OPIC
OFFICE DE LA PROPRIÉTÉ INTELLECTUELLE DU CANADA

CIPO
CANADIAN INTELLECTUAL PROPERTY OFFICE

(12) (19) (CA) **Demande-Application**

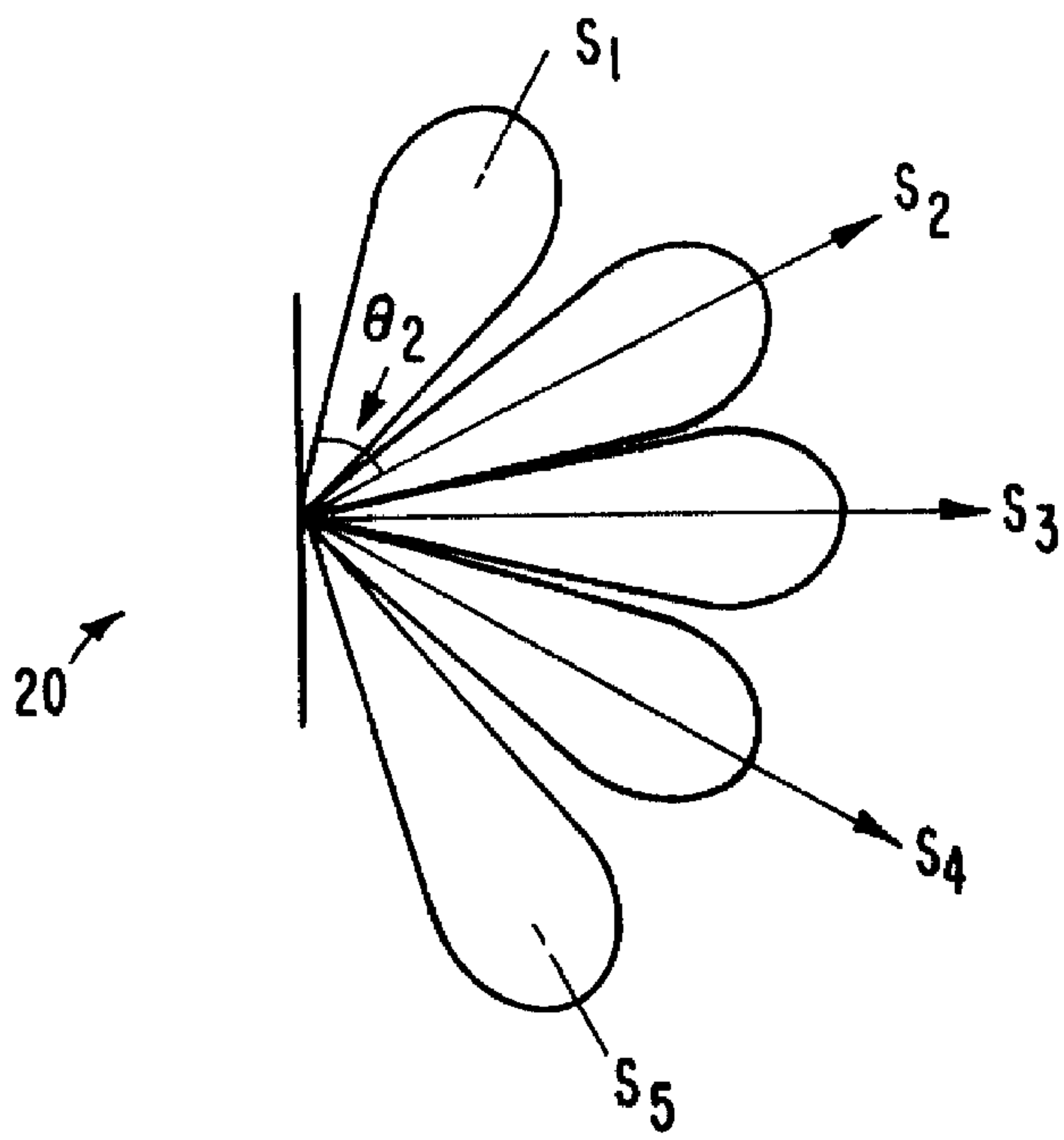
(21) (A1) **2,022,086**
(22) 1990/07/27
(43) 2001/02/01

(72) FEINTUCH, PAUL L., US
(71) RAYTHEON COMPANY, US

(51) Int.Cl.^{7} G01S 15/06, G01S 7/52

(54) **SYSTEME DE SONAR ACTIF POUR LA DETECTION DE CIBLE EN LA PRESENCE DE FORTE INTERFERENCE D'UN LOBE PRINCIPAL**

(54) **AN ACTIVE SONAR SYSTEM FOR TARGET DETECTION IN THE PRESENCE OF STRONG MAIN LOBE INTERFERENCE**



(57) An active sonar system and method of processing sonar signals which provide for target detection in the presence of main lobe interference. The system comprises a transmitter which transmits a plurality of uniquely encoded sonar signals in a plurality of angular directions. A receiver detects echoed target return signals and plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions. The receiver comprises a first processor including a plurality of adaptive filters arranged as a Gram-Schmidt spatial predictive canceler. The canceler produces an output signal having a spatial response which has nulls located in the angular directions of the interference sources. The nulls are proportional to the respective signal strengths of the interference sources. A second processor processes the output signal from the Gram-Schmidt predictive canceler by means of a plurality of filters matched to the plurality of unique codes contained in the target return signals. The second processor provide a plurality of matched filter output signals which are indicative of the signal strength and angular location of the targets. The existence of a detected target is determined by each matched filter whose output signal is above a predetermined threshold, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted.

AN ACTIVE SONAR SYSTEM FOR TARGET DETECTION IN THE PRESENCE OF STRONG MAIN LOBE INTERFERENCE

ABSTRACT

An active sonar system and method of processing sonar signals which provide for target detection in the presence of main lobe interference. The system comprises a transmitter which transmits a plurality of uniquely encoded sonar signals in a plurality of angular directions. A receiver detects echoed target return signals and plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions. The receiver comprises a first processor including a plurality of adaptive filters arranged as a Gram-Schmidt spatial predictive canceler. The canceler produces an output signal having a spatial response which has nulls located in the angular directions of the interference sources. The nulls are proportional to the respective signal strengths of the interference sources. A second processor processes the output signal from the Gram-Schmidt predictive canceler by means of a plurality of filters matched to the plurality of unique codes contained in the target return signals. The second processor provide a plurality of matched filter output signals which are indicative of the signal strength and angular location of the targets. The existence of a detected target is determined by each matched filter whose output signal is above a predetermined threshold, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted.

