United States Patent [19]

Ehrlich

[11] **3,821,740**

[45] **June 28, 1974**

[54] **SUPER-DIRECTIVE SYSTEM**

[75] Inventor: **Stanley L. Ehrlich,** Middletown, R.I.

[73] Assignee: **Raytheon Company,** Lexington, Mass.

[22] Filed: **July 3, 1972**

[21] Appl. No.: **268,416**

[52] **U.S. Cl.** .... **343/100 SA,** 340/6 R, 340/16 R, 343/7 A

[51] **Int. Cl.** **G01s 3/74,** H04b 7/04

[58] **Field of Search**..... 340/6 R, 16 R; 343/100 SA, 343/7 A

[56] **References Cited**

UNITED STATES PATENTS

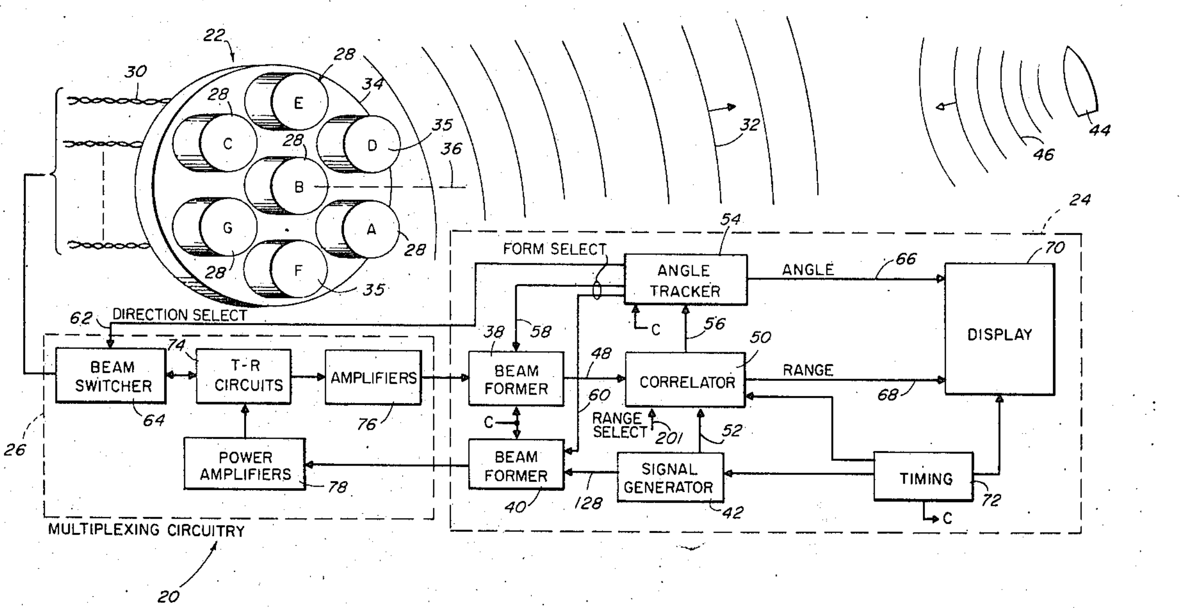
3,124,801	3/1964	Callahan, Jr.	343/100 SA
3,356,989	12/1967	Autrey	340/6 R
3,449,711	6/1969	Ricketts, Jr. et al.	340/6 R
3,560,985	2/1971	Lyon	343/100 SA
3,711,820	1/1973	Starkey	340/6 R
3,725,855	4/1973	Murphree et al.	340/6 R

Primary Examiner—Richard A. Farley
Assistant Examiner—G. E. Montone
Attorney, Agent, or Firm—Milton D. Bartlett; Joseph D. Pannone; David M. Warren

[57] **ABSTRACT**

A system of radiating elements arranged for forming one or more beams of radiation having radiation patterns such as a monopole, dipole, quadrupole, other multipoles or combination thereof. The individual radiating elements of the array are interconnected by circuitry providing for the summing and differencing of signals provided by adjacent radiating elements in response to incident radiation. In one embodiment the signal of one radiating element is delayed relative to the signal of an adjacent radiating element. The differencing of the signals provides for the deep nulls found in radiation patterns such as the dipole and quadrupole radiation patterns, while the delay between signals of adjacent radiating elements is adjusted for varying the shape of the directivity pattern. The system provides for varying the direction and shape of beams of the radiation pattern to provide for the detection, classification and/or tracking of a distant source of radiation as well as for illuminating a distant object. The system is responsive to the intensity of radiation received along one or more beams of the radiation pattern, and in response thereto, varies the delay between the signals of adjacent radiating elements and also provides for the selective coupling of specific radiating elements of the system.

1 Claim, 19 Drawing Figures



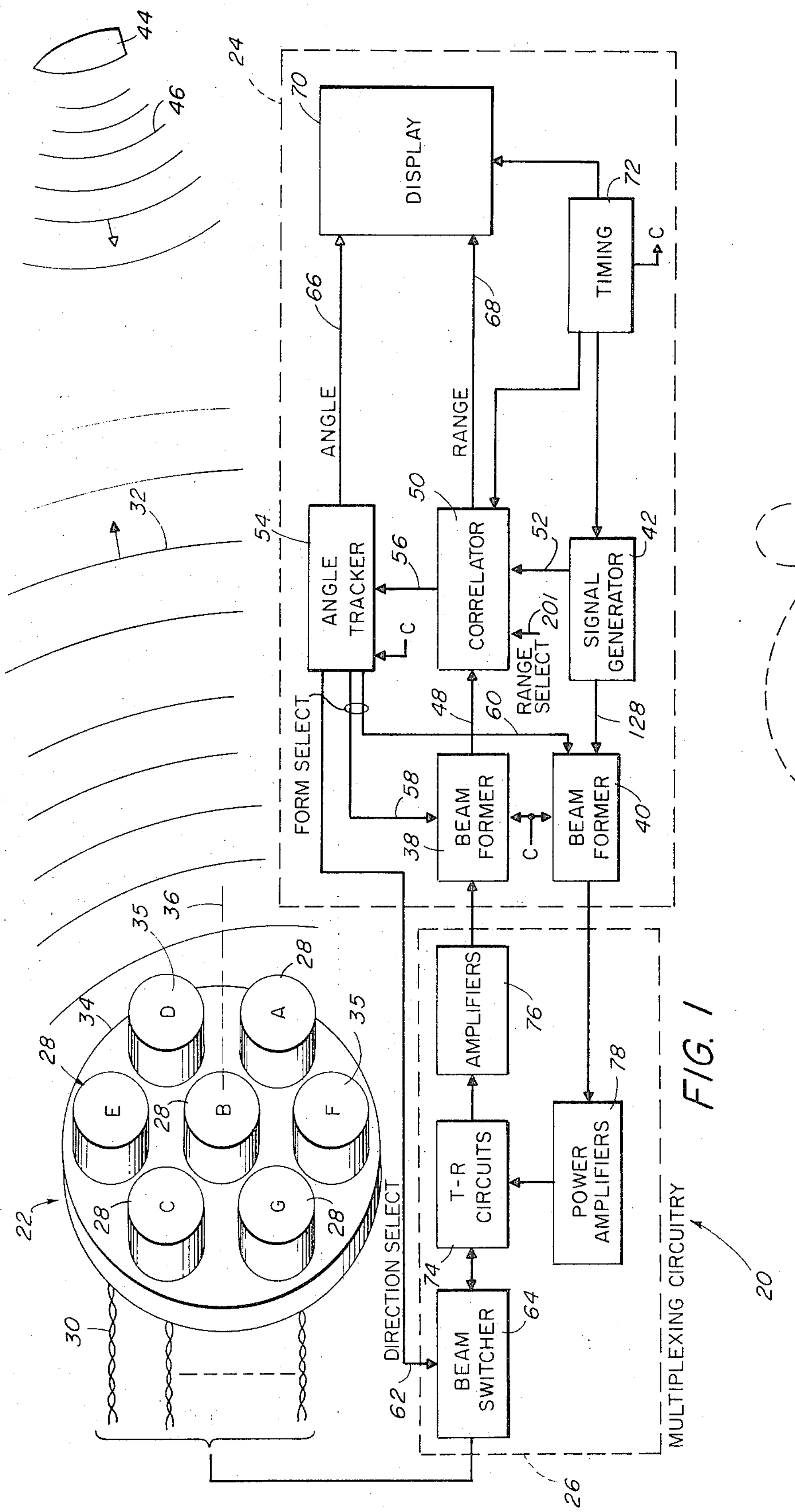

DISPLAY
TIMING
ANGLE
RANGE
ANGLE TRACKER
CORRELATOR
SIGNAL GENERATOR
RANGE SELECT
FORM SELECT
BEAM FORMER
BEAM FORMER
AMPLIFIERS
T-R CIRCUITS
POWER AMPLIFIERS
BEAM SWITCHER
DIRECTION SELECT
MULTIPLEXING CIRCUITRY
C
A
B
C
D
E
F
G
20
22
24
26
28
30
32
34
35
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
128
201

FIG. 1

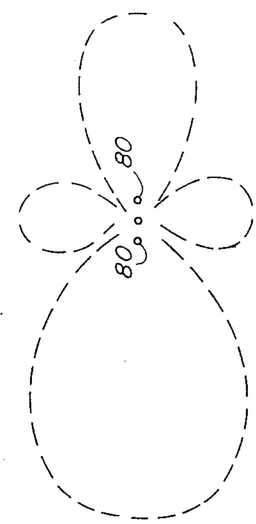

80
80

FIG. 2

FIG. 3

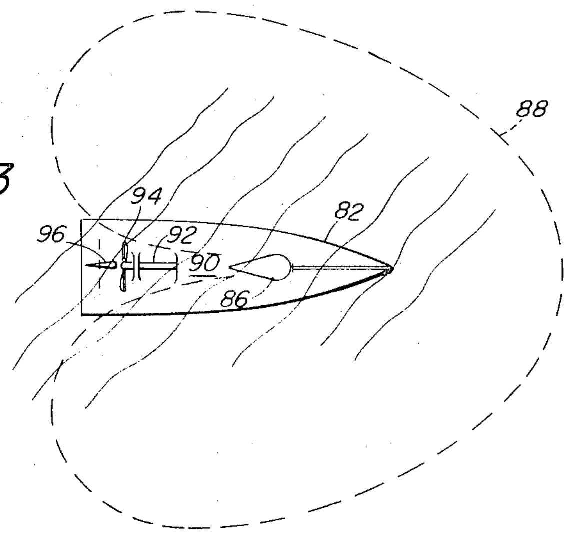


FIG. 4

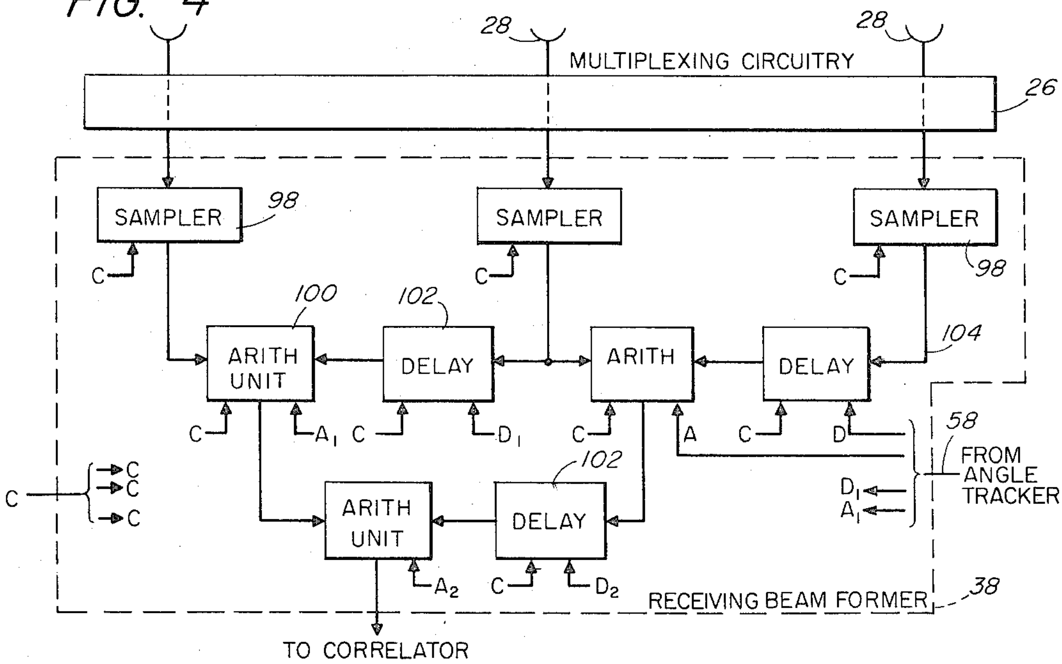
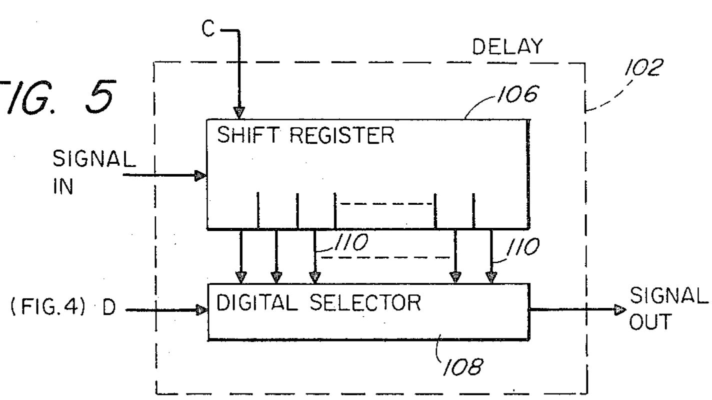


