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(54) **CORRELATION METHOD FOR SONAR OR RADAR**

(75) Inventors: **Anthony L. Scoca**, Hicksville, NY (US); **James G. Huber**, North Babylon, NY (US)

(73) Assignee: **Lockheed Martin Corporation**, Bethesda, MD (US)

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G01S 15/00 (2006.01)

(52) **U.S. Cl.** **367/89**

(58) **Field of Classification Search** 367/87, 367/89

See application file for complete search history.

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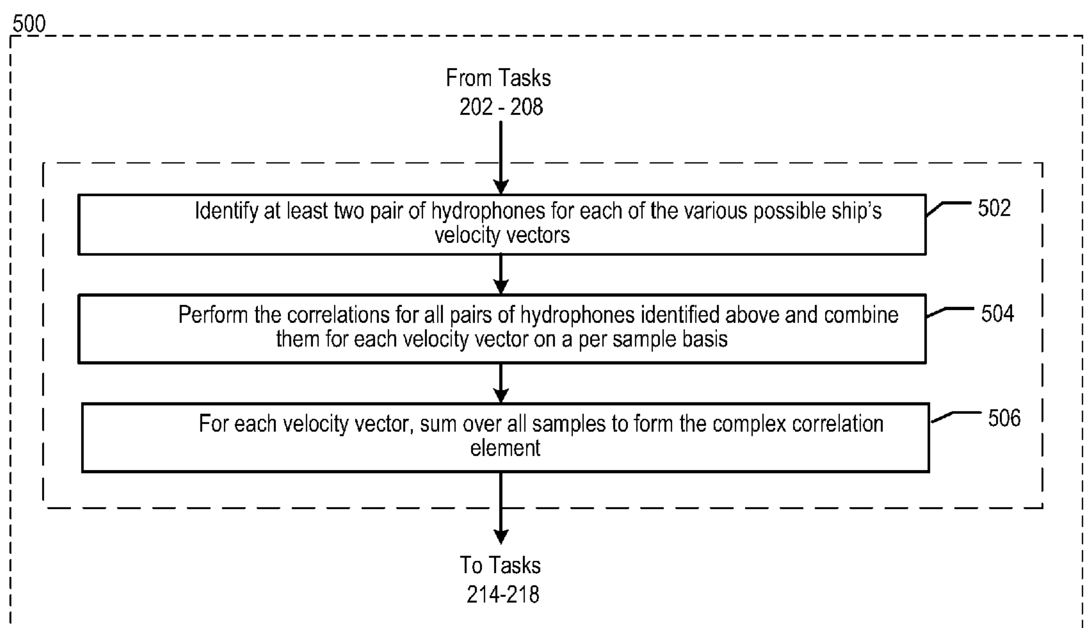
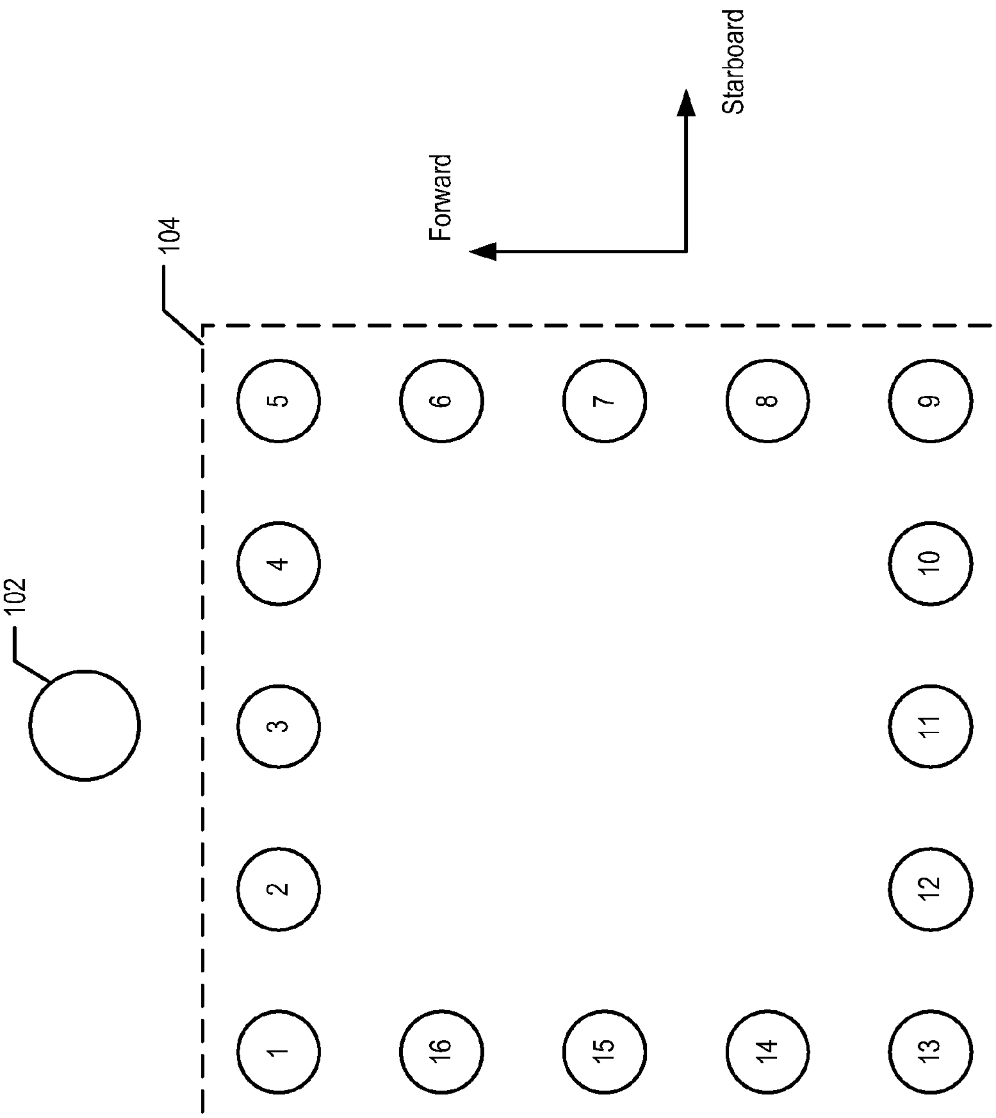
Primary Examiner — Thomas Tarcza
Assistant Examiner — James Hulka
(74) *Attorney, Agent, or Firm* — DeMont & Breyer, LLC