AN ACTIVE SONAR SYSTEM FOR TARGET DETECTION IN THE PRESENCE OF STRONG MAIN LOBE INTERFERENCE

BACKGROUND OF THE INVENTION

The present invention relates generally to active sonar systems, and more particularly to active sonar systems which provide for target detection in the presence of strong main lobe interference.

Most current sonar systems are limited in their performance by plane wave interference from multiple strong sources that dominate the acoustic field. Often the interference sources are so strong that preformed beam sidelobe rejection provided for by these systems is not sufficient to keep the interference sources from masking target return signals arriving in the main lobe steering direction.

In such situations, a variety of spatial processing techniques have been devised to reduce the interference. Among these are the use of adaptive beamformers, which place nulls in the spatial response curve of the system which are located in the direction of the interference source. In addition, multiple sidelobe cancelers have been devised which also place nulls in the direction of the interference source.

In employing either of the above-mentioned techniques, the number of controllable nulls is limited by the number of spatial degrees of freedom available to the beamformer or canceler. For the adaptive beamformer, this is one less than the total number of receiving elements in the sonar array. For the multiple sidelobe canceler, the number of reference auxiliary elements determines the number of additional nulls that can be placed in the primary beam pattern.

As long as the interference arrives in the sidelobes of the primary beams, both the adaptive beamformer and the multiple sidelobe canceler produce reasonably conventional looking beam patterns, in that the main lobe is in the vicinity of the target steering direction and the sidelobes are relatively low with nulls placed in the interference directions.

However, when the interference signals are located in the same main lobe as the target returns, the use of sidelobe cancelers, for example, places nulls on the interference, but degrades other sidelobe responses such that targets are inaccurately detected in the sidelobes. In addition, if such cancelers are employed with a multiple beam system, beams steered away from the target may have larger spatial responses in the target direction than the target beam. This can cause target detection on the beams several beams adjacent to the target direction and produce severe angle estimation errors. An adaptive beamformer used in this situation would also place a null on the interference, but may degrade the main lobe response to the point that the target signal in undetectable.

Accordingly, almost every active sonar has dramatically reduced performance when strong interference is encountered in the same main lobe as the target return. Processing in this environment usually requires a platform maneuver to place the interference in the sidelobes, or requires a time delay for the target to separate from the interference source, both of with can cause tactical problems.

For the purposes of example, consider a multiple preformed beam system that has spatial responses such that adjacent transmitted beams cross over at approximately their 3 dB points, their responses are approximately 7 dB down at the angle of the adjacent beam maximum response axis, and the array is designed to have -30 dB sidelobes. If there is an interference source having signal level J dB on the maximum response axis on the leftmost beam A, then the interference is 7 dB down on the center beam B, and 30 dB down on the rightmost beam C. If a target having signal level T appears on the maximum response axis of beam B, then the target-to-interference ratios of the three beams are:

for beam A: $(T - 7) - J = T - J - 7$,

for beam B: $T - (J - 7) = T - J + 7$, and

for beam C: $(T - 7) - (J - 30) = T - J + 23$,

and the best target-to-interference ratio appears on beam C even though the target in located on beam B.

This can be contrasted with the situation wherein a sidelobe canceler is employed to provide an N dB null. This correlates to a cancellation of the noise to the uncorrelated noise floor if it is above N dB down. The null on the maximum response axis of beam A produces 0 dB sidelobes for that beam. The null on beam B at the interference angle produces -7 dB sidelobes for that beam. The null on beam C in the interference direction is combined with the -30 dB sidelobes, and is limited by the uncorrelated noise floor. Therefore, the target-to-interference ratios of the three beams are:

for beam A: T - (J - N) = T - J + N,
for beam B: T - (J - N) = T - J + N, and
for beam C: (T - 7) - (J - 30 - N) = T - J + N + 23,

and the target may be detected on any of the beams depending upon the level of the uncorrelated noise floor.

If the noise floor is below 30 dB down, then beam C is again the beam on which a target detection will be made. The canceler for this main lobe example has not provided a definitive detection on the target beam, beam B, despite having properly placed nulls at all of the interference directions for all of the preformed beams.

Therefore, there is a need for an approach which is designed specifically to address the problems of mainlobe interference, rather than using sidelobe cancelers, or beamformers, or the like.

SUMMARY OF THE INVENTION

In order to overcome the problems associated with conventional approaches to the mainlobe interference problem, the present invention provides for a system and methodwhich provide for target detection in the presence of main lobe interference.

The system is an active sonar system which determines the angular direction of targets in the presence of plane wave interference which substantially masks the presence of the targets. The system comprises a transmitter which transmits a plurality of uniquely encoded sonar signals in a plurality of angular directions. The uniquely encoded sonar signals may generally comprise a set of mutually disjoint frequency encoded signals, for example. A receiver detects echoed target return signals from targets located at unknown angular directions and plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions

The receiver comprises a first processor which processes the target return and interference signals by means of a plurality of adaptive filters arranged as a Gram-Schmidt spatial predictive canceler. The canceler produces an output signal whose spatial response has nulls located in the angular directions of the interference sources. The nulls are proportional to the respective signal strengths of the interference sources.

A second processor processes the output signal from the Gram-Schmidt predictive canceler by means of a plurality of filters matched to detect each of the plurality of unique codes contained in the echoed target return signals. The second processor provide a plurality of matched filter output signals which are indicative of the signal strength and angular location of the targets. The existence of a detected target is determined by each matched filter whose output signal is above a predetermined threshold, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted.

The method in accordance with the present invention comprises the steps of transmitting a plurality of uniquely encoded sonar signals in a plurality of angular directions, and receiving echoed target return signals from targets located at unknown angular directions from the system and plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions with respect to the system.

The method then comprises processing the received target signals and interference signals by means of a plurality of adaptive filters arranged as a Gram-Schmidt spatial predictive canceler to produce an output signal which has a spatial response having nulls located in the angular directions of the interference sources, which nulls are proportional to the respective signal strengths of the sources.