FIG. 5



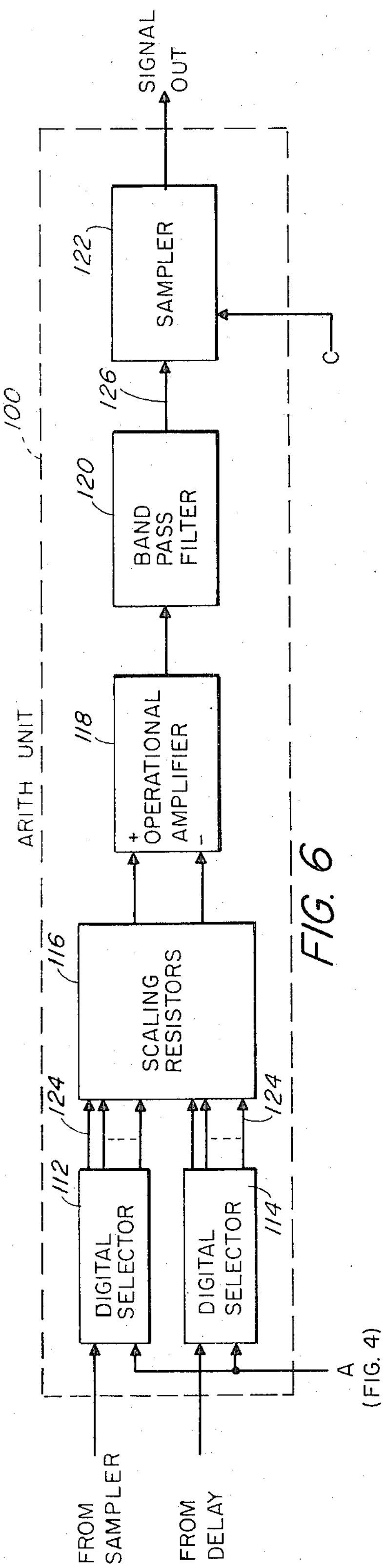

SIGNAL OUT
SAMPLER
BAND PASS FILTER
OPERATIONAL AMPLIFIER
SCALING RESISTORS
DIGITAL SELECTOR
DIGITAL SELECTOR
ARITH UNIT
FROM SAMPLER
FROM DELAY
A (FIG. 4)
C
100
112
114
116
118
120
122
124
126

FIG. 6

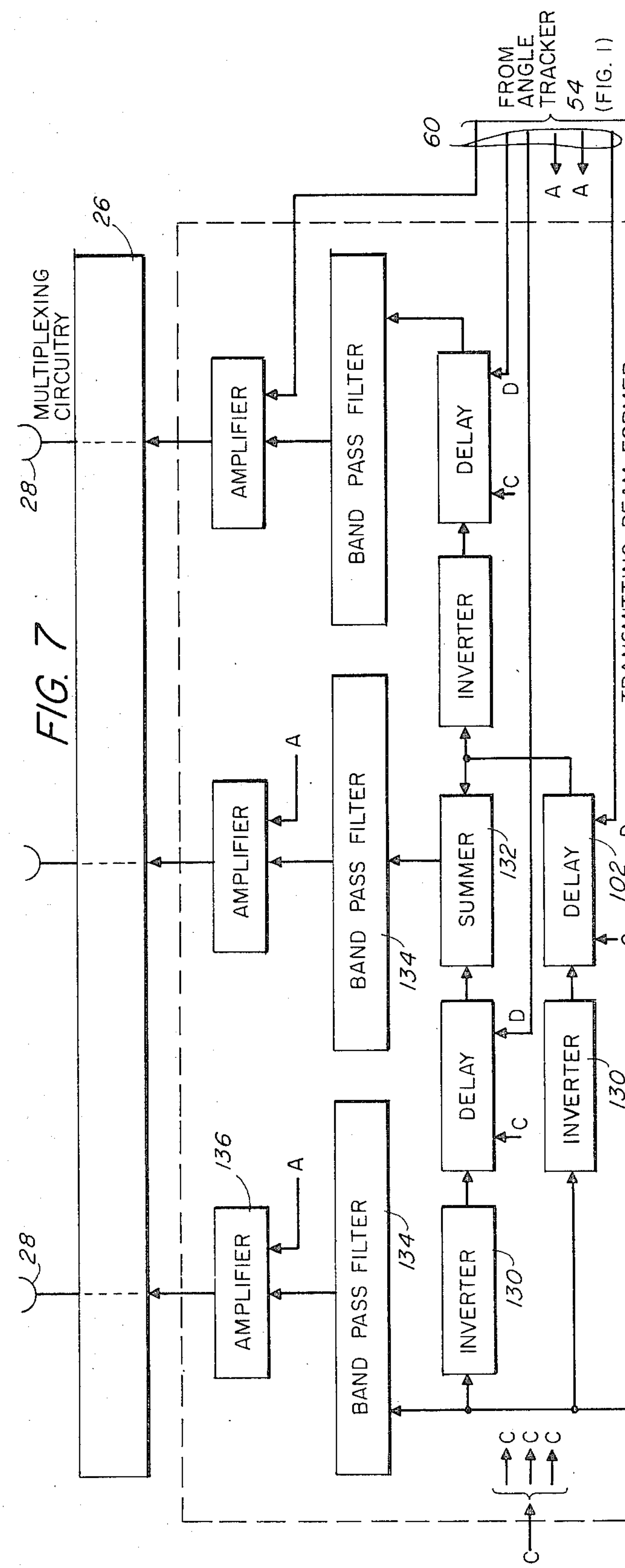

MULTIPLEXING CIRCUITRY
AMPLIFIER
BAND PASS FILTER
DELAY
INVERTER
SUMMER
TRANSMITTING BEAM FORMER
FROM ANGLE TRACKER 54 (FIG. 1)
FROM SIGNAL GEN 42 (FIG. 1)
26
28
40
60
102
130
132
134
136

