# United States Patent [19]

**Apostolos et al.**

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[54] **SIGNAL-ACQUISITION SYSTEM FOR A CIRCULAR ARRAY**


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



[21] Appl. No.: **685,175**

[22] Filed: **Dec. 21, 1984**

[51] **Int. Cl.**[4] .......................... **G01S 5/04**; G01S 3/16; G06G 7/19

[52] **U.S. Cl.** .................................... **342/445**; 342/378; 342/22; 364/827; 364/516; 364/726; 324/77 B

[58] **Field of Search** ..................... 343/5 FT, 378, 417, 343/443, 445; 324/77 B; 364/516, 725, 726, 827


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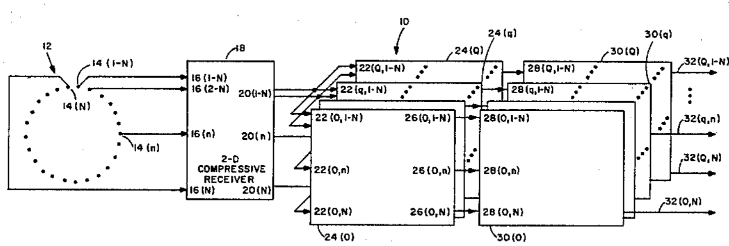
[57] **ABSTRACT**


A signal-acquisition system (**10**) for a circular antenna array (**12**) includes a two-dimensional compressive receiver (**18**) that performs a two-dimensional Fourier transformation in time and position on the outputs of the array. Each of the outputs of the compressive receiver (**18**) is fed to input ports of several processing units (**24**), which multiply them by an appropriate time-dependent function. The resultant modified signals are then processed by Butler matrices (**30**) that together have a matrix of output ports (**32**). Each output port is associated with a different combination of azimuth and elevation angles. A signal source at given azimuth and elevation angles with respect to the array (**12**) causes its greatest response in the output port (**32**) associated with those angles.