The next step in the method comprises processing the output signal from the Gram-Schmidt predictive canceler by means of a plurality of filters matched to detect each of the plurality of unique codes contained in the echoed target return signals. This processing step provides a plurality of matched filter output signals which are indicative of the signal strength and angular location of the echoed target signals.

BRIEF DESCRIPTION OF THE DRAWING

The various features and advantages of the present invention may be more readily understood with reference to the following detailed description taken in conjunction with the accompanying drawing, wherein like reference numerals designate like structural elements, and in which:

FIG. 1 illustrates encoded preformed beams employed by the transmitter of a sonar system in accordance with the principles of the present invention;

FIG. 2 illustrates the receiver of the sonar system of the present invention;

FIGS. 3a-f show transmitted beams and frequency hopped waveform encoding which may be employed in the system of the present invention and which were used in a simulation of the performance of the present invention;

FIG. 4 shows the output of the receiver of the present invention generated as part of the simulation of the present invention using the beams of FIG. 3; and

FIG. 5 shows a range-Doppler three dimensional plot illustrating the results of the simulation indicating the detection of the target in the presence of the interference signal.

DETAILED DESCRIPTION

Referring to FIG. 1, it shows a set of three encoded beams which are transmitted by a transmitter 20 of the present invention. The transmitter 20 is a conventional sonar transmitter capable of transmitting multiple beams in multiple directions. Not shown in FIG. 1 is the sonar array to which the present invention is coupled. For the purposes of example, a five element array will be disclosed. The design and construction of such arrays are well-known to those skilled in the sonar art. Such transmitters are described a book entitled "*Principles of Underwater Sound*," by R. Urick, McGraw-Hill, New York. Each of the three beams is uniquely encoded so as to have relatively low cross-ambiguity functions. One way of achieving such beam characteristics is to use an encoding scheme wherein each of the encoding signals have disjoint frequency bands. Such encoding schemes are well-known to those skilled in the art of sonar design. Alternatively, a frequency hopping scheme such as that disclosed in U.S. Patent Application Serial No.003,529, filed January 15, 1986, for "Channel Adaptive Active Sonar," and assigned to the assignee of the present invention may be employed. Also, such encoding schemes are discussed in "Time-Frequency Hop Signals - Part I: Coding Based on the Theory of Linear Congruences," by E. L. Titlebaum, *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-17, No. 4, July 1981, pages 490-493.

The receiver 22 of the present invention includes a first processor 24 which is comprised of a plurality of adaptive filters 26 arranged as a Gram-Schmidt spatial predictive canceler. In particular, the disclosed first processor 24 utilizes least mean square adaptive filters 26. Gram-Schmidt predictive cancelers are well-known in the signal processing art, Such cancelers are generally discussed in the textbook "*An Introduction to Adaptive Arrays*," by R. A. Monzingo and T. W. Miller, pages 364-369, published by John Wiley & Sons., New York, 1980.

The first processor 24 comprises a plurality of least mean square adaptive filters 26 coupled in a cascaded fashion and coupled to a plurality of summing elements 28, as shown in FIG. 2. The total number of adaptive filters 26 comprises N(N+1)/2, where N is the number of sonar array elements utilized array. The first sonar element provides input signals to N-1 adaptive filters 26 and the outputs of each respective filter is summed with the output signal of the second through Nth sonar element, respectively, the second sonar element provides input signals to N-2 adaptive filters 26 and the outputs of each respective filter is summed with the output signal of the third through Nth sonar element, respectively, and so forth, with the Nth sonar element providing input signals to summing elements 28 only.

The receiver 22 also includes a second processor 32 coupled to receive an output from the Gram-Schmidt predictive canceler. The second processor 32 comprises a matched filter portion which has a plurality of matched filters 34 employed to detect the unique codes contained in the target return signals and a threshold detector portion which comprises a plurality of threshold detectors 36. The second processor 32 provides a plurality of matched filter output signals which are indicative of the signal strength and location of the targets.

The matched filters 34 and threshold detectors 36 are shown as connected in parallel, but serial interconnection to the matched filter portion is considered a routine matter for those skilled in the art. The threshold detectors 36 are individually coupled to each of the matched filters and are set to predetermined thresholds which are commensurate with the signal levels of the detected targets and the noise levels.

In operation, the transmitter 20 transmits the three uniquely encoded signals and the signals are echoed from targets present in the sonar far field. Unidentified noise sources also present in the far field broadcast broadband noise signals intended to mask the echoed target return signals. The target return signals and noise signals are received and processed by the receiver 22. The first processor 24, which implements the Gram-Schmidt predictive canceler, produces an output signal whose spatial response has nulls located in the directions of the interference sources. The nulls are also proportional to the respective signal strengths of the interference sources.

The second processor 32 then processes the output signal provided by the first processor 24. The second processor 32 employs the matched filters 34 to detect each of the plurality of unique codes contained in the target return signals. The second processor produces matched filter output signals which are indicative of the signal strength and angular location of the targets. The existence and angular direction of each target is determined as indicated above.

The least mean square adaptive filter is well-known to those in the signal processing art, but for purposes of completeness, each filter functions as if it were a tapped delay line, and implements the following equation:

$$w_k(n + 1) = w_k(n) = \mu\varepsilon(n)\, x(n - k),$$
where $\varepsilon(n) = d(n) - y(n)$, and
$$y(n) = \sum_{i=0}^{n} w_i(n)\, x(n-1),$$ and where

$x(n)$ is the input signal, μ is the feedback coefficient, ε is the error waveform, $d(n)$ is the desired signal, $w_k(n)$ is the weighting on the kth element of the tapped delay line, with $w_0(n)$ having no delay, and $y(n)$ is the output signal from the filter.

The above system has been modeled in a computer simulation. The simulation employed the use of five transmitter waveforms covering the direction forward of the system. The bandwidth was chosen such that it was divided into two disjoint frequency regions. Three of the transmitted waveforms were allocated to one sub-band and the remaining two to the other sub-band. The simulations employed nine-chip frequency hop waveforms that were selected such that for all possible relative shifts in time and frequency, the code words overlap in at most one chip location.

FIGS. 3a-f show five transmitted beams employed in the simulation and the frequency hopped waveforms associated with each beam direction. A single interference source is utilized at zero degrees, and a weak target return is found in the same beam at 5 degrees. When this situation is simulated for a conventional beamformer system, range Doppler maps representing the output of the conventional preformed beam system reveal that the interference signal masks the weak target return through the sidelobes and completely dominates range Doppler maps. Accordingly, the signal return is totally undetectable.