FIG. 7

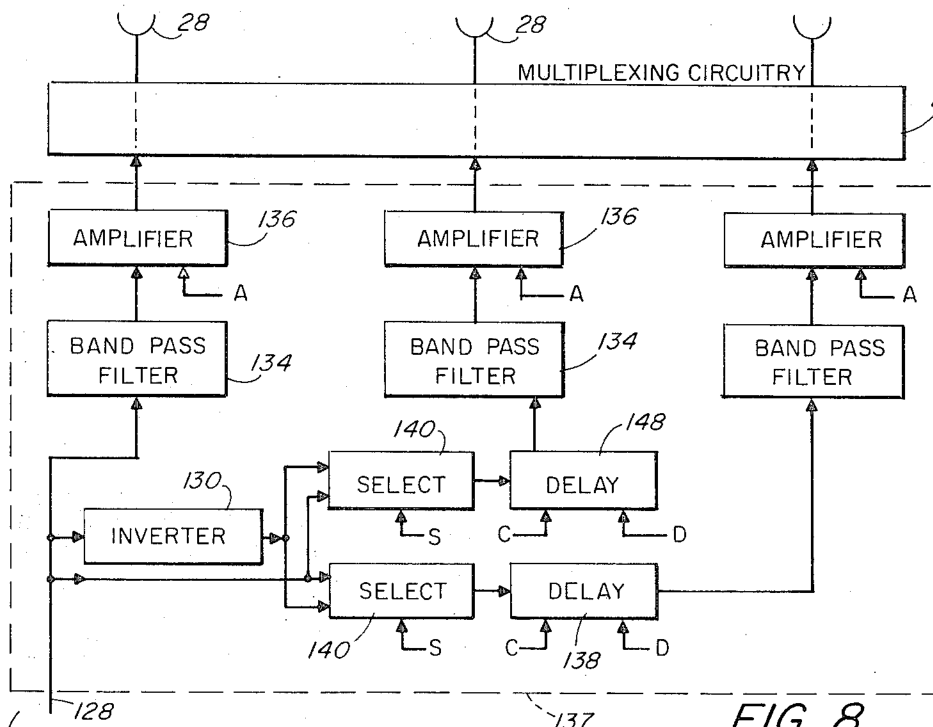


FIG. 8

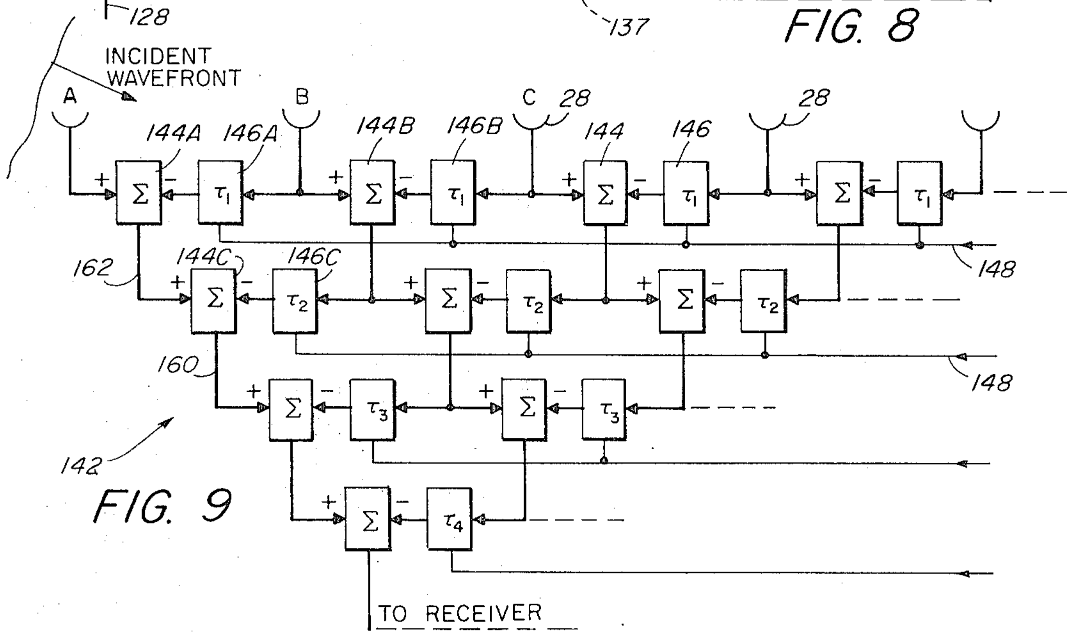


FIG. 9

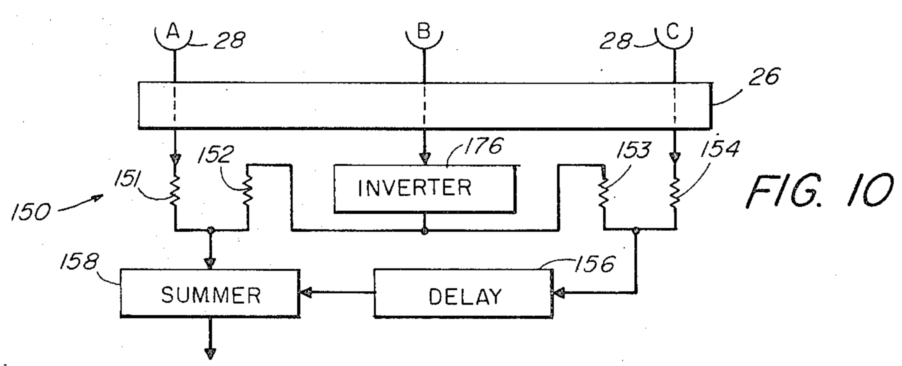


FIG. 10

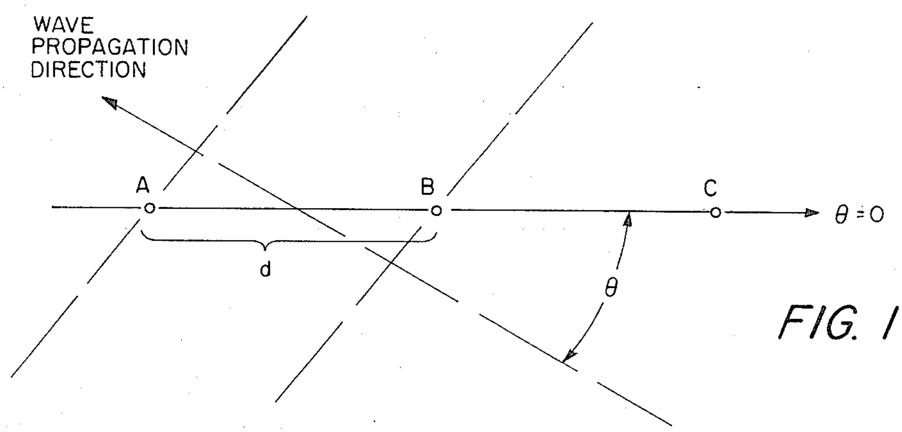


FIG. 11

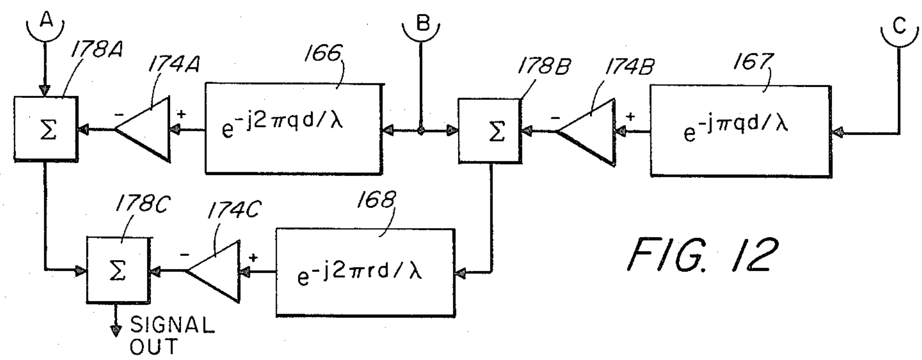


FIG. 12

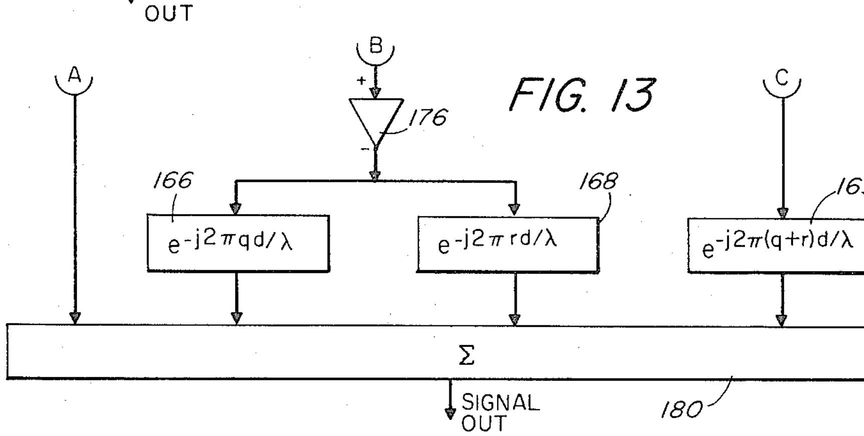


FIG. 13

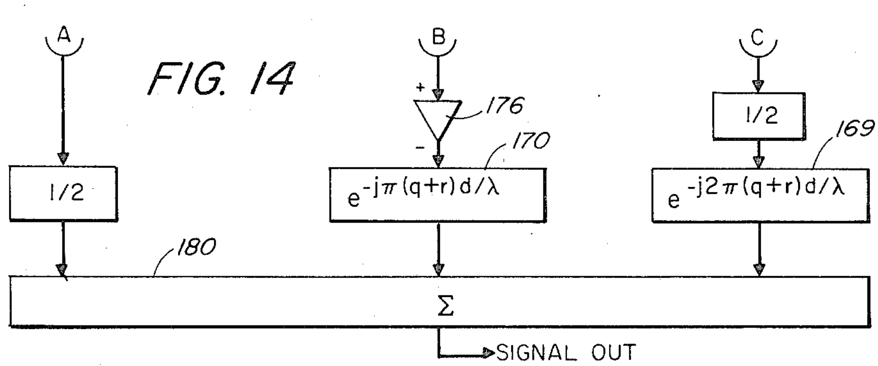


FIG. 14

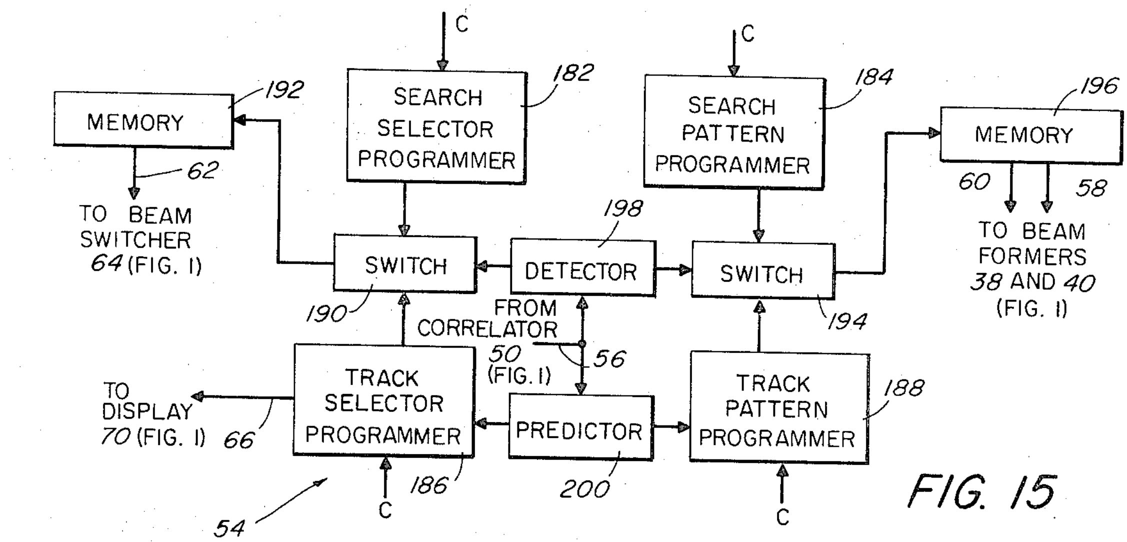


FIG. 15

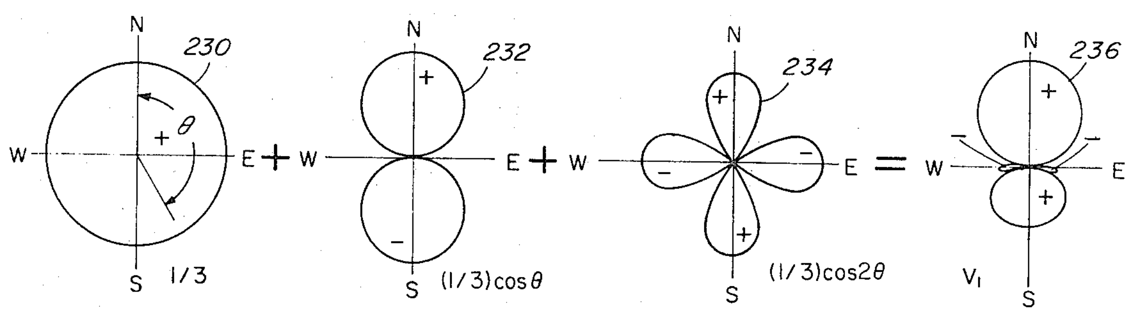


FIG. 17

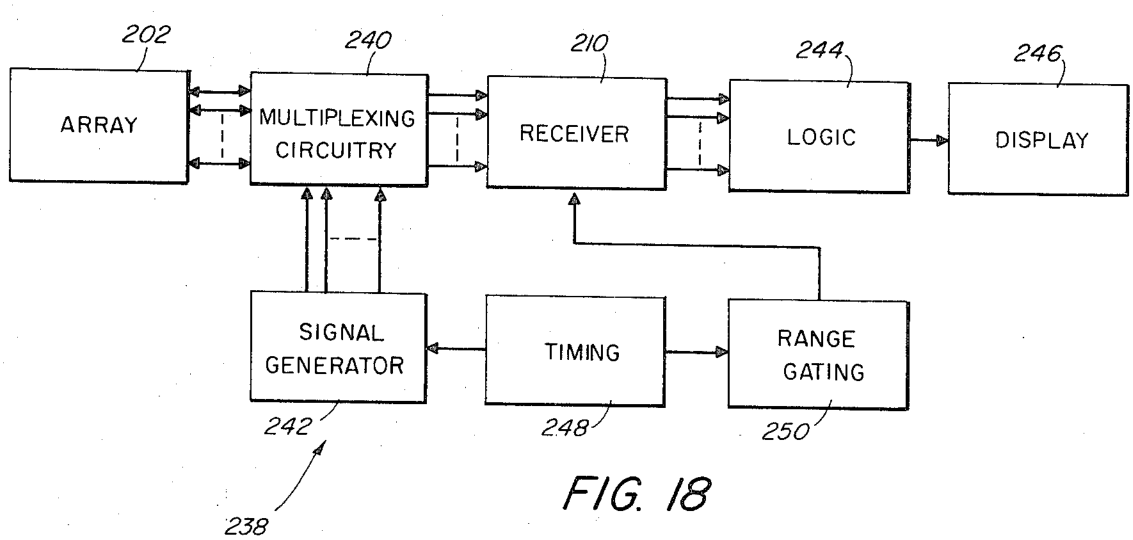
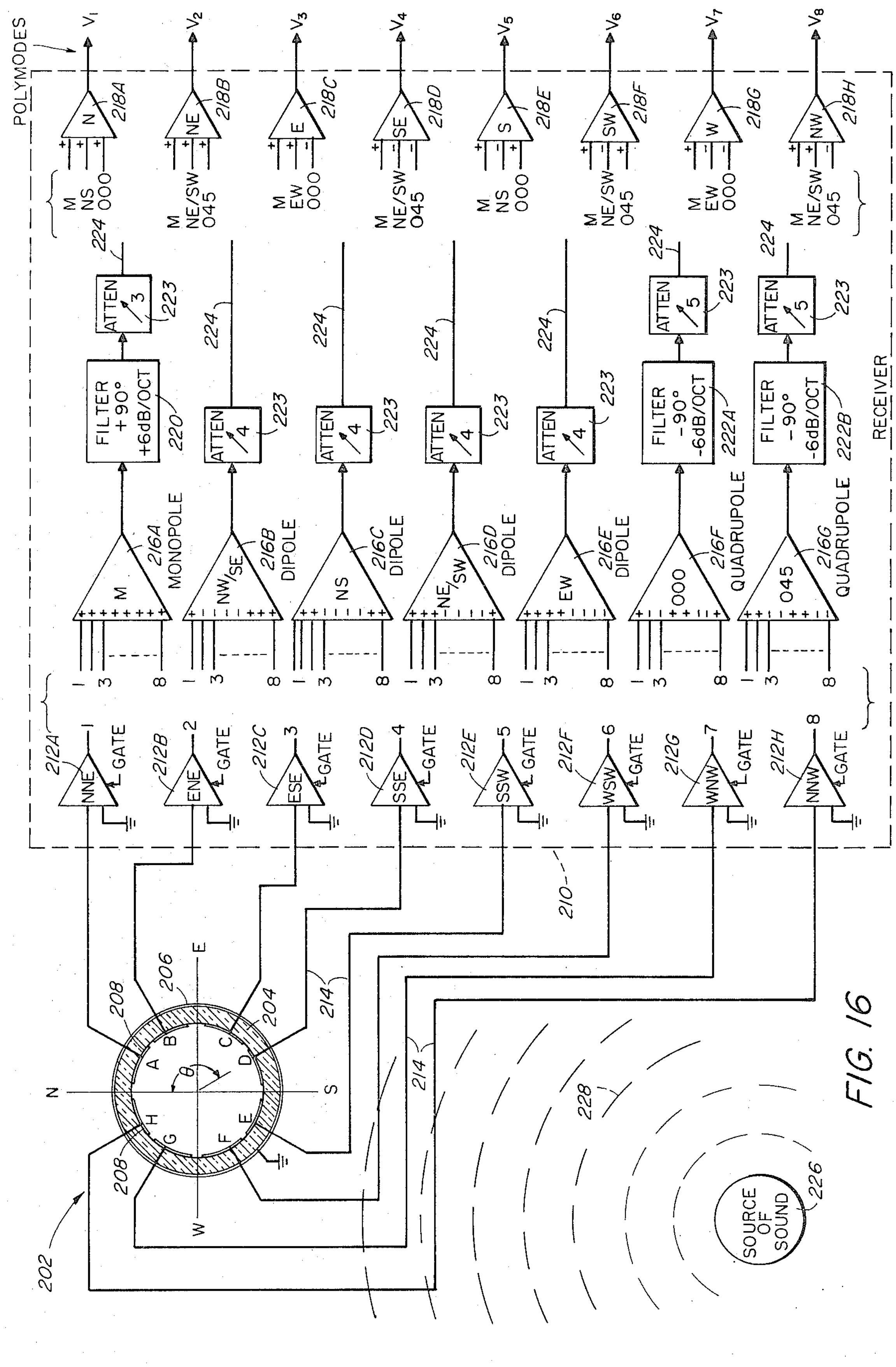