**7 Claims, 3 Drawing Figures**



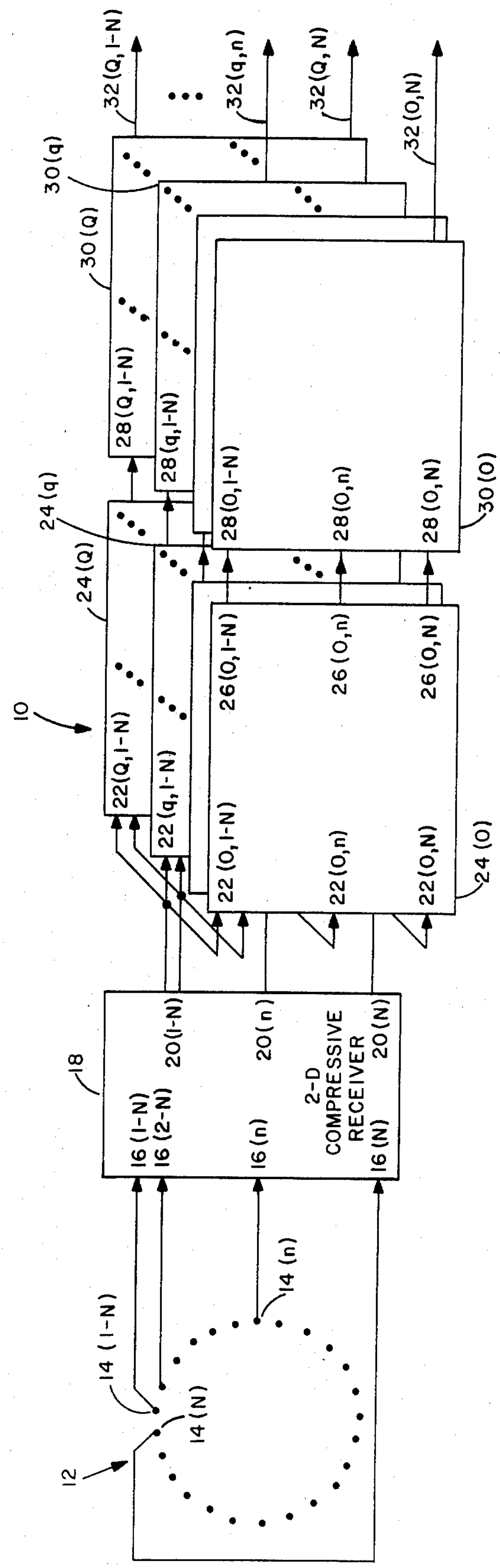

10
12
14 (1-N)
14 (N)
14 (n)
18
16 (1-N)
16 (2-N)
16 (n)
16 (N)
2-D
COMPRESSIVE
RECEIVER
20(1-N)
20(n)
20(N)
22(Q,1-N)
22(q,1-N)
22(0,1-N)
22(0,n)
22(0,N)
24(q)
24(Q)
24(0)
26(0,1-N)
26(0,n)
26(0,N)
28(Q,1-N)
28(q,1-N)
28(0,1-N)
28(0,n)
28(0,N)
30(q)
30(Q)
30(0)
32(Q,1-N)
32(q,n)
32(Q,N)
32(0,N)

FIG. 1

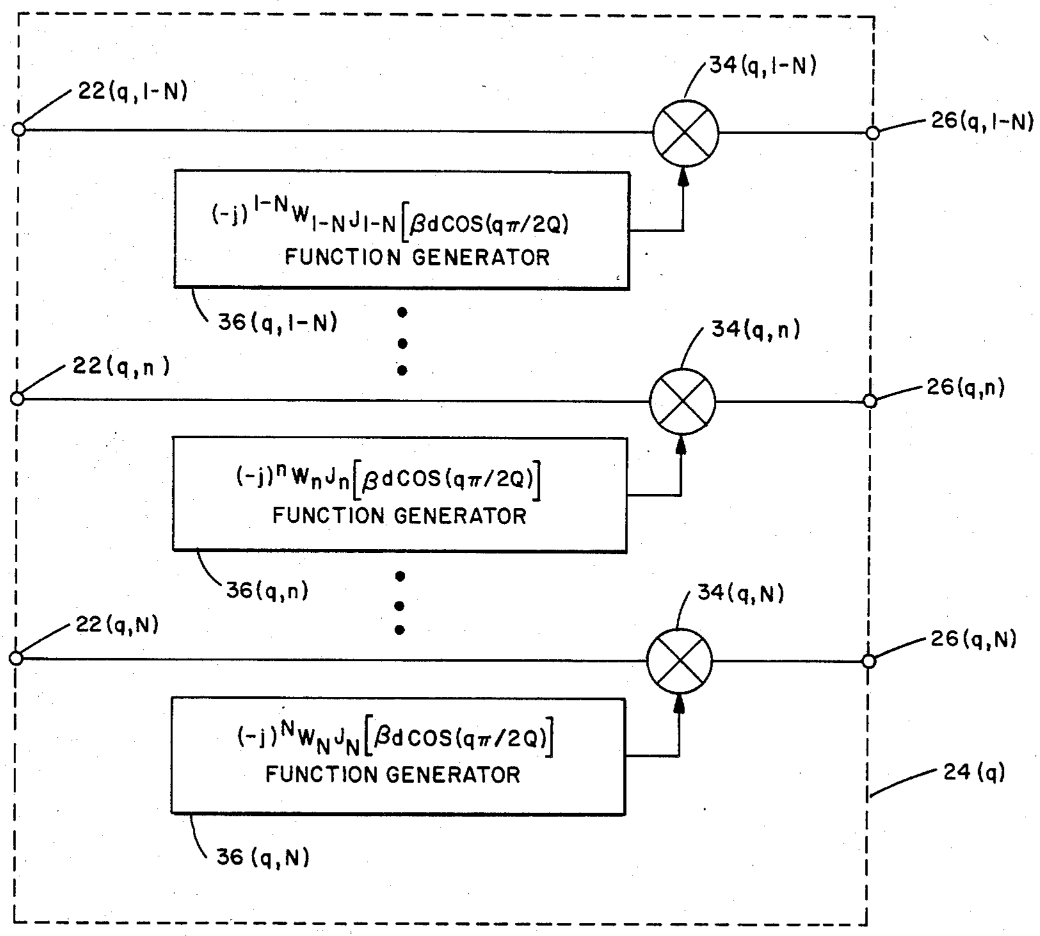

22(q,1-N)
34(q,1-N)
26(q,1-N)
$(-j)^{1-N}W_{1-N}J_{1-N}[\beta d \cos(q\pi/2Q)$
FUNCTION GENERATOR
36(q,1-N)
22(q,n)
34(q,n)
26(q,n)
$(-j)^{n}W_{n}J_{n}[\beta d \cos(q\pi/2Q)]$
FUNCTION GENERATOR
36(q,n)
22(q,N)
34(q,N)
26(q,N)
$(-j)^{N}W_{N}J_{N}[\beta d \cos(q\pi/2Q)]$
FUNCTION GENERATOR
24(q)
36(q,N)