However, the output of the receiver 22 of the present invention, generated as part of the simulation of the present invention, as shown in FIG.4, provides a spatial null in the direction of the interference source, and preserves the spatial response in the target return direction. Range-Doppler maps generated for this system as part of the simulation of the present invention indicate that the weak target signal was detected in the presence of the strong interference source present in the same main lobe. FIG. 5 shows the particular range-Doppler map indicating such target detection.

One method in accordance with the principles of the present invention starts with the step of transmitting a plurality of uniquely encoded sonar signals in a plurality of angular directions. Target return signals are then processed along with interference signals generated by interference sources by means of a first processor 24 comprising a plurality of spatial adaptive filters 26 arranged as a Gram-Schmidt predictive canceler. This processing step produces an output signal which has a spatial response having nulls located in the directions of the interference sources, which nulls are proportional to the respective signal strengths of the sources.

The next step in the method comprises processing the output signal from the first processor 24 by means of a plurality of matched filters 34 matched to detect each of the plurality of unique codes contained in the target return signals. This processing step provides a plurality of matched filter output signals which are indicative of the signal strength and angular location of the echoed target signals. The existence of a detected target is determined by each matched filter whose output signal is above respective predetermined thresholds, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted. Other methods in accordance with the present invention should be readily apparent from a reading of the foregoing disclosure and thus will not be discussed in detail.

Thus there has been disclosed a new and improved active sonar system and method which provides for target detection in the presence of strong main lobe interference that masks the target signal.

It is to be understood that the above-described embodiments are merely illustrative of some of the many specific embodiments which represent applications of the principles of the present invention. Clearly, numerous and other arrangements can be readily devised by those skilled in the art without departing from the scope of the invention.

What is claimed is:

1. An active sonar system which determines the angular direction of targets in the presence of plane wave interference present in the main lobe which substantially masks the presence of the targets, said system comprising:

transmitter means for transmitting a plurality of uniquely encoded sonar signals in a plurality of angular directions;

receiver means for receiving echoed target return signals from targets located at unknown angular directions, and simultaneously receiving plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions, said receiver means comprising;

first processing means for processing the echoed target return signals and interference signals by means of a plurality of spatial adaptive filters arranged as a Gram-Schmidt predictive canceler to produce an output signal comprising signals received from the target and interference sources, said output signal having a spatial response with nulls located in the angular directions of the interference sources; and

second processing means for processing the output signal from the first processing means by means of a plurality of matched filters which detect each of the plurality of unique codes contained in the echoed target return signals and which provide a plurality of matched filter output signals which are indicative of the signal strength and angular location of the targets;

whereby the existence of a detected target is determined by each matched filter whose output signal is above a predetermined threshold, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted.

2. The system of Claim 1 which further comprises:

third processor means for processing the matched filter output signal by means of individual threshold detectors respectively coupled to each of the matched filters to identify those matched filter output signals having signal strengths above the predetermined threshold.

3. The system of Claim 2 wherein the plurality of threshold detectors are coupled in parallel.

4. The system of Claim 1 wherein said first processor comprises a plurality of least mean square adaptive filters coupled in a cascaded fashion and coupled to a plurality of summing elements, and wherein the total number of filters comprises N(N+1)/2, where N is the number of receiving elements utilized in the receiver means, and wherein the first receiver element provides input signals to N-1 adaptive filters and the outputs of each respective filter is summed with the output signal of the second through Nth receiver element, respectively, the second receiver element provides input signals to N-2 adaptive filters and the outputs of each respective filter is summed with the output signal of the third through Nth receiver element, respectively, and so forth, with the Nth receiver element providing input signals to summing elements only.

5. The system of Claim 1 wherein the plurality of uniquely encoded sonar signals comprise signals having disjoint frequency bands.

6. An active sonar system that determines the angular direction of targets in the presence of plane wave interference present in the main lobe which substantially masks the presence of the targets, said system comprising:

transmitter means for transmitting a plurality of uniquely encoded sonar signals having relatively low cross-ambiguity functions in a plurality of angular directions with respect to the system;

receiver means for receiving echoed target return signals from targets located at unknown angular directions from the system, and plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions with respect to the system, said receiver means comprising:

first processor means for processing the echoed target return signals and interference signals by means of a plurality of spatial adaptive filters arranged as a Gram-Schmidt predictive canceler to produce an output signal having a spatial response with nulls located in the angular directions of the interference sources, which nulls are proportional to the respective signal strengths of the sources; and

second processor means for processing the output signal from the first processor means by means of a plurality of matched filters which detect each of the plurality of unique codes contained in the echoed target return signals and which provide a plurality of matched filter output signals which are indicative of the signal strength and angular location of the echoed target signals;

whereby the existence of a detected target is determined by each matched filter whose output signal is above a predetermined threshold, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted.

7. The system of Claim 6 which further comprises:

third processor means for processing the matched filter output signals by means of individual threshold detectors respectively coupled to each of the matched filters to identify those matched filter output signals having signal strengths above the predetermined threshold.

8. The system of Claim 6 wherein said first processor comprises a plurality of least mean square adaptive filters coupled in a cascaded fashion and coupled to a plurality of summing elements, and wherein the total number of filters comprises N(N+1)/2, where N is the number of receiving elements utilized in the receiver means, and wherein the first receiver element provides input signals to N-1 adaptive filters and the outputs of each respective filter is summed with the output signal of the second through Nth receiver element, respectively, the second receiver element provides input signals to N-2 adaptive filters and the outputs of each respective filter is summed with the output signal of the third through Nth receiver element, respectively, and so forth, with the Nth receiver element providing input signals to summing elements only.

9. The system of Claim 6 wherein the plurality of uniquely encoded sonar signals having relatively low cross-ambiguity functions comprise signals having disjoint frequency bands.