FIG. 18


POLYMODES
RECEIVER
SOURCE OF SOUND
226
228
202
204
206
208
210
214
N
S
E
W
A
B
C
D
E
F
G
H
θ
NNE
ENE
ESE
SSE
SSW
WSW
WNW
NNW
GATE
212A
212B
212C
212D
212E
212F
212G
212H
M
216A MONOPOLE
NW/SE
216B DIPOLE
NS
216C DIPOLE
NE/SW
216D DIPOLE
EW
216E DIPOLE
000
216F QUADRUPOLE
045
216G QUADRUPOLE
FILTER +90° +6dB/OCT
220
FILTER -90° -6dB/OCT
222A
FILTER -90° -6dB/OCT
222B
ATTEN
223
224
218A
218B
218C
218D
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218F
218G
218H
V1
V2
V3
V4
V5
V6
V7
V8

FIG. 16

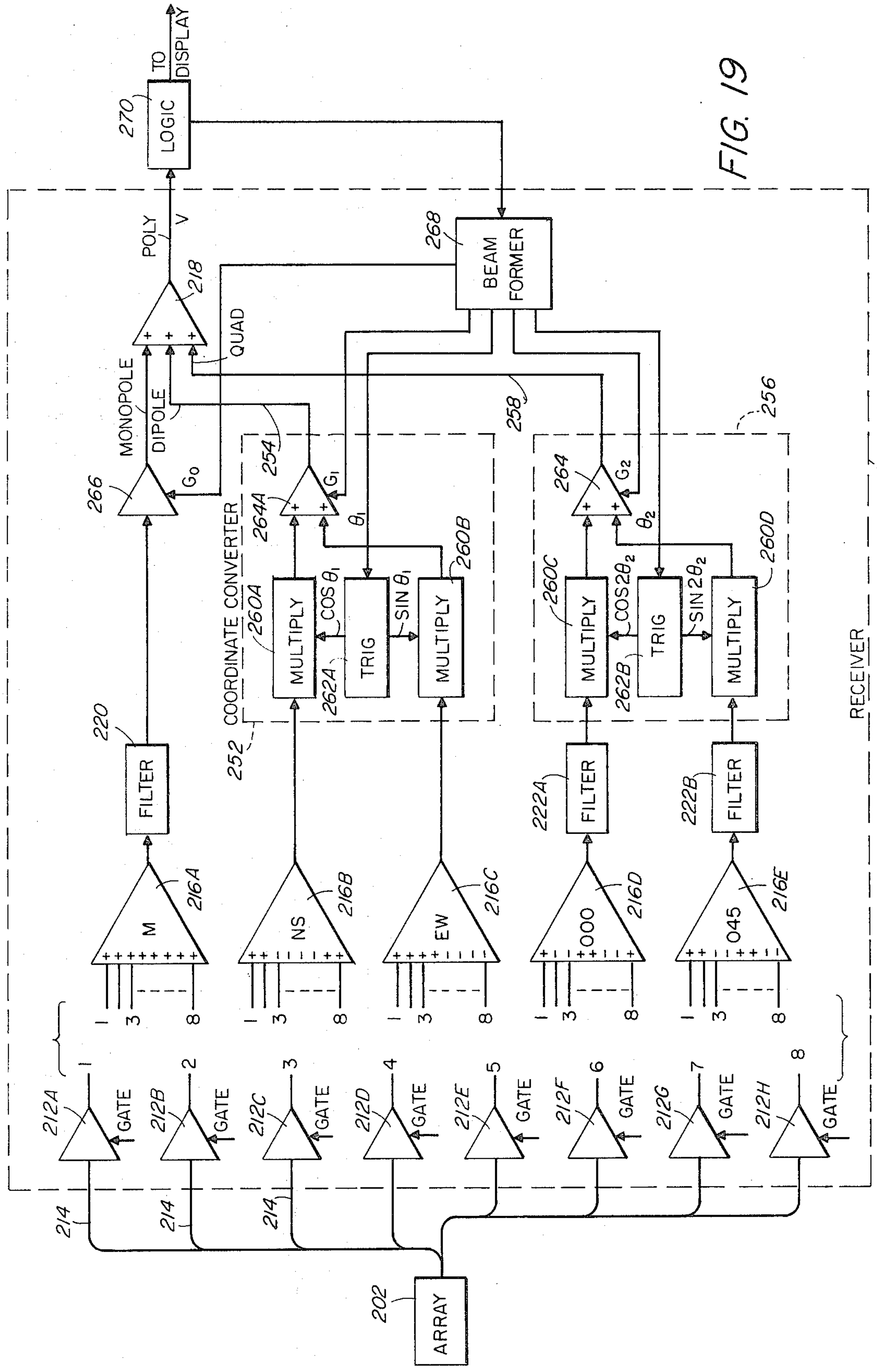
TO DISPLAY
LOGIC
270
POLY
V
218
268
BEAM FORMER
QUAD
MONOPOLE
DIPOLE
266
G_0
254
G_1
264A
258
256
264
G_2
θ_1
θ_2
COORDINATE CONVERTER
MULTIPLY
TRIG
COS θ_1
SIN θ_1
COS $2\theta_2$
SIN $2\theta_2$
260A
260B
260C
260D
262A
262B
252
250
RECEIVER
220
FILTER
222A
222B
M
NS
EW
000
045
216A
216B
216C
216D
216E
GATE
212A
212B
212C
212D
212E
212F
212G
212H
214
202
ARRAY

FIG. 19

SUPER-DIRECTIVE SYSTEM

BACKGROUND OF THE INVENTION

This invention relates to super-directive arrays and more particularly to a system including such an array wherein signals from adjacent elements of the array are delayed with respect to each other by preselectable amounts of delay.

Dipole and quadrupole radiators have been well known for many years in the fields of electromagnetic and acoustic radiators. These radiation patterns are obtained at all frequencies for which the interelement spacing and the size of an element are substantially smaller than a wavelength of the radiation transmitted or received by the radiator or array of radiators. For example, in the case of the electromagnetic dipole radiator, the two active regions of the radiator, namely, the positively and negatively charged termini of the radiating element are spaced apart, preferably less than one-quarter wavelength. In the case of the acoustic dipole radiator, a pair of monopole or omnidirectional radiating elements are placed close together, preferably less than one-quarter wavelength spacing, and the effect of a positive and negative pulsation is provided by subtracting the signal received by one of the elements from that of the other element. A directional sonar system employing omnidirectional and dipole radiation patterns is disclosed in U.S. Pat. No. 3,176,262 which issued to S. L. Ehrlich et al. on Mar. 30, 1965. Since the invention to be described hereinafter is particularly useful for acoustic radiators, the ensuing description will be directed towards acoustic systems while it is understood that these teachings are also applicable to electromagnetic systems.

It is evident that an array of closely spaced radiating elements is essential for the directional transmission and reception of acoustic energies at very low frequencies since a typical phased array antenna in which the radiating aperture is many wavelengths long would be prohibitively large in many applications utilizing frequencies as low as, for example, 10 hertz. However, even with higher frequencies, an array of closely spaced radiating elements may be useful since the directivity pattern of such an array is substantially invariant with the frequency of radiation for all radiations having a wavelength substantially larger than the overall dimensions of the array. At still higher frequencies where the wavelength becomes smaller than the array, the array may still be useful for specific applications such as where a multiple lobed beam pattern is desired, however, such a system tends to be of very narrow band width. It is also apparent that an array of closely spaced radiating elements is inherently useful in situations requiring small size and expense.

A problem arises in that such an array produces beam widths which are excessively wide for the standard techniques utilized in sonar tracking, for example, the tracking of an object submerged in the ocean. In addition, due to the subtraction of signals of adjacent elements as compared with the summation of such signals in the standard phased array antenna, the sensitivity of such an array, namely, the amplitude of the resultant signal produced by the array in response to an incident amplitude of sound pressure, is significantly reduced thereby increasing the unwanted effects of noise.

SUMMARY OF THE INVENTION

In accordance with the invention there is provided a system incorporating an array of radiating elements which overcome the aforementioned problems in the prior art to permit the use of such an array for communicating information by acoustic signals. In one embodiment providing for a polypole radiation pattern, the invention comprises a plurality of radiating elements each of which provides signals in response to incident acoustic energy, the radiating elements being intercoupled via delay lines and circuitry for combining the signals to permit the summing of such signals, the differencing of such signals and the scaling of such signals. In another embodiment utilizing three radiating elements, a simplification is presented which permits the use of a single delay line by connecting the radiating elements via summing resistors having values which provide for a scaling of the signal voltage of one radiating element relative to the signal voltage of the other radiating element; this provides, in the case of small phase angles, (less than approximately 20°), the equivalent of three delay lines. There is also disclosed a multiple element array including a switching circuit for selectively coupling groups of three radiating elements whereby a beam of acoustic radiation can be directed in any one of a plurality of directions by appropriately selecting the group of three elements. In addition there is disclosed the use of an angle tracking circuit interconnected with the switching circuit and the delay lines for operating the switching circuit and the delay lines to rotate a beam of radiation by means of the switching circuit and to alter the shape of the array directivity pattern by varying the amount of delay provided by each of the delay lines. The combination of signals from the radiating elements provides for polypole radiation patterns described mathematically by a power series and polymode radiation patterns described mathematically by a Fourier series. Means are also disclosed for digitizing the signal as by means of a sampling circuit which provides voltage states corresponding to logical 1's for the positive portions of the sinusoidal waveform of the acoustic wave and logical 0's for the negative portions of the wave. A digital delay line in the form of a shift register with multiple outputs is utilized in the digital embodiment as a variable delay line.

BRIEF DESCRIPTION OF THE DRAWINGS

The aforementioned features and other advantages of the invention are explained in the following description and taken in connection with the accompanying drawings wherein:

FIG. 1 is a view, partially isometric and partially diagrammatic, of the radiating system in accordance with the invention;

FIG. 2 shows, by way of example, one form of directivity pattern obtainable with the array of radiating elements of FIG. 1;

FIG. 3 shows the underside of a boat in the ocean with a radiating array of the invention mounted thereon, the figure further showing a cardioid radiating pattern with the notch in the direction of the propeller for inhibiting propeller noise;

FIG. 4 shows a block diagram of a beam former of the system of FIG. 1 for received signals;

FIG. 5 shows a block diagram of a delay unit of the beam former of FIG. 4;

FIG. 6 shows a block diagram of an arithmetic unit of the beam former of FIG. 4;

FIG. 7 shows a block diagram of a beam former of FIG. 1 for transmitted signals;

FIG. 8 is a block diagram of an alternative embodiment of the beam former of FIG. 7;

FIG. 9 is a diagrammatic presentation of a generalized beam forming system for a multiple element array;

FIG. 10 is a block diagram, partially schematic, of a simplified embodiment of the beam former of FIG. 4;

FIG. 11 is a diagram of a portion of an array illuminated by a wave of radiant energy for use in a mathematical description of the beam formers of FIGS. 4 and 9;

FIGS. 12, 13 and 14 represent successive mathematical transformations utilized in developing the simplified beam forming system of FIG. 10;

FIG. 15 is a block diagram of an angle tracking unit of the system of FIG. 1;

FIG. 16 is a schematic diagram of a polymode transducer and receiver of the invention;

FIG. 17 is a pictorial equation showing the combination of various receiving directivity patterns provided by the receiver of FIG. 16 to form a polymode directivity pattern;

FIG. 18 is a block diagram of a transmitting and receiving system incorporating the polymode array and receiver of FIG. 16; and

FIG. 19 is a block diagram of an alternate embodiment of the receiver of FIG. 16.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, there is shown a system 20 comprising, in accordance with the invention, an array 22 of radiating elements which is coupled to a transceiver 24 via multiplexing circuitry 26. Each of the radiating elements takes the form of a transducer 28 suitable for converting electrical energy signals on wires 30 to sonic energy signals indicated by waves 32, and for converting from sonic energy to electrical energy.