FIG. 2

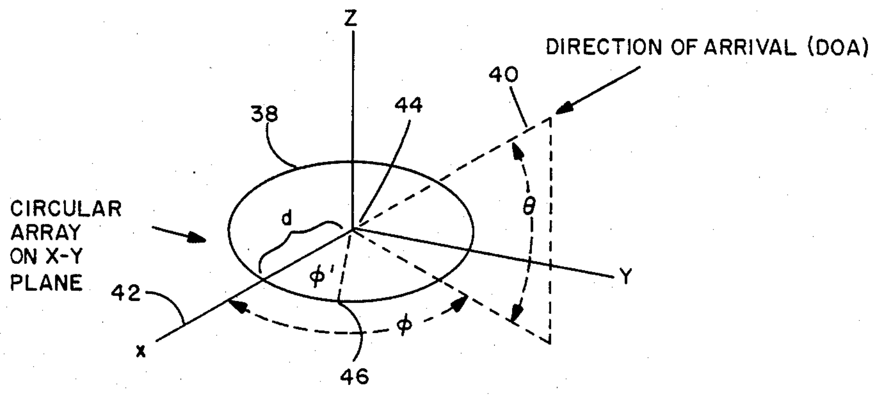

Z
DIRECTION OF ARRIVAL (DOA)
40
44
38
CIRCULAR
ARRAY
ON X-Y
PLANE
d
θ
φ'
42
Y
φ
x
46

FIG. 3

## SIGNAL-ACQUISITION SYSTEM FOR A CIRCULAR ARRAY

### BACKGROUND OF THE INVENTION

The present invention is directed to signal-acquisition systems. It is concerned specifically with a system for processing the output of a circular array of antenna elements so as to determine both the azimuth and the elevation angles of the source of signals that the antenna array receives.

U.S. patent application Ser. No. 551,664, filed on Nov. 14, 1983, by Apostolos, Boland, and Stromswold for an ACQUISITION SYSTEM EMPLOYING CIRCULAR ARRAY, discloses a powerful system for determining the directions of arrival and frequencies of many signals simultaneously. An improvement in that system is disclosed in U.S. patent application Ser. No. 536,477, filed on Sept. 28, 1983, by John T. Apostolos for a TWO-DIMENSIONAL ACQUISITION SYSTEM USING CIRCULAR ARRAY. In both of these systems, a spatial Fourier transformation is performed on the outputs of a circular antenna array. The resultant transform is processed with certain correction factors related to the antenna pattern of the array and then subjected again to a spatial Fourier transformation. A temporal Fourier transformation is also performed. The result of each system is an ensemble of signals at a group of output ports in which each output port represents a different azimuthal direction. Signals from a source in a given azimuthal direction result in a maximum output at the port associated with that azimuthal direction. Thus, the azimuthal direction of each source is readily identified in real time. The descriptions included in these patent applications are helpful in understanding the present invention, and they are accordingly incorporated by reference.

The assumption on which the design of the systems of those two applications is based is that the source has a negligible elevation angle. That is, there is only a very small angle between the direction of arrival of the signal and the plane of the circular antenna array. For a wide range of applications, this is an accurate assumption. For sources whose angle of elevation is significant, however, the direction indications produced by the systems of those two applications are inaccurate.

An object of the present invention is to eliminate the inaccuracies that can be caused in such systems by significant elevation angles.

It is a further object of the present invention to determine the values of the elevation angles of signal sources.

### SUMMARY OF THE INVENTION

The foregoing and related objects are achieved in the method described below and in apparatus for carrying out that method. The method includes performing a spatial Fourier transformation on an ensemble of input signals from a circular antenna array to generate an ensemble of input-transform signals, each of which is associated with a separate integer index n. A signal associated with an index n represents the spatial-frequency component of n electrical degrees per spatial degree around the circular antenna array and consists of components representing all of the antenna-signal temporal-frequency components that give rise to that spatial frequency. According to the invention, an ensemble of modified-transform signals is generated from these input signals for each of a plurality of elevation angles.