(57) **ABSTRACT**

A method for improving the accuracy of velocity-measuring spatial correlation SONAR or RADAR is disclosed. The method uses data from multiple receiver pairs for each velocity vector, thereby providing improved utilization of a fixed sized receiver array.

14 Claims, 6 Drawing Sheets





100

FIG. 1 (Prior Art)

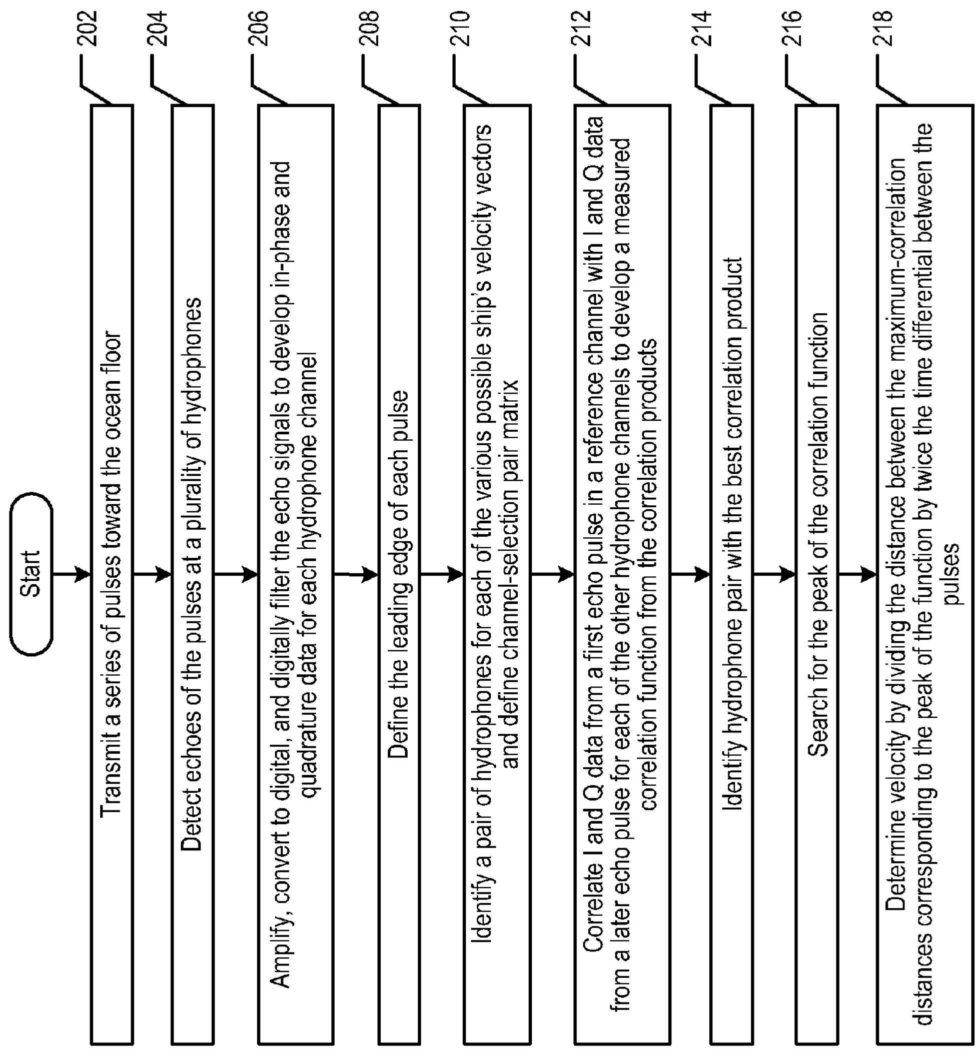


FIG. 2 (Prior Art)