The transducers 28 are of a well-known construction typically comprising an electrostrictive ceramic material such as barium titanate and are suitably mounted upon a base plate 34 to serve as monopole radiators. The surface 34 of each transducer 28 pulsates to provide a directivity pattern having axial symmetry. Six transducers 28 have been arranged, in this embodiment of the invention, in a circle about a seventh transducer 28 at the center of the array 22. As will be described hereinafter, this arrangement of the transducers 28 in the array 22 is particularly useful for providing a variety of radiation patterns as well as a capability for steering beams of radiation about a central axis 36 which is normal to the base plate 34.

The transceiver 24 comprises a beam former 38 for forming the receiving beam for radiation incident upon the array 22 and a beam former 40 for forming the transmitted beam of radiation. In the transceiver 24 a signal generator 42 provides a signal suitable for transmission via the array 22 to a distant object such as a boat 44, and is coupled to the array 22 via the beam former 40 and the multiplexing circuitry 26. Detection of a signal such as an echo from the boat 44, indicated by waves 46, is accomplished by processing the output of the beam former 38 on line 48 by conventional means. Accordingly, the transceiver 24 utilizes a correlator 50 which correlates the received signal on line 48 with a replica of the transmitted signal provided on line 52 from the signal generator 42. Such a correlator may employ recirculating delay lines which may be implemented digitally by shift registers as is disclosed in U.S. Pat. No. 3,594,718 which issued to Charles I. Black et al. on July 20, 1971.

The transceiver 24 further comprises an angle tracker 54 which, in response to the correlator output on line 56, provides signals on lines 58 and 60 to the beam formers 38 and 40, as well as along line 62 to a beam switcher 64 for providing a desired shape to the directivity pattern of the array 22 and for switching the direction of a beam of radiation provided by the array 22. The beam switcher 64 comprises a well-known switching circuitry which may be either electrical or mechanical, such as a stepping switch for coupling individual ones of the transducers 28 to the beam formers 38 and 40, the specific coupling arrangement being in accordance with the signal provided on line 62. This switching of the beam, analogous to sequential lobing in the radar art, enables the angle tracker 54 to obtain information on the direction of radiation, such as the waves 46, incident upon the array 22. Angle data provided by the angle tracker 54 on line 56 and range data provided by the correlator 50 on line 68 are presented on a display 70 which may be of conventional form such as a cathode ray tube or a graphical display. The signal generator 42, correlator 50, angle tracker 54, display 70 and the beam formers 38 and 40 are coordinated by timing signals from the timing unit 72. The timing signals applied to the beam formers 38 and 40 and the angle tracker 54 are clock pulses indicated by the symbol C.

The multiplexing circuitry 26 comprises in addition to the beam switcher 64, a transmit-receive circuit 74 and amplifiers 76 and 78 for amplifying respectively the received and transmitted signals. The transmit-receive circuit 74 is of conventional form and may comprise, for example, a diode circuit such as is frequently utilized in sonar applications.

Referring now to FIG. 2, there is seen a typical directivity pattern achievable with a linear array of three radiating elements 80 which may be, for example, the transducers 28 of FIG. 1. In FIG. 2 the radiation pattern is that of a quadrupole radiator modified such that one lobe is substantially larger than any other lobe. The particular spacings between the radiating elements 80 and the signal delays to be applied between signals of these elements 80 for producing a specific radiation pattern will be disclosed hereinafter. Comparing the array 22 of FIG. 1 with the arrangement of radiating elements 80 of FIG. 2, it is apparent that any set of three transducers 28 arranged along a diameter of the array 22 correspond to the linear array of three radiating elements 80 of FIG. 2. Accordingly, the radiation pattern of FIG. 2 can be obtained with any three transducers 28 arranged along a diameter of the array 22. Furthermore, by selectively switching in any such set of three transducers 28 by means of the beam switcher 64, the radiation pattern of FIG. 2 can be rotated about the axis 36 of the array 22 of FIG. 1.

Referring now to FIG. 3 there is shown a bottom view of a boat 82 sailing through the ocean waters 84 and having an enclosure 86 mounted on the boat 82 in acoustic contact with the water, the enclosure housing the array **22** of FIG. **1**, not seen in FIG. **3**. The multiplexing circuitry **26** and the transceiver **24** of the system **20** are not shown in FIG. **3** but are carried within the boat **82**. The system **20** is seen providing a directivity pattern **88** having the general cardioid-type form with a notch **90** in the direction of the stern of the boat **82** so that noise caused by the movement of the ocean water **84** past the propeller shaft **92**, the propeller **94** and the rudder **96** is greatly attenuated. It is noted that the directivity pattern **88** differs from that of the typical phased array antenna in that there are no reduced level side lobes in the direction of the propeller **94** but rather the notch **90** which can be accurately positioned to exclude the propeller noise. This feature permits the use of the invention in a relatively high noise environment even though the sensitivity of the array **22** of FIG. **1** is substantially decreased when the signal from the transducers **28** are combined in a manner, to be described hereinafter, wherein the signals of adjacent transducers **28** are subtracted from each other to produce cardioid-type or polypole-type radiation patterns.

Referring now to FIG. **4**, there is seen a block diagram of the receiving beam former **38**. The beam former **38** may utilize conventional analog delay lines for delaying the signals between adjacent radiating elements of the array **22** of FIG. **1** or, alternatively, may employ digital techniques in the form of shift registers for providing this delay. In the preferred embodiment of the invention the beam former **38** utilizes digital techniques, and, accordingly, the beam former **38** comprises samplers **98** for sampling the signals of the transducers **28** indicated diagrammatically in FIG. **4**, arithmetic units **100** for combining the signals of the transducers **28** and delay units **102** for delaying the signals between the transducers **28**. The delay unit **102** and the arithmetic unit **100** will be more fully described with reference to FIGS. **5** and **6**.

The beam former **38** operates as follows. Signals received by the transducers **28** pass via the multiplexing circuitry **26** to respective samplers **98**. Each sampler is of conventional design and is driven by clock pulses received from the timing unit **72** of FIG. **2**. Each sampler **98** preferably comprises a switch or gate driven by the clock pulses for obtaining samples of the incoming signal, and a comparator (not seen in the figures) which produces an output pulse on line **104** when the sample of the incoming signal is above a preset threshold. To simplify this explanation, it is assumed that the incoming acoustic signal is a sinusoid and, accordingly, the value of this threshold is selected so that for each positive half cycle of the incoming sinusoidal signal, a succession of pulses having a logic state of 1 is provided along line **104**, and that during each negative portion of the sinusoid there is an absence of the pulses on line **104** or, equivalently, the 0 logic state is present on line **104**. The clock pulse frequency is greater than the frequency of the incoming signal by a factor of, for example, 1,024 so that a total of 1,024 samples can be taken during each cycle of the incoming signal. The 1,024 samples permit a 10-bit resolution of the phase of the incoming signal, namely, increments of approximately one-third degree.

Referring now to the block diagram of FIG. **5**, the delay unit **102** comprises a shift register **106** and a digital selector **108** (also known as a decoder or multiplexer switch). The shift register **106** has a single terminal in which the input signal is applied, and a plurality of output terminals on lines **110**, each of the lines **110** corresponding to one stage of the shift register **106**. The shift register **106** is driven by clock pulses, indicated by the letter C in the figure, with the result that each pulse of the input signal appears after successive increments of delay at successive ones of the output terminals on lines **110**, with each of these delay increments being equal to the interval between clock pulses. The digital selector **108** has multiple input terminals corresponding to each of the lines **110** and a single output terminal. A specific connection is made between one of the input terminals and the output terminal in accordance with a binary number applied at terminal D and provided by the angle tracker **54** as seen in FIG. **4**. Thus, the angle tracker **54** is able to select, via the digital selector **108**, a specific output terminal of the shift register **106** so that the delay unit **102** provides a desired amount of delay between the input and output signals of the delay unit **102**.

Referring now to the block diagram of FIG. **6**, the arithmetic unit **100** comprises digital selectors **112** and **114**, each of which is similar to and functions in a fashion analogous to the digital selector **108** of FIG. **5**. The arithmetic unit **100** further comprises a scaling unit **116**, an operational amplifier **118**, a band-pass filter **120** and a sampler **122** similar to the sampler **98** of FIG. **4**. The arithmetic unit **100** has two inputs, one providing a signal from the sampler **98** and the other providing a signal from the delay unit **102**, and combines these two signals to provide a single output signal. The two input signals may be combined by summing the two together by taking their difference or by first scaling the signals to combine a fraction of one with the other. This is readily accomplished by summing resistors (not seen in the figures) applied to the input terminals of the operational amplifier **118**; in this case; a multiplicity of such summing resistors of differing values are provided by the scaling unit **116**, with the digital selectors **112** and **114** interconnecting each input signal with any desired summing resistor. The digital selectors **112** and **114** provide the inverse function of the digital selector **108**, that is, each digital selector **112** and **114** has a single input and a multiplicity of outputs on lines **124** with a specific interconnection of one of the outputs to the input being provided in accordance with a binary number appearing at terminal A and provided by the angle tracker **54** as seen in FIG. **4**. The two input signals to the arithmetic unit **100** are in binary digital format and, after being combined by the operational amplifier **118**, are converted by the band-pass filter **120** to an analog signal on line **126**. The pass band of the filter **120** is selected to pass the frequency of the acoustic radiation incident upon the array **22** of FIG. **1** while excluding the sampling frequencies introduced by the samplers **122**. The analog signal on line **126** is then converted by the sampler **122** to a binary digital format to appear at the output terminal of the arithmetic unit **100**.

Referring now to FIG. **7**, there is shown a block diagram of the transmitting beam former **40** of FIG. **1**. The beam former **40** accepts a signal in sampled format on line **128** from the signal generator **42** of FIG. **1** and converts this signal into analog signals suitable for being transmitted via the transducers **28**. The beam former **40** comprises inverters **130**, delay units **102** previously described with reference to the receiving beam former **38**, a summer **132** and band-pass filters **134**.

The beam former **40** may utilize analog signals and analog delay lines, however, the preferred embodiment of the invention, as shown in FIG. **7**, utilizes digital delay units **102** with the aforementioned sampled or digital format of the signal on line **128**. Each of the three transducers **28**, namely, the left, the center and the right transducers **28**, receive separate signals in order to radiate energy having a desired directivity pattern. The amplitude of the signals for each of the transducers **28** is controlled by amplifiers **136** and in accordance with a signal provided at terminal A from the angle tracker **54** of FIG. **1**. To provide the signal for the left transducer **28**, the digital format signal on line **128** is passed through the band-pass filter **134** having a pass band centered at the frequency of the acoustic signal radiated by the transducers **28**; the pass band is sufficiently narrow to attenuate components of the sampling frequency so that only the baseband signal passes via the amplifier **136** and the multiplexing circuitry **26** to the transducer **28**. To provide the signal for the right transducer **28**, the digital format signal on line **128** is first applied to inverter **130**, then delayed by delay unit **102**, again inverted by a second inverter **130** and again delayed by a delay unit **102**, and is finally filtered by a band-pass filter **134** to remove all of the sampling frequency components thereby converting it to the baseband signal suitable for radiation from the right transducer **28**. Each of the inverters **130** is a digital inverter and converts a logic state of 1 to a logic state of 0 and vice versa. The reason for using two inverters as well as two delays will become apparent in a mathematical description of the operation to be provided hereinafter. Each of the delays **102** provides a suitable phase shift between the signals emanating from the right and left transducers **28** as is required for producing the desired directivity pattern. The center transducer **28** obtains its signal via the summer **132** which sums together the delayed signal provided by a pair of delay units **102** and the inverters **130**. It is evident that the diagram of FIG. 7 can be simplified, as shown in FIG. 8, however, the diagram of FIG. 7 parallels that of FIG. 4 and thus shows an arrangement suitable for forming a polypole radiation pattern just as the diagram of FIG. 4 is suitable for receiving a polypole radiation pattern.

Referring now to FIG. **8** there is shown an alternative transmitting beam former **137** which may be substituted in place of the transmitting beam former **40**. The beam former **137** is simpler than the beam former **40** in that the three delay units **102** of FIG. **7** have been replaced in FIG. **8** with two delay units **138** similar in operation to the delay units **102** but having different delays. In addition two selector switches **140** are provided to select either the signal on line **128** or the inverted form of the signal and thereby provide a more general synthesis of directivity patterns.