Each ensemble includes a modified-transform signal associated with each input-transform signal. Each modified-transform signal consists of modified-transform components, each of which represents a value that is substantially proportional to an associated component in the input-transform signal multiplied by $(-1)n$ times the azimuth-independent factor in the antenna pattern that would be generated by the antenna array at the associated elevation angle if the antenna array were driven by signals whose temporal frequency is the frequency with which that input-transform component is associated and whose phases vary with element position at the spatial frequency represented by that input-transform signal.

A spatial Fourier transformation is performed on each ensemble of modified-transform signals to generate an ensemble of output-transform signals for each of the plurality of elevation angles. Within a given output-transform ensemble, each output-transform signal is associated with a different azimuth angle. The result of this process is that radiation emitted by a source and received by the antenna array causes a maximum response in the output-transform signal associated with the azimuth and elevation angles of that source.

### BRIEF DESCRIPTION OF THE DRAWINGS

These and further features and advantages of the present invention are described in connection with the accompanying drawings, in which:

FIG. **1** is a block diagram of the system of the present invention for determining the elevation and azimuthal position of the source of signals detected by a circular array of antenna elements;

FIG. **2** is a more-detailed block diagram of a portion of the system of FIG. **1**; and

FIG. **3** is a diagram used to define variables employed in the mathematical treatment of the invention.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention will be described initially by simultaneous reference to FIGS. **1**, and **2**. The system **10** of the present invention is a device for determining the angle of elevation, the azimuth angles, and the temporal frequencies of radiation received from a plurality of sources by a circular antenna array **12** of 2N elements **14**(1−N) through **14**(N). The outputs of the antenna elements **14** are fed to corresponding input ports **16** of a two-dimensional compressive receiver **18**. In essence, the two-dimensional compressive receiver performs a two-dimensional Fourier transformation on the signal ensemble that it receives at its input ports. The transformation is from time to temporal frequency and from position to spatial frequency. The compressive receiver **18** has 2N output ports, each of which is associated with a spatial-frequency component, and a spatial-frequency component in the input ensemble causes its greatest response at the output port **20**(n) associated with that spatial-frequency component.

Spatial frequency in this context refers to the instantaneous phase advance around the elements of the circular array. For instance, suppose that the signals on all of the elements **14** of the circular array **12** are sinusoidal signals of the same temporal frequency but having different phases. Suppose further that these phases advance with element position by n electrical degrees per spatial degree, where n is an integer. In such a situation, the array output has a single temporal-frequency component and a single spatial-frequency component. For such an ensemble of signals, the output of the compressive receiver **18** is a burst of oscillatory signal whose frequency is the center frequency of the compressive receiver. This output is greatest on the output port **20**(n) associated with the spatial frequency of n electrical degrees per spatial degree. The compressive receiver is repeatedly swept in frequency, and the burst occurs at a time within the sweep that is determined by the temporal frequency of the radiation that causes the signal ensemble. For the ensemble just described, the response at any of the other output ports **20** is negligible—because there are no other spatial-frequency components—and a significant output on output port **20**(n) occurs only at the time within the sweep associated with the temporal frequency of the radiation.

Of course, this signal ensemble, which has only one spatial-frequency component, is extremely artificial; even a single plane-wave signal at a single temporal frequency gives rise to many spatial-frequency components in a circular array. In ordinary operation, many spatial-frequency components, and usually many temporal-frequency components, are present in the ensemble of signals processed by the two-dimensional compressive receiver **18**, which processes all of these components simultaneously.

Those skilled in the art will recognize that the two-dimensional compressive receiver includes a two-dimensional dispersive delay line and that the position of an output port on the output edge of the delay line determines the spatial-frequency component with which that output port **20** is associated. Therefore, the output ports of compressive recievers can in general be positioned so as to be associated with other than integral numbers of electrical degrees per spatial degree. However, compressive receiver **18** is arranged so that the spatial frequencies associated with the output ports **20** are integral; as was stated before, each output port **20**(n) is associated with a spatial frequency of n electrical degrees per spatial degree.