10. An active sonar system which determines the angular direction of targets in the presence of plane wave interference present in the main lobe which substantially masks the presence of the targets, said system comprising:

transmitter means for transmitting a plurality of uniquely encoded sonar signals in a plurality of angular directions;

receiver means for receiving echoed target return signals from targets located at unknown angular directions from the system and plane wave interference signals having different signal strengths transmitted from sources located at unknown angular directions;

first processor means for processing the echoed target return signals and interference signals by means of a plurality of spatial adaptive filters arranged as a Gram-Schmidt predictive canceler to produce an output signal having a spatial response with nulls located in the angular directions of the interference sources, which nulls are proportional to the respective signal strengths of the sources;

second processor means for processing the output signal from the first processor means by means of a plurality of matched filters which are respectively matched to detect each of the plurality of unique codes contained in the echoed target return signals and which provide a plurality of matched filter output signals which are indicative of the signal strength and angular location of the echoed target signals; and

third processor means for processing the matched filter output signals by means of individual threshold detectors respectively coupled to each of the matched filters to identify those matched filter output signals having signal strengths above a predetermined threshold;

whereby the existence of a detected target is determined by each matched filter whose output signal is above the predetermined threshold, and the angular direction of each target corresponds to the direction that the corresponding encoded sonar signal was transmitted.

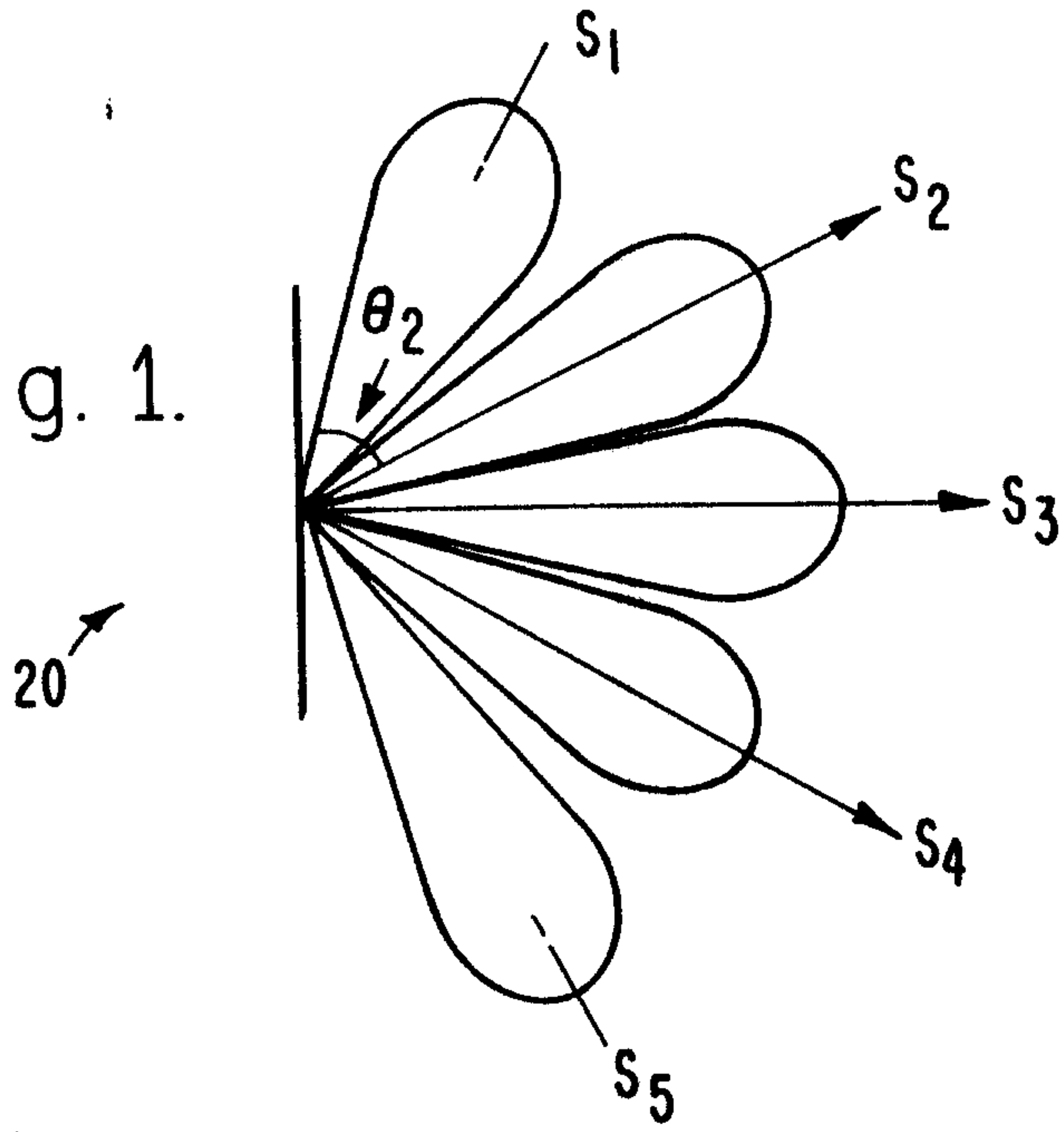

S1
S2
S3
S4
S5
θ2
20

Fig. 1.