200

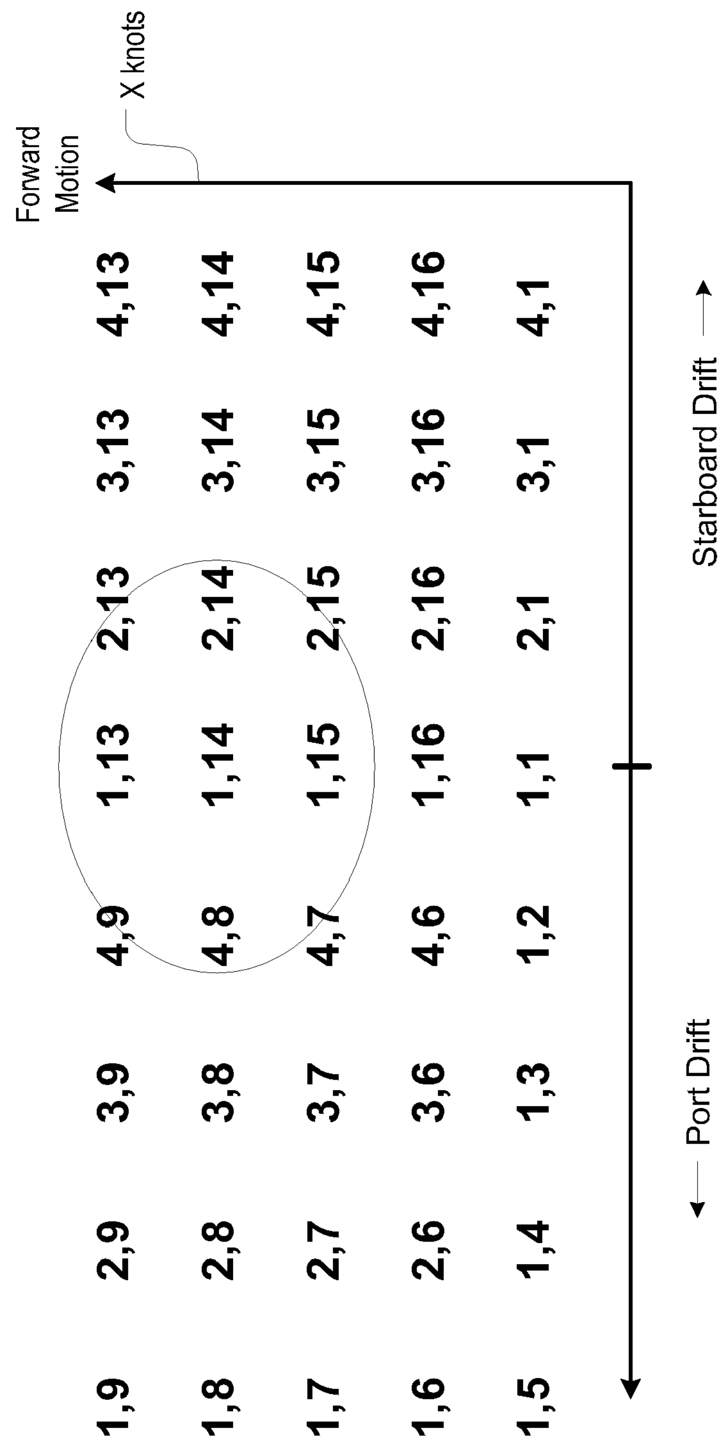


FIG. 3 (Prior Art)