The signal from each compressive-receiver output port **20**(n) is fed to a corresponding input port on each of Q+1 different processing units **24**(Ø)–**24**(Q). These processing units **24** multiply the input signals by processing factors that are functions of time within the compressive-receiver sweep and depend on the particular input port **22**(q,n) to which the signal is applied. The signal resulting from multiplication of the signal on each input port **22**(q,n) is presented on a corresponding output port **26**(q,n) to a corresponding input port **28**(q,n) of one of Q+1 modified Butler matrices **30**(Ø)–**30**(Q). Each modified Butler matrix **30**(*q*) performs a spatial Fourier transformation but no temporal Fourier transformation.

The Butler matrix **30**(*q*) is a modified version of a conventional Butler matrix of the type described in U.S. Pat. No. 3,255,450, which issued on June 7, 1966, to Jesse L. Butler for a Multiple Beam Antenna System Employing Multiple Directional Couplers in the Leadin. In the conventional Butler matrix, the two adjacent central output ports represent opposite phase gradients, or spatial frequencies, of the same magnitude, and the other output ports represent spatial frequencies that are odd harmonics of these spatial frequencies. For example, with N=4, the outputs of a conventional Butler matrix would correspond to spatial frequencies of ±22 ½, ±67 ½, +112 ½, and ±157 ½ electrical degrees per



input port. In the modified Butler matrix **30**(*q*), the spatial-frequency difference between any two adjacent output ports is the same as that for a conventional Butler matrix. However, the spatial frequencies represented by the output ports **32**(*q,n*) of the modified Butler matrix **30**(*q*) differ from those of a conventional Butler maxtrix by one-half of that spatial-frequency difference. For N=4, therefore, the output ports **32**(*q*) correspond to spatial frequencies of 0, ±45, ±90, ±135, and 180 electrical degrees per input port.

The modified Butler matrix can be constructed in a number of ways. The most straightforward conceptually is to provide phase shifters (not shown in the drawings) at the input ports of a conventional Butler matrix. Each of the phase shifters provides a different phase shift, the phase shifts increasing with input-port position in such a manner that the phase shifts of adjacent phase shifters differ by one-half the spatial-frequency spacing of the output ports **32**.

The ultimate result of the system is that each output port **32**(*q,n*) is associated with an elevation angle of 90°×q/Q and an azimuth angle of 180°×n/N. A plane wave that arrives at the antenna array **12** at a given combination of azimuth angle and elevation angle causes the greatest response on the output port associated with that combination of angles, and the time within a compressive-receiver sweep at which the response occurs is an indication of the temporal frequency of the plane wave.

FIG. **2** shows one of the processing units **24**(*q*) of FIG. **1** in more detail. Associated with each input port **22**(*q,n*) and output port **26**(*q,n*) is an analog multiplier **34**(*q,n*) which multiplies the signal from the input port **22**(*q,n*) by a processing factor represented by a signal that a function generator **36**(*q,n*) produces. The value of the processing factor is shown in FIG. **2**, where $J_n$ is the nth-order Bessel function of the first kind. The $W_n$'s are weighting factors that would be used in most practical applications to improve the dynamic range of the system output, as will be described in more detail below. The weighting factors are constants that differ for different function generators within a processor unit **24** but are the same for corresponding function generators in different processor units.

The processing factors depend on q, n, and the wave number B. The wave number, in turn, is proportional to the antenna-signal temporal-frequency component to which the compressive receiver is responding at the current point in the compressive-receiver sweep; that is, the processing factors are functions of time within a sweep. The processing factor produced by function generator **36**(*q,n*), if a factor of 2π is ignored, is the weighting factor multiplied by $(-1)^n$ times a quantity that, as will shortly be explained, can be described as the azimuth-independent factor in a particular antenna pattern. This antenna pattern is one that is generated by an appropriate phasing of the circular array **12**. Specifically, if the antenna elements were used for transmission and driven at the temporal frequency corresponding to B but at different phases so that the phases advance around the array at a spatial frequency of n electrical degrees per spatial degree, then the far-field antenna pattern associated with processing unit **24**(*q*) is:

$$2\pi jhu\ ne^{jnd}J_n[\beta d\cos(q\pi/2Q)]$$

This is the antenna pattern mentioned above. The only azimuth-dependent factor in this pattern is is $e^{jn\phi}$. The

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