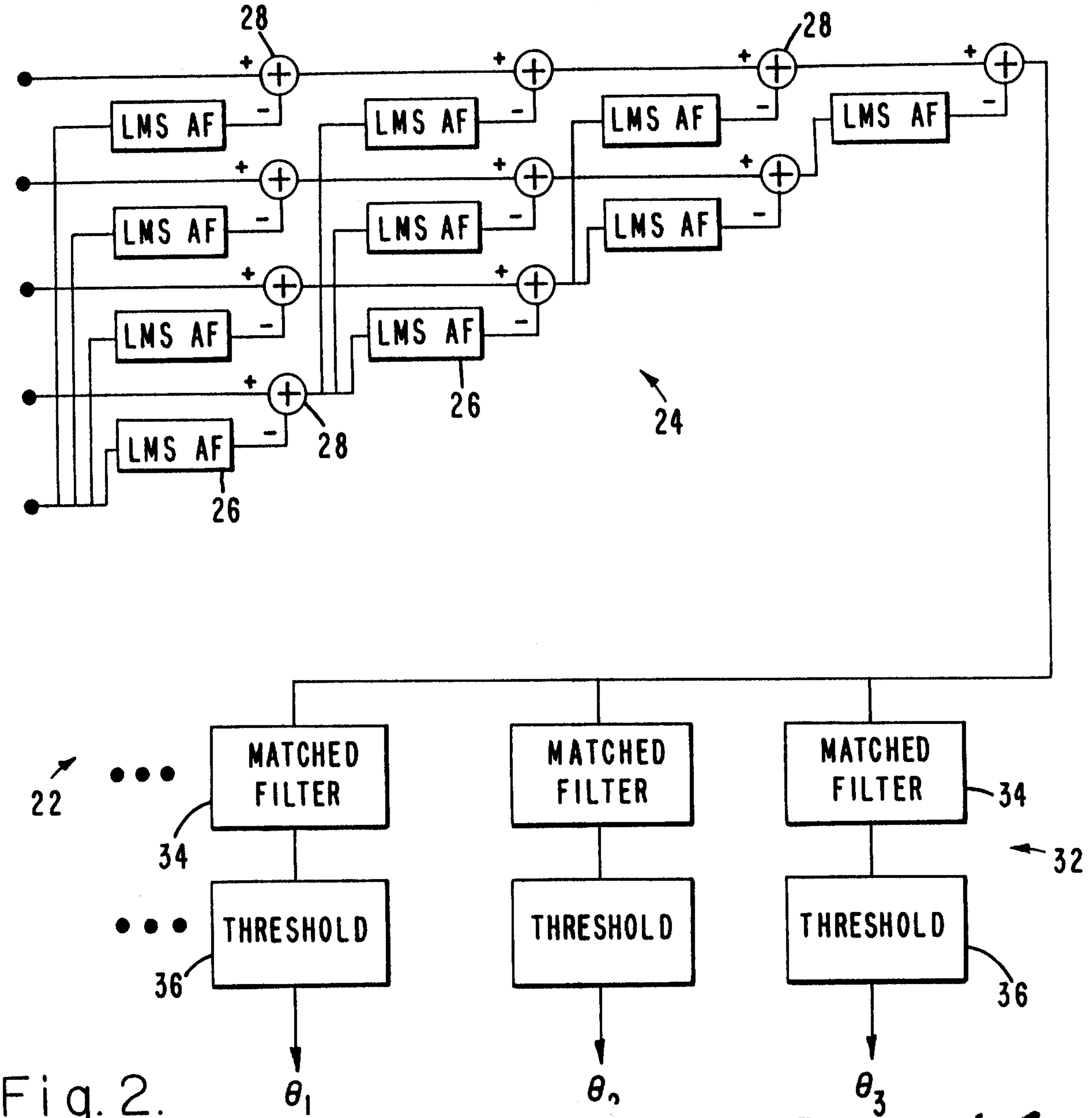

28
28
28
LMS AF
LMS AF
LMS AF
LMS AF
LMS AF
LMS AF
LMS AF
LMS AF
LMS AF
LMS AF
26
26
24
22
MATCHED FILTER
MATCHED FILTER
MATCHED FILTER
34
34
32
THRESHOLD
THRESHOLD
THRESHOLD
36
36
θ1
θ2
θ3

Fig. 2.

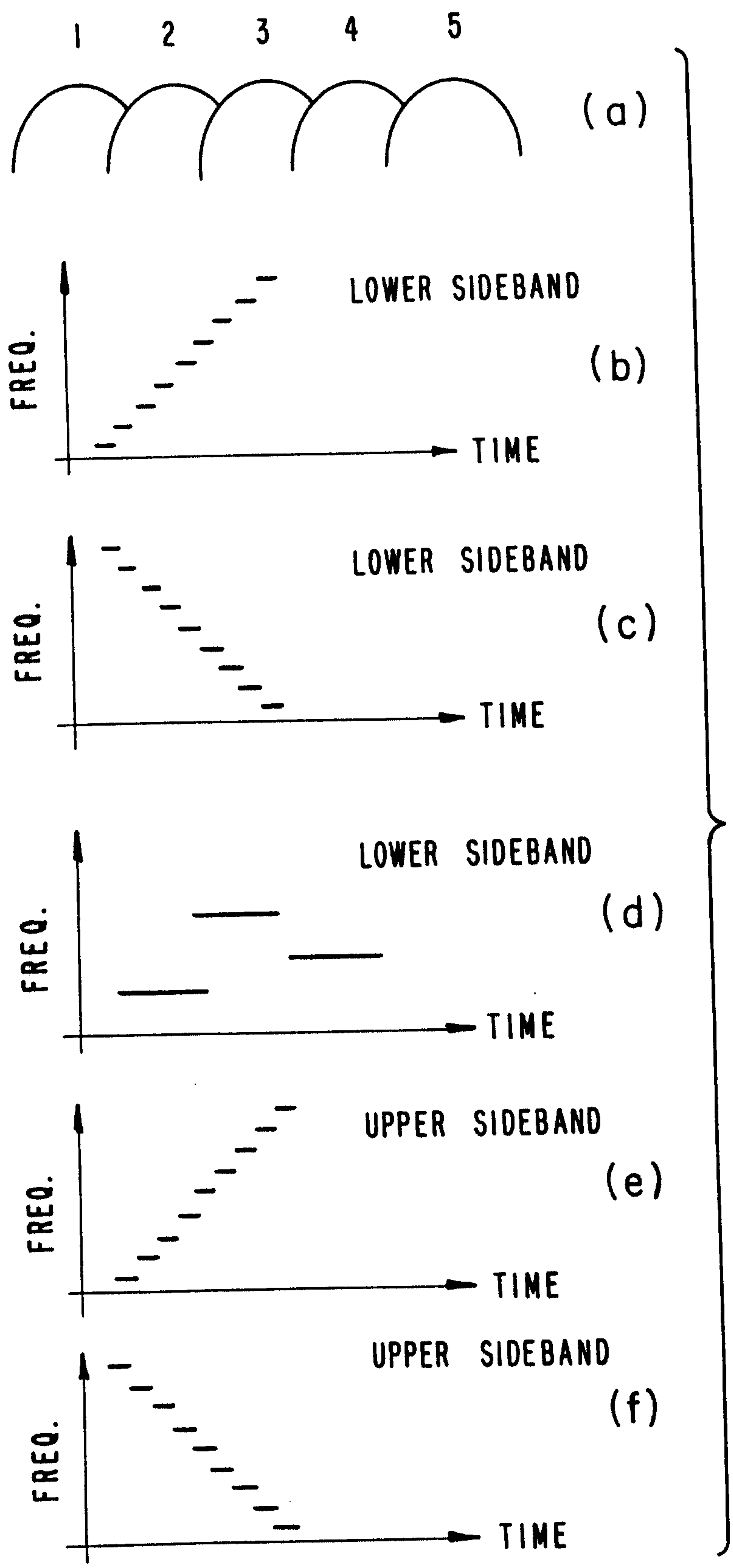

1
2
3
4
5
(a)
LOWER SIDEBAND
FREQ.
(b)
TIME
LOWER SIDEBAND
FREQ.
(c)
TIME
LOWER SIDEBAND
FREQ.
(d)
TIME
UPPER SIDEBAND
FREQ.
(e)
TIME
UPPER SIDEBAND
FREQ.
(f)
TIME

Fig. 3.

