresight axis,
means for supporting said array for movement about elevation and azimuth axes,
said elements comprising a plurality of horns equally spaced from the boresight axis with equal spacing between adjacent horns,
a switch circuit having first and second outputs and comprising a plurality of switches,
means for connecting said horns to pairs, respectively, of said switches,
means for connecting one switch of each pairs of switches to the first output of the switch circuit,
means for connecting the other switch of each pair to the second output of the switch circuit,
comparator means having an input connected to the outputs of said switch circuit for adding in quadrature signals at said switch circuit outputs and having an output from which the sum of said signals is derived,
means for controlling the operating state of each switch for selectively electrically connecting and disconnecting said horns to and from the first and second outputs of the switch circuit, and
a utilization circuit connected to the output of said comparator means.

4. The system according to claim 3 in which said switch controlling means comprises a timing and driver circuit for relating the time of operation of each of said switches to the others to electrically connect said horns to said switch circuit outputs in a predetermined sequence.

5. The system according to claim 4 with a bypass switch for changing the connection of the switch circuit outputs between said comparator means and said utilization circuit.

6. The system according to claim 4 in which said switches comprise diodes, said timing and driver circuit producing a switching bias for each diode to control the operating state of the latter.

7. An antenna system comprising
an array of antenna elements having a boresight axis,
means for supporting said array for movement about elevation and azimuth axes,
each of said elements comprising a horn supported in said array with its longitudinal axis inclined outwardly from the boresight axis,
a switch circuit having first and second outputs and comprising a plurality of switches,
means for connecting said elements to pairs, respectively, of said switches,
means for connecting one switch of each pair of switches to the first output of the switch circuit,
means for connecting the other switch of each pair to the second output of the switch circuit,
means for controlling the operating state of each switch for selectively electrically connecting and disconnecting said horns to and from the first and second outputs of the switch circuit, and
a utilization circuit connected to the outputs of said switch circuit.

8. An antenna system comprising
an array of horns having a boresight axis and supported for movement about azimuth and elevation axes,
switch means electrically connected to said horns for sampling one or more of the horns in selected sequences and producing an output,
means responsive to the output of said switch means for combining the outputs of more than one horn to angularly displace the resultant patterns of the combined horns relative to the boresight axis,
a utilization circuit connected to the output of said combining means, and
means for selectively connecting the output of the switch means between the input to the combining means and the input to the utilization circuit.

9. An antenna structure comprising
a pedestal,
a truss supported on said pedestal for movement about orthogonal axes in azimuth and elevation directions, respectively,
a plurality of basket frames rigidly connected to said truss and equally spaced from and symmetrical about a boresight axis perpendicular to said orthogonal axes,
an antenna horn rotatably supported in each basket frame with the axis of each horn inclined outwardly from the boresight axis, and
means for angularly displacing the horns simultaneously about their respective axes relative to the frames for varying the polarization of the horns.

10. The antenna structure according to claim 9 in which each horn has a bearing race intermediate its ends rotatably supported on the associated basket frame, said horn displacing means comprising toothed rings on the horns adjacent said bearing races, pinions engageable with said rings, and means for simultaneously driving said pinions to rotate said horns.

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