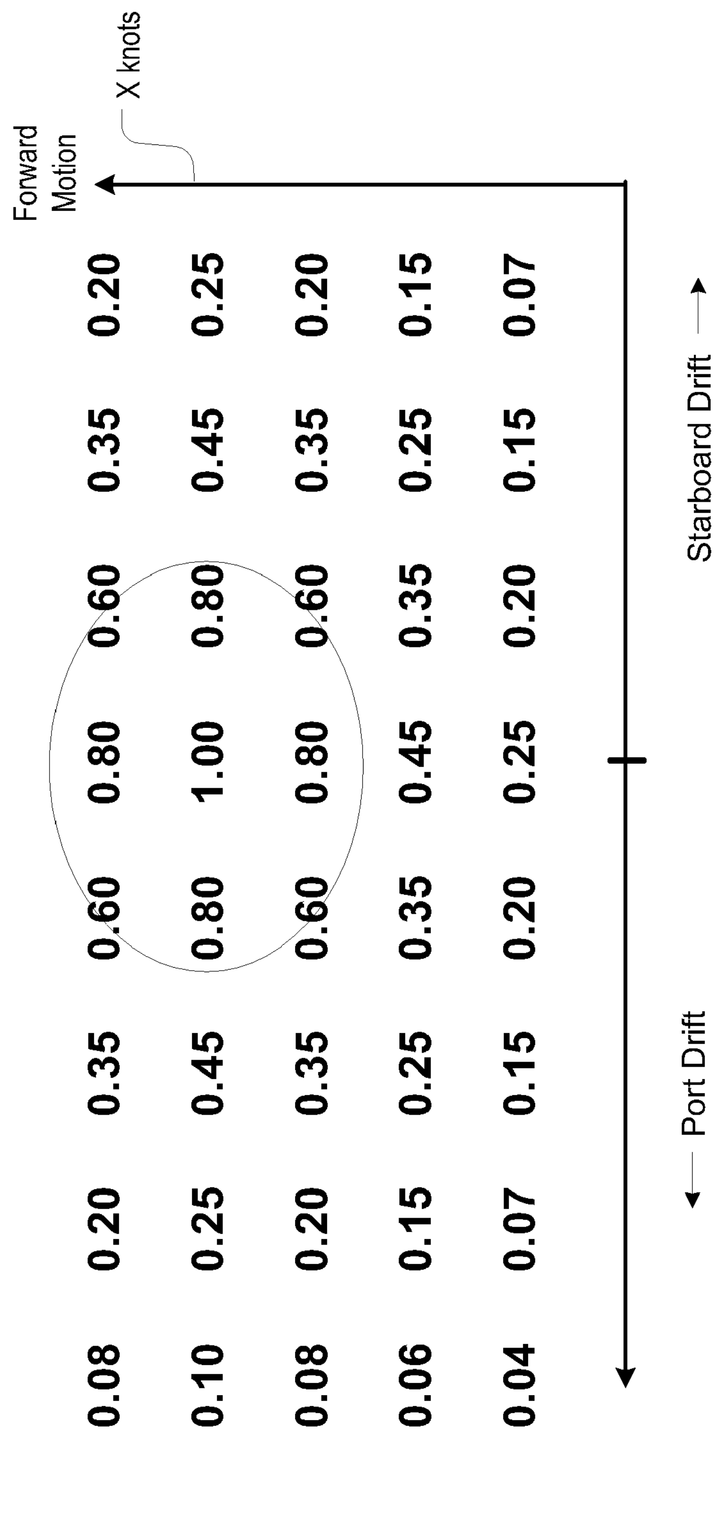


FIG. 4 (Prior Art)