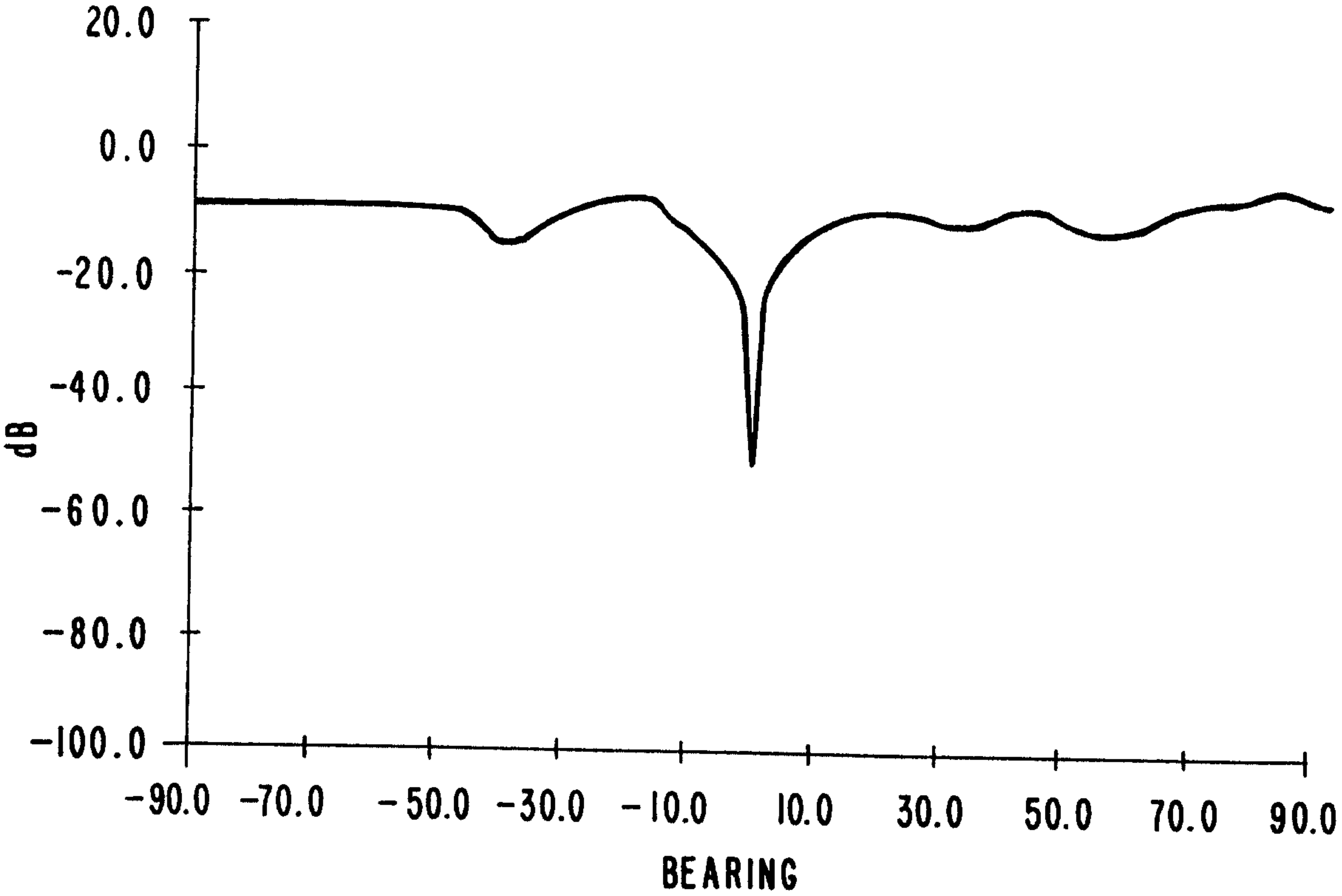

20.0
0.0
-20.0
-40.0
dB
-60.0
-80.0
-100.0
-90.0 -70.0 -50.0 -30.0 -10.0 10.0 30.0 50.0 70.0 90.0
BEARING

Fig. 4.