Referring now to FIG. **9** there is shown a schematic diagram of the arithmetic units and delay units of a beam former **142** which is similar to the receiving beam former **38** of FIG. **1** except that the beam former **142** is shown in a generalized form which is suitable for any number of radiating elements such as the transducers **28**. Arithmetic units **144**, some of which are further identified by the letters A-C, are shown providing the differences between signals of neighboring transducers **28** while delay units **146** are shown providing the appropriate delays. In the beam former **38** of FIG. **4**, the arithmetic units **100** are shown as being capable of forming either the sum or the difference of signals from neighboring transducers **28**, however, in FIG. **9** the arithmetic units are presumed to be forming only the difference and this is adequate for demonstrating one form of higher order system in which any number of elements may be utilized for multiple radiation patterns. It is also noted that the delay units **146** in the first row of the diagram of FIG. **9** are of equal value as is indicated by the symbol τ_1; similarly the values of the delays provided by the delay units **146** in the second row of the diagram are of equal value as is indicated by the symbol τ_2, and that furthermore, there is one less delay in the second row than in the first row of the diagram. Similar comments apply to the third and subsequent rows of the diagram. Control lines **148** select the desired amount of delay, each control line **148** being energized from a suitable source similar to the angle tracker **54** of FIG. **1**.

Referring now to FIG. **10** there is shown a simplified embodiment of a beam former **150** which may be used in lieu of the receiving beam former **38** of FIG. **1** in the situation wherein a polypole radiation pattern is to be received. The beam former **150** comprises four resistors **151–154**, a delay unit **156** and summer **158**. The appropriate values for the resistors and the value of delay of the delay unit **156** will be derived in terms of the values of delay utilized in the beam former **38** of FIG. **4** in the ensuing mathematical analysis.

The directivity patterns obtainable with a pair of radiating elements, such as the elements A and B seen diagrammatically in FIG. **11**, may readily be expressed mathematically. A plane wave of radiation having an angular frequency ω is impinging upon the array of the two elements A and B at an angle θ to an axis of the array. Each radiating element is an omnidirectional hydrophone and has a sensitivity of K volts/microbar. If a pressure of 1 microbar is assumed, the voltages provided by each element in response to the impinging radiation is, in exponential notation,

$$V_A = Ke^{j\omega t}e^{j\pi(d/\lambda)\cos\theta} \qquad (1)$$

and

$$V_B = Ke^{j\omega t}e^{-j\pi(d/\lambda)\cos\theta} \qquad (2)$$

respectively for the elements A and B where the point of zero phase is taken for convenience at the midpoint between the two elements and where d is the interelement spacing. The sum of these two voltages forms a monopole v_M given by

$$v_M = 2Ke^{j\omega t}\cos[\pi(d/\lambda)\cos\theta] \approx 2Ke^{j\omega t} \qquad (3)$$

the approximation being valid for small values of d/λ such that

$$\pi(d/\lambda)\cos\theta \leq 20°$$

approximately. The difference of these two voltages is proportional to the pressure gradient and forms a dipole v_D given by

$$v_D = 2jKe^{j\omega t}\sin[\pi(d/\lambda)\cos\theta] \approx 2jK\pi(d/\lambda)e^{j\omega t}\cos\theta \qquad (4)$$

the approximation being valid similarly for small values of the argument $\pi(d/\lambda)\cos\theta$. A cardioid response is obtained by combining the monopole and dipole patterns $(j\pi d/\lambda)v_M + v_D$ wherein the factor $(j\pi d/\lambda)$ is the same as that seen in the expression for v_D in Equation 4. The cardioid expression contains a term invariant with θ and a term dependent on θ. A quadrupole radiation pattern has a term dependent on $\cos^2\theta$ or $\cos 2\theta$. The general representation of the voltage $p_N(\theta)$ provided by the beam pattern of a polypole line array of (N + 1) elements may be expressed as

$$p_N(\Theta) = \sum_{n=0}^{N} a_n \cos^n \Theta \qquad (5)$$

where $\theta = 0°$ and 180° along the endfire directions of the line, and where the a_n are normalized such that

$$\sum_{n=0}^{N} a_n = 1 \qquad (6)$$

Since reciprocity applies, the same expression may be utilized for a transmitting array.

Considering the case of the three elements A, B and C in the array of FIG. 11 and, for convenience, setting the point of zero phase at the radiating element nearest the impinging wave, namely, element A, the output voltages are respectively

$$v_A = Ke^{j\omega t} \qquad (7)$$

$$v_B = Ke^{j\omega t}e^{-j2\pi(d/\lambda)\cos\theta} \qquad (8)$$

$$v_C = Ke^{j\omega t}e^{-j4\pi(d/\lambda)\cos\theta} \qquad (9)$$

These voltages are readily combined in accordance with the invention by reference to FIG. 9 where the array is understood to contain only the first three transducers **28** further identified by the letters A, B and C. Three arithmetic units **144A–C** and three delay units **146A–C** are utilized with the three element array and the combined output voltage appears on line **160**. It is presumed for the purposes of this calculation that each arithmetic unit **144** forms the difference of two voltages without performing any scaling. Each of the delay units **146** are presumed for the purposes of this calculation to be analog delays (for ease of mathematical representation) with the delays and resultant phase shifts expressed in terms of the interelement spacing *qd* and *rd* where *q* and *r* are constants, typically fractions. Thus, letting τ_1 and τ_2 be delays equivalent to the incident wave propagating through distances *qd* and *rd* respectively, the voltage present on line **162** is given by

$$V_{162} = 2jKe^{j\omega t}\sin[\pi(d/\lambda)(q+\cos\theta)]e^{-j\pi(d/\lambda)(q+\cos\theta} \qquad (10)$$

the voltage on line **164** is given by

$$V_{164} = 2jKe^{j[\omega t - 2\pi(d/\lambda)\cos\theta]}\sin[\pi(d/\lambda)(q+\cos\theta)]e^{-j\pi(d/\lambda)(q+\cos\theta)} \qquad (11)$$

and the voltage on line **160** is given by

$$V_{160} = -4Ke^{j[\omega t - \pi(d/\lambda)(r+q+2\cos\theta]}\sin[(\pi d/\lambda)(q+\cos\theta)]\sin[(\pi d/\lambda)(r+\cos\theta)] \qquad (12)$$

For small values of the arguments $\pi(d/\lambda)(q+\cos\theta)$ and $\pi(d/\lambda)(r+\cos\theta)$ in the expression for the voltage on line **160**, the peak amplitude of this voltage may be approximated by

$$V_p = 4K(\pi d/\lambda)^2(q+\cos\theta)(r+\cos\theta) \qquad (13)$$

or

$$V_p = 4K(\pi d/\lambda)^2(1/p)[p\,qr + p\,(q+r)\cos\theta + p\cos^2\theta] \qquad (14)$$

where $(1/p)$ serves a normalization factor $(1/p = qr + q + r + 1)$ in Equation 14, and in which the bracketed term is recognized as a power series such as the polypole representation of Equation 5. It is also interesting to note that for small values of these arguments the voltages on the lines **162** and **164** are approximated by the sum of a monopole and a dipole radiation pattern, the monopole being provided by the factor q and the dipole being provided by the factor $\cos\theta$.

The three constants pqr, $p(q+r)$ and p may be given any desired values for providing a desired directivity pattern to the three element array. In particular, a maximum directivity, in the sense of a maximum fraction of the overall radiant energy being found in the main lobe, is obtained in the three element case for the following values, namely,

$$\left.\begin{aligned} pqr &= -1/6 \\ p(q+r) &= 1/3 \\ p &= 5/6 \end{aligned}\right\} \qquad (15)$$

for which

$$\left.\begin{aligned} q &= -0.29 \\ r &= 0.69 \end{aligned}\right\} \qquad (16)$$

The minus sign in front of q simply means that the delay units **146A–B** should provide a time advance or equivalently, the delay units **146A–B** need be placed on the opposite input ports of the arithmetic units **144A–B** respectively so that a delayed voltage from element A is combined with an undelayed voltage from the element B, and similarly, with respect to elements B and C.

The preceding mathematical development also applies to the beam former **38** of FIG. **4** in the case where the arithmetic units **100** perform simply a subtraction operation as did the arithmetic unit **144** of FIG. **9.** In such a case, the simplified beam former **150** of FIG. **10** closely approximates the beam former **38** and may be substituted in its place as will now be seen.

Referring now to the signal flow diagrams of FIGS. **12, 13** and **14,** the simplified configuration of the beam former **150** of FIG. **10** is now derived. There are provided in FIGS. **12–14** delay units **166–170,** and in each delay unit the exponential phase factor of the preceding mathematics is shown. The radiating elements are identified as in FIG. **9** by the letters A, B and C. Inverters **174A–C** are provided in FIG. **12,** and each applies a 180° phase shift to a sinusoidal signal waveform applied thereto from delay units respectively **166–168.** These inverters **174A–C** will be replaced by inverter **176** in FIGS. **13** and **14.** Summers **178A–C** in FIG. **12** combine the various signals by adding them together, the subtraction of FIG. **9** being accomplished by the use of the inverters **174A–C.** In FIGS. **13** and **14,** these summers **178A–C** will be replaced by summer **180.**

The beam former of FIG. **12** is functionally equivalent to that portion of the generalized beam former of FIG. **9** comprising the first three radiating elements A–C and the delay units **146A–C** described above with reference to FIG. **9**; and the preceding mathematics applies also to FIG. **12.** In FIG. **13** the delays presented to a signal from radiating element C by the delay units **167** and **168** have been combined into a single delay provided by the delay unit **169,** and the delayed and inverted signals from radiating element B are now shown by an equivalent representation wherein inverter **176** replaces the inverters **174A** and **174C.** Since, in the FIG. **13** a single delay unit, namely, delay unit **169,** provides all of the delay for the radiating element C, the summing together of the various signals can now be accomplished with a single summer, the summer **180.**

The two delays provided by delay units **166** and **168** in FIG. **13** can be combined into the single delay of delay unit **170** of FIG. **14** in the following manner. In summing together the signals of the delay units **166** and **168,** it is seen that the exponential delay terms add (since the two signals are otherwise equal and may be factored out) with the result

$$e^{-j2\pi qd/\lambda} + e^{-j2\pi rd/\lambda} = 2\cos[\pi(r-q)d/\lambda]e^{-j\pi(q+r)d/\lambda} \approx 2e^{-j\pi(q+r)d/\lambda} \quad (17)$$

where $\pi(r-q)d/\lambda$ is small. The factor of 2 is provided for in the diagram of FIG. **14** by scaling the signals of the elements A and C by a factor of one-half.

FIG. **10** is readily seen to be equivalent to FIG. **14** since the resistors **151–154** provide for the scaling of one-half, these resistors being of equal value, and the inverter **176** as well as the amplifiers of the multiplexing circuitry **26** function as voltage sources. With respect to the signal from element A, the signal splits between the resistors **152** and **153** so that one-half goes to the summer **158** and one-half goes to the delay unit **156.** Thus, at the output of the summer **158** there appears the following combination of delay factors

$$1/2e^{-j2\pi(q+r)d/\lambda} + \tfrac{1}{2} = \cos[\pi(q+r)d/\lambda]e^{-j\pi(q+r)d/\lambda} \approx e^{-j\pi(q+r)d/\lambda} \quad (18)$$

where $\pi(q+r)d/\lambda$ is small. The final expression in the above equation is seen to be the delay factor in the delay unit **170** of FIG. **14.**

Referring now to the block diagram of FIG. **15,** the angle tracker **54** comprises four programming units, respectively, a search selector programmer **182,** a search pattern programmer **184,** a track selector programmer **186,** and a track pattern programmer **188,** a switch **190** for selectively coupling the programming units **182** and **186** to a memory **192,** and a switch **194** for selectively coupling the programming units **184** and **188** to a memory **196.** The angle tracker **54** further comprises a detector **198** and a predictor **200** both of which are responsive to signals on line **56** from the correlator **50** of FIG. **1,** the detector **198** actuating the switches **190** and **194,** and the predictor adjusting the programs of the track selector programmer **186** and the track pattern programmer **188.**

In operation, the detector **198** senses the magnitude of the correlator signal on line **56** to determine the presence of a distant source of sound such as the reflected waves **46** from the boat **44** in FIG. **1.** The detector **198** has a preset threshold for determining that such a distant source of sound is or is not present. When no such source of sound is present, the switch **190** couples the search selector programmer **182** to the memory **192,** and the switch **194** couples the search pattern programmer **184** to the memory **196.** The memory **192** stores data with respect to specific ones of the transducers **28** of FIG. **1** which are to be coupled by the beam switcher **64** for orienting the radiation directivity pattern of the array **22** in a specific direction. The search selector programmer **182** provides a succession of directions, in response to the clock pulses at terminal C, for redirecting the directivity pattern of the array **22** for searching for a distant source of acoustic radiation. These directions are sent from the search selector programmer **182** via the switch **190** to the memory **192** which, in response thereto, provides signals along line **62** for operating the beam switcher **64** to couple the appropriate ones of the transducers **28.** In a similar manner, the search pattern programmer **184** sequentially selects specific shapes for the directivity pattern during each orientation of the directivity pattern as provided by the beam switcher **64** to aid in the searching. Accordingly, the search pattern programmer **184** designates a specific shape via the switch **194** to the memory **196** which, in response thereto, commands the appropriate set of delays and scaling factors for the beam formers **38** and **40** of FIG. **1,** these commands being transmitted in the form of digital signals on the lines **58** and **60.**

When the detector **198** determines that a suitable source of acoustic radiation is present, it actuates the switches **190** and **194** to couple the track selector programmer **186** to the memory **192,** and the track pattern programmer **188** to the memory **196.** The track selector programmer **186** continually reorients the directivity pattern of the array **22** of FIG. **1** so that the source of acoustic radiation is present on alternating sides of a null in the directivity pattern, this providing effectively a tracking error signal analogous to the tracking error signal developed by a monopulse feed in a radar antenna. Similarly, the track pattern programmer **188** commands the beam formers **38** and **40** via the switch **194** and the memory **196** to adjust the directivity pattern to provide a shape more amenable to tracking the source of radiation.