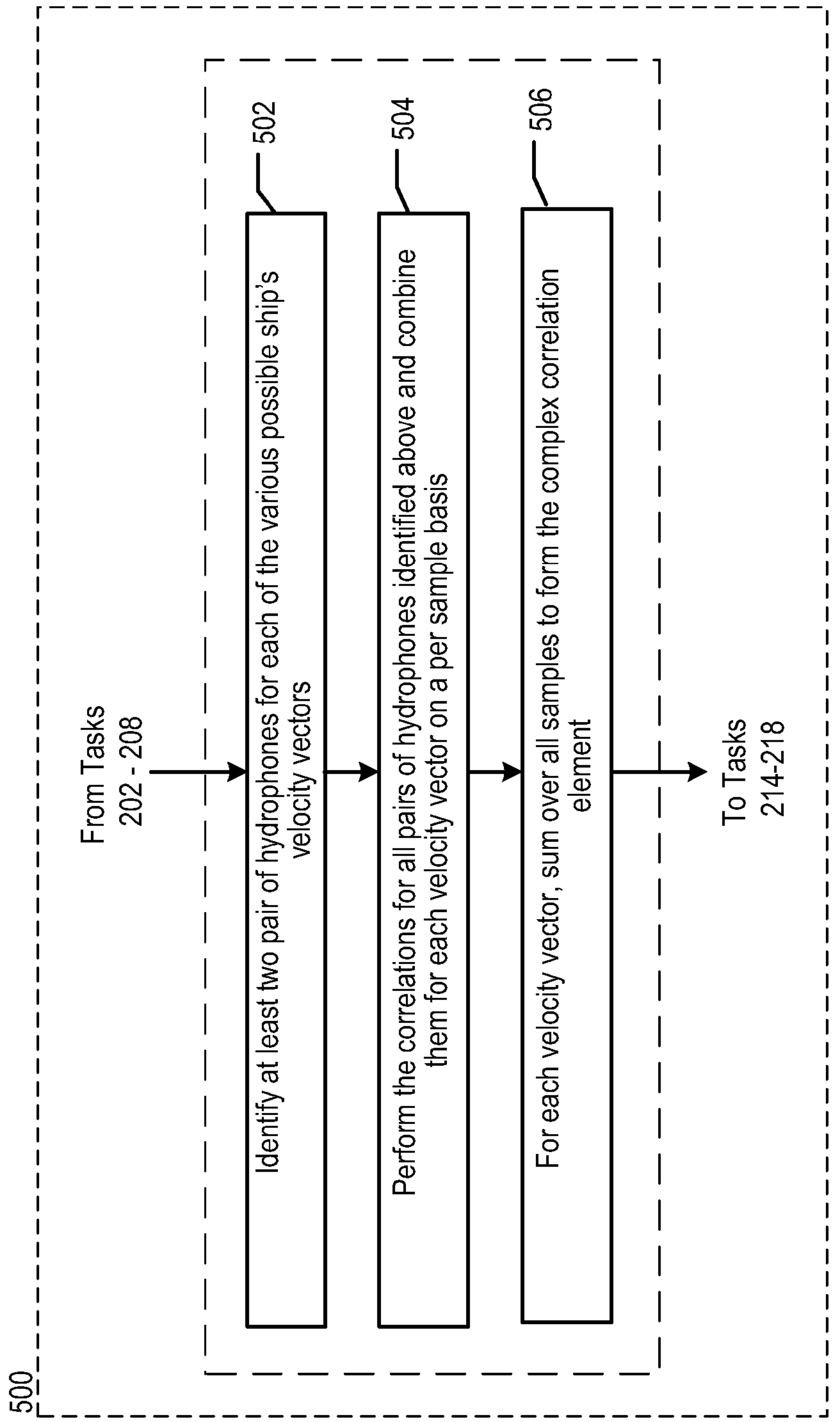

500
From Tasks
202 - 208
502
Identify at least two pair of hydrophones for each of the various possible ship's velocity vectors
504
Perform the correlations for all pairs of hydrophones identified above and combine them for each velocity vector on a per sample basis
506
For each velocity vector, sum over all samples to form the complex correlation element
To Tasks
214-218