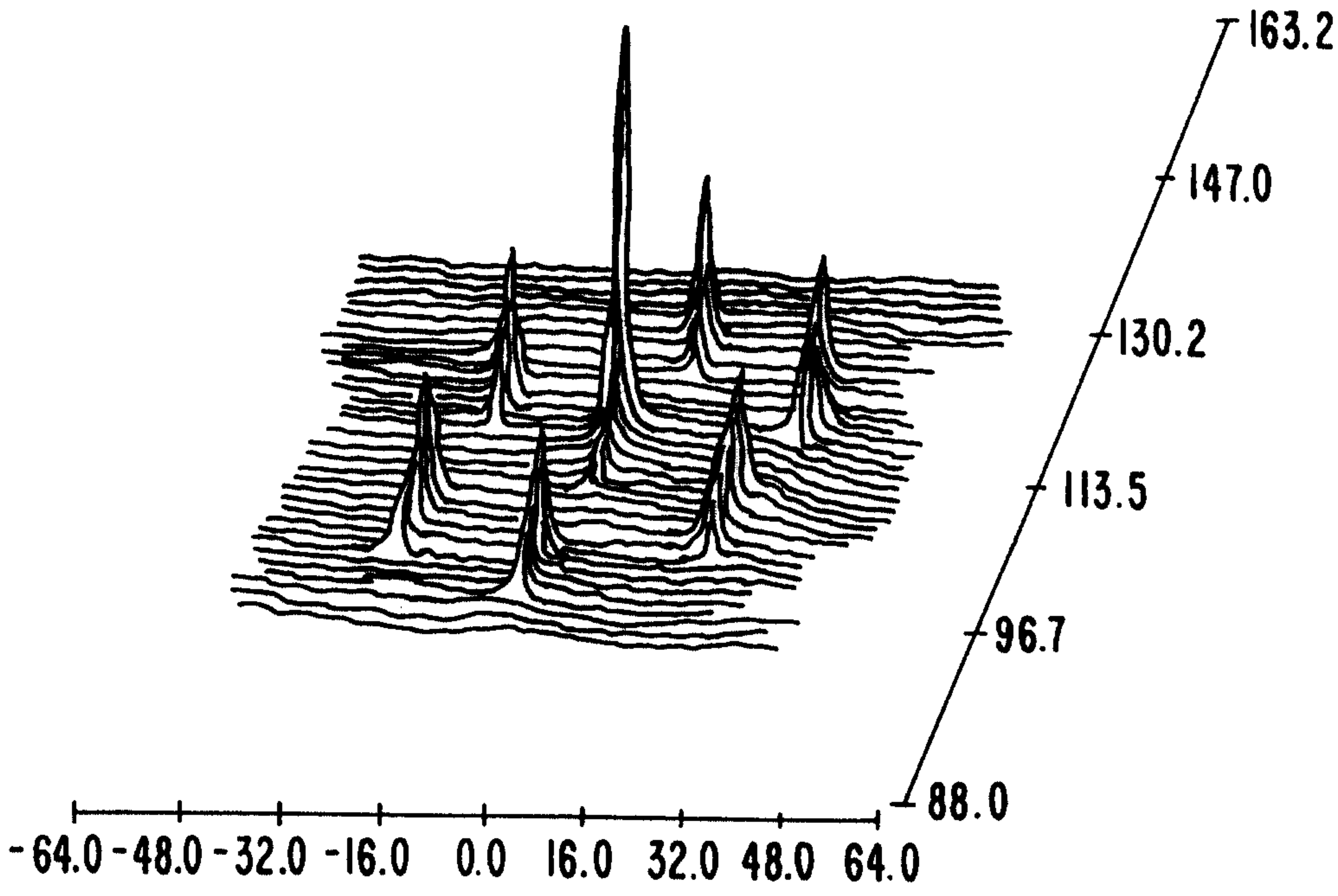
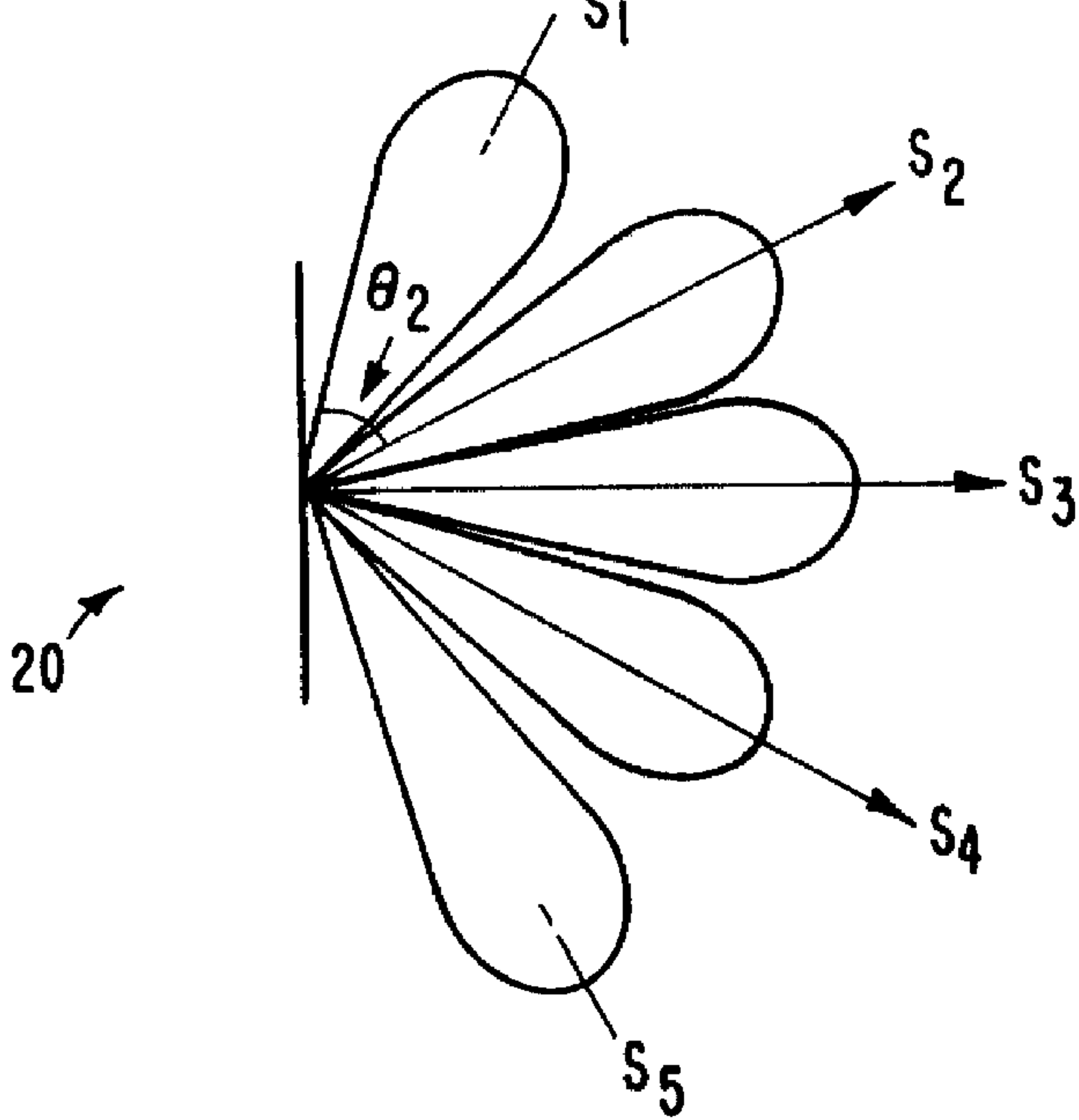

163.2
147.0
130.2
113.5
96.7
88.0
-64.0 -48.0 -32.0 -16.0 0.0 16.0 32.0 48.0 64.0

Fig. 5.



S_1
S_2
θ_2
S_3
20
S_4
S_5