The predictor **200** monitors the angle coordinates of successive positions of the source of radiation and instructs the track selector programmer **186** to reorient the directivity pattern when the source of radiation tends to move away from the null in the directivity pattern. When the source of radiation moves an angular distance smaller than an angular increment that can be provided by the beam switcher **64**, the predictor **200** commands the track pattern programmer **188** to move the null of the directivity pattern to accommodate the angular movement of the source of radiation rather than to command the track selector programmer **186** to update the orientation of the directivity pattern. The average angular orientation of the null in the directivity pattern corresponds to the angular coordinate of the source of radiation, and this information is transmitted from the track selector programmer **186** along line **66** to the display **70** of FIG. **1.** To facilitate discrimination between targets of differing ranges from the array **22** of FIG. **1,** the correlator **50** of FIG. **1** is provided with a range gate, not seen in the figures, which, in response to a signal from the timing unit **72,** passes only those pulses on line **56** corresponding to a radiation source at the desired range, this range being selected by a manual control provided on line **201** in FIG. **1.**

It is also apparent that while the preceding discussion has described the implementation of a directivity pattern formed by a linear array of three of the transducers **28** of FIG. **1,** it is apparent that four or more of the transducers **28** can be switched into the circuit to further tailor the directivity pattern to a desired shape so that it is possible to keep a null of the directivity pattern oriented towards the stern of the boat **82** to reduce the effects of propeller noise. It is also apparent that a cylindrical array of the transducer elements **28** can be provided by coupling all of the transducers **28,** except for the central transducer **28,** to the beam formers **38** and **40.** Such an interconnection of the transducers **28** with the beam formers **38** and **40** can be accomplished, for example, by coupling together the pair of the transducers **28** labeled A and D, the pair of transducers labeled F and E, and the pair of transducers labeled E and C with these three pairs of transducers **28** being connected to the beam formers **38** and **40** in lieu of the previous connections of the transducers indicated earlier in FIG. **9** with reference to the transducers A, B and C.

The description of the preferred embodiment of the invention, hereinbefore presented, provided for an implementation of the expression for a polypole radiation pattern as given by Equation **5.** An analogous embodiment of the invention will now be presented with reference to FIGS. **16–18** for providing a polymode radiation pattern given by Equation 19

$$p_N(\Theta) = \sum_{n=0}^{N} b_n \cos n\Theta \qquad (19)$$

which is readily seen to be of the same form as Equation 5 except that the summation is seen to be a Fourier series rather than a power series. For the three element array considered in FIG. **2,** or the eight element array to be described in FIG. **16,** the Fourier series of Equation 19 can readily be converted by trigonometric identities to the power series of Equation 5. Accordingly, the terms polypole and polymode are seen to be convenient terms for describing the mathematical series representation of multiple mode types of radiation patterns.

Referring now to FIG. **16,** there is seen a schematic diagram of an alternative embodiment of the invention showing an array **202** of radiating elements which are in the form of a cylindrical radiator having inner and outer concentric metallic electrodes located on the inner and outer surfaces of a ceramic cylinder **204.** The outer electrode is identified by the numeral **206** while the inner electrode is segmented into eight segments, each of which are insulated from each other and are identified generally by the numeral **208** with specific segments being further identified by the letters A–H. In the most general form the array is of spherical or spheroidal shape; however, the preferred practical configuration is cylindrical when, for example, elevation angles are secondary to azimuthal angles.

The array **202** is shown coupled to a receiver **210** having eight preamplifiers which will be identified generally by the numeral **212** with individual ones of these preamplifiers **212** being further identified by the letters A–H which correspond respectively to the eight inner electrode segments **208**A–H. The inner electrode segments **208** are coupled to their respective preamplifiers **212** via wires **214.** Each of the preamplifiers **212** are also identified in the figures by legends such as NNE meaning north-by-northeast and WSW means west-by-southwest. A coordinate axis indicating the directions north, east, south and west is also seen overlaid upon the array **202.**

The receiver **210** further comprises a first set of operational amplifiers **216** and a second set of operational amplifiers **218** with individual ones of these amplifiers being identified respectively by **216**A–G and **218**A–H. A filter **220** is provided at the output of the operational amplifier **216**A and filters **222**A–B are provided at the outputs of the operational amplifiers respectively **216**F–G. Adjustable attenuators **223** are coupled to the outputs of the filters **220, 222**A and **222**B as well as to the outputs of the amplifiers **216**B–E for scaling the respective signals, these attenuators being further identified by the letters A–G corresponding respectively to the amplifiers **216**A–G. The operational amplifiers **216** are further identified by legends such as the legend M representing a monopole or an omnidirectional radiation pattern, NW/SE representing a dipole radiation pattern oriented with its axis running from northwest to southeast, 000 which identify a quadrupole radiation pattern having its reference axis at an angle of 0° (along the north-south axis) with respect to the array **202,** and 045 which represents a quadrupole radiation pattern having its reference axis inclined at an angle of 45° with respect to the array **202.** Each of the preamplifiers **212** is connected to all of the operational amplifiers **216,** however, for purposes of simplifying the drawing, these interconnections are indicated by means of the numerals 1–8 identifying the output terminals of the preamplifiers **212** and the corresponding numerals 1–8 at each of the eight input terminals to each of the seven operational amplifiers **216.** As is well known, operational amplifiers are typically provided with a positive input and a negative input with summing resistors connecting with both the positive and the negative inputs to provide an algebraic combination in which a plurality of signals may be summed together and subtracted from a second plurality of signals which are summer together.

The filters 220 and 222A–B serve as equalizing networks to equalize the frequency response of the omnidirectional pattern and the frequency response of the quadrupole pattern with that of the dipole pattern. As is well known from the mathematics of dipole patterns in acoustic systems, the receiving frequency response of ceramic transducers for frequencies below resonance tends to rise at a rate of 6 dB/oct (decibles per octave) change in frequency. Accordingly, the omnidirectional pattern which has a flat frequency response below resonance is passed through the filter 220 which may be, for example, a lead network, introducing a phase shift of +90° and having a frequency response of +6 dB/oct. Since quadrupole radiating patterns have a frequency response for frequencies below the second order mode resonance frequency of the array 202, wherein the amplitude of signals provided by the amplifiers 216F and 216G rises at a rate of +12 dB/oct, each of the filters 222A–B which may be, for example, a lag network, provide a phase shift of −90° and a frequency responsivity of −6 dB/oct. Thus the signals on each of the lines 224 are characterized by a frequency responsivity which varies at the rate of +6 dB/oct for all frequencies below the resonance region of the array 202. In the situation where a source of sound 226 transmits sound waves 228 towards the array 202, the sound waves 228 having become substantially planar waves in the vicinity of the array 202, the array 202 is built with a diameter which is sufficiently smaller than the wavelength of the waves 228 so that the frequency of these waves is below the resonance region of the array 202.

Each of the lines 224 is connected to at least some of the operational amplifiers 218 but not necessarily all of these amplifiers. Here again, in order to simplify the drawings, the interconnections of individual ones of the lines 224 are indicated by legends affixed to each of the inputs of the respective operational amplifiers 218A–H. Thus, with respect to the operational amplifier 218A, the omnidirectional signal provided by the filter 220 is supplied to one input, the NE/SW dipole signal provided by the operational amplifier 216D is applied to a second input, and the quadrupole signal provided by the filter 222A is applied to the third input of the operational amplifier 218A. As is indicated by the plus signs adjacent each input of the operational amplifier 218A, each of these inputs are summed together to give a voltage V1 which is the voltage associated with one polymode directivity pattern for receiving the waves 228, as will now be described with reference to FIG. 17.

Referring now to FIG. 17, there is shown a schematic representation of the combination of an omnidirectional radiation pattern 230, a dipole radiation pattern 232 and a quadrupole radiation pattern 234 to give a polymode pattern 236 represented by the voltage V1 of the operational amplifier 218A of FIG. 16. The omnidirectional pattern 230 is a graph of the voltage appearing at the output of the filter 220 of FIG. 16 as the source 226 is moved in a large circle around the array 202. Similarly, the dipole radiation pattern 232 and the quadrupole radiation pattern 234 represent the voltages provided by respectively the operational amplifier 216C and the filter 222A as the source of sound 226 is moved in a large circle around the array 202. The summation of these voltages by the operational amplifier 218A is represented in FIG. 17 by the pictorial equation having two plus signs and an equal sign. It is noted that the polymode pattern 236 has one main lobe in the north direction corresponding to the contributions of the northerly portions of the three radiation patterns 230, 232 and 234, each of which have a positive voltage in the northerly direction. On the east and west axis the negative portions of the lobes of the quadrupole radiation pattern 234 are portrayed as having equal and opposite amplitudes to the amplitude of the omnidirectional radiation pattern 230 at the east and west directions and therefore cancel each other so that zero amplitude appears at the east and west directions of the polymode pattern 236. Similar comments apply to the construction of the polymode pattern 236 and other directions. Mathematically this construction is indicated by the algebraic expressions beneath each of the radiation patterns 230, 232 and 234 in which the maximum amplitudes of these radiation patterns have all been set equal to one-third so that the peak amplitude of the polymode pattern 236 is equal to unity.

It is frequently desirable to scale the respective amplitudes of the respective radiation patterns 230, 232 and 234 to provide a maximum directivity for the polymode pattern 236 with the maximum directivity being understood to be a maximization of the ratio of energy received from the northerly direction of the radiation pattern 236 to the total isotropic incident energy received by all of the lobes of the pattern 236. This can be readily accomplished mathematically by integrating the energy received in each direction and forming the standard ratio for the directivity index, with the result that the maximum directivity is obtained for the scaling factors indicated in the attenuators 223A–G of FIG. 16. These scaling factors are, respectively, a value of 3 for the attenuator 223A a value of 4 for each of the attenuators 223B–E, and a value of 5 for each of the attenuators 223F–G. In FIG. 16, the arrow adjacent the scaling factor in each of the attenuators 223 indicates that the attenuation of these attenuators 223 may be varied to provide selective scaling of the monopole, dipole and quadrupole radiation patterns to produce a polymode pattern in which the positions of the nulls can be varied as well as for providing a selective tailoring of the shapes of the various lobes in the polymode radiation pattern.

Returning momentarily to FIG. 16, the operational amplifier 218B is seen to provide a polymode pattern having the same shape as the polymode pattern 236 of FIG. 17 but being oriented at an angle of 45° with respect to the coordinate system of the array 202. This results because of the summation of the monopole signal of the filter 220 with the signal of the operational amplifier 216B and the quadrupole signal of the filter 222B, for which the dipole radiation pattern and the quadrupole radiation patterns have their main axis in the 45° or NW/SE direction. With respect to the voltage V3, provided by the operational amplifier 218C, a polymode radiation pattern perpendicular to that of the polymode pattern 236 of FIG. 17 is provided since here the quadrupole pattern provided by the filter 222A is subtracted from the sum of the monopole pattern of the filter 220 and the east-west dipole pattern of the operational amplifier 216E; this subtraction is indicated by the minus sign adjacent the third input of the operational amplifier 218C. Similar comments apply to the remaining voltages V4–V8 wherein it is seen that a family of eight polymode radiation patterns are simultaneously produced by the receiver **210**.