FIG. 5

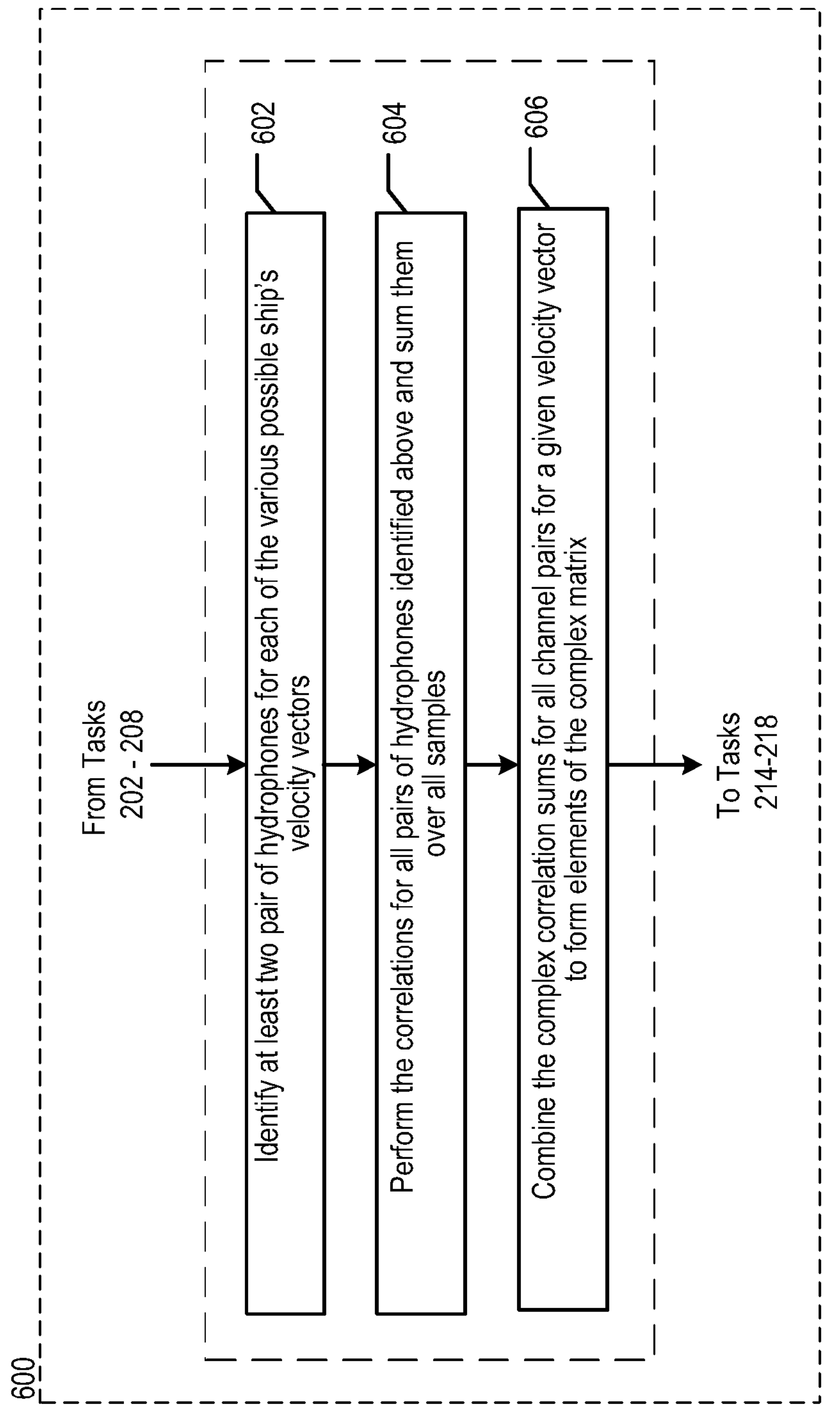

600
From Tasks
202 - 208
602
Identify at least two pair of hydrophones for each of the various possible ship's velocity vectors
604
Perform the correlations for all pairs of hydrophones identified above and sum them over all samples
606
Combine the complex correlation sums for all channel pairs for a given velocity vector to form elements of the complex matrix
To Tasks
214-218

FIG. 6

CORRELATION METHOD FOR SONAR OR RADAR

FIELD OF THE INVENTION

The present invention relates generally to velocity-measuring correlation SONAR or RADAR systems.

BACKGROUND OF THE INVENTION

A velocity-measuring correlation SONAR or RADAR functions by correlating a first echo of a first transmitted pulse received at a first receiver with a first echo from a later-transmitted pulse received at a second receiver. Maximum correlation occurs when the ray path of the initial transmission (e.g., from the transmitter to the ocean floor and back to the first receiver, etc.) is equal to the ray path of the second transmission. The velocity of the vessel is calculated based upon the distance traveled by the vessel between the transmission and reception of the pulses. See, for example, U.S. Pat. No. 4,244,026 to Dickey and U.S. Pat. No. 5,315,562 to Bradley et al.

Examples of velocity-measurement SONARs are spatial correlation SONAR and temporal correlation SONAR, which rely on selecting a maximum correlation between hydrophones in the case of spatial correlation or pulses in the case of temporal correlation.

Spatial correlation SONAR calculates the velocity of a vessel by transmitting two or more pulses towards the ocean bottom, detecting echoes of the pulses on a planar two-dimensional array of hydrophones, determining which two hydrophones in the array correlate the best, and dividing the distance between those hydrophones by twice the time differential between the pulses. Peak correlation might take place between hydrophones, in which case an interpolation scheme is used. Since the later echo is received on a number of receivers located in the two-dimensional array, a velocity solution can be estimated for more than a single direction (e.g., forward and athwart components, etc.).

Velocity estimates from correlation SONARs are subject to accuracy degradation due to various random and bias errors, and accuracy is particularly degraded under extended operational conditions, such as shallow ocean bottom depths and high ship's speed.

The prior art has attempted to improve the accuracy of velocity-measuring spatial correlation SONARs via a variety of techniques, including (1) processing more data via increased processing throughput, (2) altering the physical dimensions of the hydrophone array, (3) altering the number of hydrophones in the array, (4) modifications to transmit pulses and/or pulse patterns, and (5) applying temporal correlation SONAR techniques, among others.

A further approach to improving the accuracy of velocity-measuring correlations SONARs was patented by the present inventors in U.S. Pat. No. 7,295,492. The method disclosed therein develops multiple velocity estimates using different receiver pairs. The velocity estimates are filtered to yield a single improved velocity solution.

It would be beneficial to improve the accuracy of velocity-measuring spatial correlation SONARs via a method that (1) does not physically alter an existing receiver array, (2) is less-processing intensive than prior art enhanced-processing approaches, and (3) provides particularly improved accuracy under extended operational conditions.

SUMMARY OF THE INVENTION

The illustrative embodiment of the present invention provides an improvement in velocity-measurement accuracy of a

spatial correlation SONAR. After reading this specification, those skilled in the art will be able to apply the techniques described herein to RADAR (RAdio Detection And Ranging).

In accordance with the illustrative embodiment of the invention, multiple receiver (e.g., hydrophone channel, etc.) pair data is utilized for each velocity vector. In some embodiments all available receiver pair data is used for each velocity vector. That is, multiple (or all) receiver pairs are correlated and these correlations are combined for each velocity matrix position. This yields a single matrix of combined correlation values. The method executes the velocity solution using the array with these combined correlations.

In the illustrative embodiment, receiver pair data is correlated on a data sample by sample basis and then all those samples are summed to form a matrix element. A data sample is typically a pair of in-Phase (I) and Quadrature (Q) values formed as a result of receiving echo data on an array of sensors (such as hydrophones), amplification, analog-to-digital conversion, band pass filtering, and base-banding.

In an alternative embodiment, a correlation is formed for a pair of receiver channels as per the prior art, but then this correlation process is repeated for up to all available receiver pairs which support the velocity vector for a particular matrix element. These elements are then combined to yield a final matrix element.