Referring now to FIG. **18**, there is seen a system **238** comprising the array **202** and the receiver **210** of FIG. **16**, here shown coupled via multiplexing circuitry **240** similar to the multiplexing circuitry **26** of FIG. **1**. A signal generator **242** similar to the signal generator **42** of FIG. **1** provides signals which are coupled via the multiplexing circuitry **240** to the array **202** for transmission therefrom as in an active sonar system. The receiver **210** receives either echoes, which are reflected from an object such as the boat **44** of FIG. **1**, or signals generated by a distant source of sound such as the source of sound **226** of FIG. **16**. The direction of such a distant source of sound can readily be determined by means of logic circuitry **244** which performs the function of noting which of the voltages V1–V8 has a maximum value. A display **246**, such as a cathode ray tube display, is coupled to the logic circuitry **244** for displaying the direction of the distant source of sound. Additionally, a timing unit **248**, similar to the timing unit **72** of FIG. **1**, and a range gating unit **250** may be utilized in an active sonar mode for gating out all received signals except those corresponding to echoes emanating from a preselected range from the array **202**. To implement this range gating, the timing unit **248** supplies timing signals to both the signal generator **242** and the range gating unit **250** so that a range gate can be set corresponding to a preselected time interval subsequent to the transmission of a signal generated by the signal generator **242**. The range gating unit **250** is coupled to the receiver **210** at the "gate" terminals of the preamplifiers **212** (FIG. **16**) to gate out all the polymode voltages of the receiver **210** except for such voltages falling within the designated range gate.

Referring now to FIG. **19** there is shown a block diagram of a receiver **250** which is similar to the receiver **210** of FIG. **16** in that it utilizes the eight preamplifiers **212**, five of the operational amplifiers **216**, namely, the operational amplifiers **216**A, **216**C, and **216**E–G, and one of the operational amplifiers **218**. Each of the preamplifiers **212** connect via the wires **214** to the array **202** as in FIG. **16**. The receiver **250** differs from the receiver **210** in that the receiver **250** combines the output from a pair of dipole operational amplifiers, namely, the north-south and east-west dipole operational amplifiers **216C** and **216E** via a coordinate converter **252** to obtain a dipole, represented by a voltage on line **254**, with an axis having any desired orientation with respect to the coordinate system of the array **202**. The omnidirectional channel comprises the operational amplifier **216A** and the filter **220** of FIG. **16** but no coordinate converter is utilized since the omnidirectional pattern is symmetric about the axis of the array **202**. A quadrupole radiation pattern oriented in any direction about the axis of the array **202** is provided by the operational amplifiers **216F–G** and the filters **222A–B** of FIG. **16** in combination with a coordinate converter **256** providing a voltage on line **258** representing the magnitude of signals received by the polypole radiation pattern.

The coordinate converters **252** and **256** comprise multipliers **260A–D**, trigonometric units **262A–B** and amplifiers **264A–B** each of which has a variable gain control as indicated by the legend G_1 and G_2. The output signals of the multipliers **260A** and **260B** are summed together by the amplifier **264A**, and the output signals of the multipliers **260C** and **260D** are summed together by the amplifier **264B**. The multipliers **260A–D** may operate in an analog or in a digital fashion. Thus, the multiplier **260A** multiplies the north-south dipole signal by $\cos\theta_1$ and the multiplier **260B** multiplies the east-west dipole signal by $\sin\theta_1$ whereupon the two products are summed together to give a resultant dipole having the same amplitude as the north-south dipole but having a dipole axis inclined at an angle θ_1 relative to the axis of the array **202**. Subscripts 1 and 2 are utilized with the angle θ to indicate that the dipole pattern may be rotated at different amounts from the quadrupole pattern. Similar comments apply to the operation in the coordinate converter **256** except that here the multiplying factors are $\cos(2\theta_2)$ and $\sin(2\theta_2)$ since the expression for the quadrupole radiation pattern is in terms of $\cos(2\theta)$, while that of the dipole is in terms of $\cos\theta$ where θ is the angle relative to the coordinate system of the array **202**.

With respect to the capability of rotating the dipole patterns relative to the quadrupole pattern, as seen with the embodiment of FIG. **19**, it is noted that such a capability exists also in the embodiments of FIGS. **1** and **16** but to a limited extent. Thus, in FIG. **1** a rotation of 180° imparted by the beam switcher **64** rotates the dipole pattern 180° while rotating the quadrupole pattern 0°, ± 90° or 180° since each of these rotations are fully equivalent with the quadrupole pattern which is periodic with each rotation of 180°. With respect to the embodiment of FIG. **16**, a dipole pattern can be rotated with respect to a quadrupole radiation pattern by simply selecting the outputs from a different operational amplifier **216** such as the combination of the outputs of the operational amplifier **216C** and **216F** as is provided by the operational amplifier **218A** or the combination of the outputs of the operational amplifiers **216E** and **216F** as is provided by the operational amplifier **218C**.

To implement the coordinate conversion digitally, the multipliers **260A–D** would comprise an analog-to-digital converter, a digital multiplier, and a digital-to-analog converter (not seen in the drawings). The trigonometric units **262A–B** in digital form would comprise, by way of example, a read-only memory in which the value of $\cos\theta_1$ and of $\sin\theta_1$ would be presented in response to an address supplied on the line labeled θ_1; and with respect to the trigonometric unit **262B** the values of $\cos(2\theta_2)$ and $\sin(2\theta_2)$ would appear in response to an address supplied along the line labeled θ_2.

To implement the multiplication of the multipliers **260A–D** in analog fashion, the multipliers would comprise, for example, gain control amplifiers in which the gain would be proportional to $\cos\theta_1$ in the case of the multiplier **260A**, and similarly for the other multipliers **260B–D**. With respect to the trigonometric units **262A–B**, in analog form they would comprise, for example, a non-linear diode-resistor circuit in which the output voltage approximates $\cos\theta_1$ in response to input voltage of θ_1 with a second such circuit being provided to produce $\sin\theta_1$ in response to θ_1.

The omnidirectional channel also comprises an amplifier **266** coupled to the output of the filter **220** and having a variable gain in accordance with a voltage applied at terminal G_0 for varying the gain of the omnidirectional pattern relative to the gains of the dipole and quadrupole patterns. The relative gains for the three channels, namely, G_0, G_1 and G_2, as well as the angles of rotation of the dipole, θ_1, and of the quadrupole θ_2, are provided by a beam former **268** in response to signals provided by a logic circuit **270.** The logic circuit **270** is similar to the logic circuit **244** of FIG. **18** and is useful for tracking a source of sound such as the source **226** of FIG. **16.** Thus, the logic circuit **270** in response to the polymode voltage, V, at the output of the operational amplifier **218** provides signals to the beam former **268** for rotating the polymode directivity pattern, and furthermore, for varying the shape of the directivity pattern by varying the gain G_0, G_1, and G_2. The shape of the directivity pattern can also be varied by making θ_1 different from θ_2, this providing a flexibility not found in the receiver **210** of FIG. **16.** The receiver **250** and the logic circuit **270** may be substituted in the system **238** of FIG. **18** in place of the receiver **210** and the logic circuit **244** to provide a tracking system with improved tracking capability.

It is also evident with respect to the receivers **210** and **250** of FIGS. **16** and **19** that an octopole radiation pattern could be formed by summing and differencing alternate outputs of the amplifiers **212.** In this respect it is noted that alternate pairs of inputs to the operational amplifiers **216F–G** are summed and differenced to provide the quadrupole radiation pattern, there being two such patterns spatially offset by 45°. In the case of the octopole pattern, only one fixed pattern could be produced with the eight inner electrode segments **208,** it being necessary to employ sixteen such segments for providing a second octopole radiation pattern, and similarly for providing a combination of these patterns to give a resultant octopole radiation pattern in any arbitrary direction. Via the same reasoning, it is also evident that if only four inner electrode segments **208** were employed in the array **202,** then one fixed quadrupole radiation pattern could also be produced; however, there would be no facilities for altering the directional quality of such a pattern.

It is also apparent from a comparison of the array **202** of FIG. **16** and the array **22** of FIG. **1** that the two arrays may be combined into a single composite array (not seen in the figures) in which one or more transducers **28** of the array **22** are replaced with an array having the form of the array **202.** In view of the fact that the diameter of the array **202** is substantially smaller than a wavelength, such a radiator may readily be substituted for a transducer **28.** With respect to connecting this composite or hybrid array to the multiplexing circuitry **26** and the transceiver **24,** the multiplexing circuitry **26** must be enlarged to accommodate a transmit-receive circuit for each of the wires **214** of FIG. **16** for each one of the arrays **202** utilized in the composite array. A plurality of the receivers **210** of FIG. **16** are utilized, one for each of the arrays **202** with the omnidirectional channel in each of these receivers being connected to the receiving beam former **38** of FIG. **1.** This provides a composite receiving system having both features of the system **20** of FIG. **1** and features of the system **238** of FIG. **18,** and may be referred to as a polypole, polymode receiving system; the composite array may similarly be referred to as a polypole-polymode array. Transmission of signals generated by the signal generator **42** of FIG. **1** may still be accomplished in the polypole fashion by energizing each of the inner electrode segments **208** of an array **202** in parallel circuit from a single output of the transmitting beam former **40** of FIG. **1.**

A polypole or polymode or hybrid array may also be constructed in three dimensions, such as a four element array in which each of the radiating elements are located at the vertices of a tetrahedron. Such an array is readily implemented for polypole operation with radiating elements having a spherical radiating surface so as to radiate an omnidirectional pattern in three dimensions. In the case of the polymode operation, a radiating element must be segmented in three dimensions as by utilizing sectors of a sphere. The resultant radiating patterns of the tetrahedronal array are significantly more complex than those presented hereinbefore for the planar array, as may be understood by noting that the projections of the interelement spacing upon an axis of the radiation pattern is dependent on the orientation of the axis relative to the tetrahedron configuration. In particular, there are six major axes each of which passes through the center of the tetrahedron and is parallel to an edge of the tetrahedron. It may also be desirable to place a radiating element at the center of the tetrahedron to provide greater flexibility in forming the radiation pattern in any desired direction. The same form of circuitry as has been disclosed hereinbefore, may be utilized for the tetrahedronal array, however, the beam forming circuitry and the logic control for the beam forming circuitry is extended to encompass all three dimensions in a manner which may be seen by extending the preceding mathematics to three dimensions.

It is understood that the above described embodiments of the invention are illustrative only and that modifications thereof will occur to those skilled in the art. Accordingly, it is desired that this invention is not to be limited to the embodiments disclosed herein but is to be limited only as defined by the appended claims.

What is claimed is:

1. A radiating system comprising:

a plurality of radiating elements;

a first means for combining the signals of a first set of radiating elements of said plurality of radiating elements, said first combining means including means for delaying the signal of a radiating element of said first set of radiating elements relative to the signal of another radiating element of said first set of radiating elements;

a second means for combining the signals of a second set of radiating elements of said plurality of radiating elements, said second combining means including means for delaying a signal of a radiating element of said second set of radiating elements relative to another radiating element of said second set of radiating elements, each of said delay means being a variable delay for delaying their corresponding signals a preselectable amount of delay;

a third means for combining signals, said third means including means for delaying a signal provided by said second means relative to a signal provided by said first means, said third means combining said delayed signal of said second means with said combined signal of said first combining means;

the radiating elements of said plurality of radiating elements being arranged in an array suitable for forming at least one beam of radiation, the directivity pattern of radiation of said array having a notch and being adjustable in accordance with the magnitude of the delays provided by said variable delay means;

means for selectively coupling energy from individual ones of said radiating elements to said first and said second combining means, said selector means moving said notch for detecting a source of radiant energy;

angle tracking means responsive to the energy of radiation received by said beam of said array, said angle tracking means being connected to each of said variable delay means and selecting the amount of delay to be provided by each of said variable delay means, said angle tracking means selecting and varying the directivity pattern of said beam of said array and providing a signal having information relative to the propagation direction of radiation when such radiation is received by said array of radiating elements, said angle tracking means operating said selector means to vary the position of said beam about a direction from which said energy is received; and wherein

said angle tracking means comprises a memory for storing preselected values of delay for each of said variable delay means, and programming means for addressing said memory to select a set of delays to be provided by each of said variable delay means.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,821,740 Dated June 28, 1974

Inventor(s) Stanley L. Ehrlich

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

Column 10, line 46, Equation (15), delete "1/3", second occurrence.

Column 11, line 43 of Equation (17) should read as follows:

$$e^{-j2\pi qd/\lambda}+e^{-j2\pi rd/\lambda} =$$

Column 14, line 67, change "summer" to -- summed --.

Signed and Sealed this

thirtieth Day of *September 1975*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks

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