The methods described herein result in a more efficient use of a fixed-size hydrophone array for all operating conditions and are particularly beneficial for improving velocity solutions in extended operational environments such as high ship's speed or shallow ocean-bottom depths.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts a schematic diagram of prior-art, spatial correlation SONAR transceiver system **100**.

FIG. **2** depicts a prior-art method **200** for performing velocity measurement using spatial correlation SONAR.

FIG. **3** depicts prior-art receiving hydrophone array pairs for peak correlation of a first pulse on one receiver and a later pulse on another receiver in the array illustrated in FIG. **1**, all as a function of the velocity being measured (magnitude, forward and athwart components). The ellipse in FIG. **3** depicts receiver pairs which yield highest correlation for (x,0) velocity.

FIG. **4** depicts typical correlation magnitude in the prior art for (x,0) case in which each value corresponds to a position in the receiver pairs array of FIG. **3**.

FIG. **5** depicts method **500** for performing velocity measurement using spatial correlation SONAR in accordance with the illustrative embodiment of the present invention.

FIG. **6** depicts alternative method **600** for performing velocity measurement using spatial correlation SONAR.

DETAILED DESCRIPTION

FIG. **1** depicts a schematic diagram of prior-art, spatial correlation SONAR transceiver system **100** for transmitting and receiving signals for measuring velocity, among any other purposes. System **100**, which may be mounted on the underside of a ship, comprises transmitter **102** and receiver array **104**. Receiver array **104** comprises receivers **1** through **16**, wherein each receiver is commonly referred to as a "hydrophone." The terms "receiver" and "hydrophone" are used interchangeably herein.

Transceiver system **100** interfaces with other equipment (not depicted), such as amplifiers, analog-to-digital converters, digital filters, processors, and the like for processing the signals received by array **104** to ultimately provide a velocity solution.

The hydrophone arrangement depicted as array **104** is a typical prior-art hydrophone array. Array **104** is considered here for pedagogical purposes; after reading this specification, those skilled in the art will appreciate that the embodiments described herein are applicable to other transceiver systems as well.

A conventional method for performing velocity measurement via spatial correlation SONAR is discussed with respect to FIG. **2**. This discussion provides background for the illustrative embodiment of the present invention.

Discussion of Conventional Velocity-Measuring Spatial Correlation Sonar.

At task **202** of method **200**, a series of pulses are transmitted vertically towards the ocean bottom via transmitter **102**.

At task **204**, echoes are detected at each hydrophone in receiver array **104**. For a ground-referenced correlation SONAR, the echoes are returned from the ocean floor. For a water-referenced correlation SONAR, the echoes are returned from the water volume beneath the ship.

At task **206**, pulse echo data is amplified, converted from analog to digital, and then digitally filtered to yield in-phase ("I") and quadrature ("Q") data for each hydrophone channel. This I and Q data contains all of the amplitude and phase information contained in the echo pulses, but is base banded and thus vastly reduced in data rate from the A-to-D-converted echo signals.

In accordance with task **208**, a pulse location algorithm is employed to define the leading edge of each pulse.

At task **210**, a pair of prime hydrophones is identified for each of the ship's various possible velocity vectors, given the arrangement of receiver array **104**. A channel-selection pair matrix, which includes all of the possible non-redundant ship's velocity vectors, is created as the result of performing task **210**.

At task **212**, I and Q data from a first echo pulse in a reference channel is correlated with I and Q data from a later echo pulse for each of the other channels, thereby forming a correlation product for each channel-selection pair (i.e., hydrophone pair). These individual correlation products together describe a measured correlation function.

At task **214**, the hydrophone pair having the best correlation product (the "best-correlated" hydrophone pair) is identified.

At task **216**, an M-by-M array of hydrophone-pair correlation products is formed (e.g., M equals three, etc.) in the channel-selection pair matrix, wherein the array is centered about the best-correlated hydrophone pair from task **214**. A search for the peak of the correlation function is performed, which can possibly lie somewhere between the best-correlated hydrophone pair and another hydrophone pair in the M-by-M array. For example, an interpolation algorithm can be used on the correlation products, in order to find the location of the peak in relation to the hydrophone pairs.

The correlation function that is described by the correlation products and the peak is a relationship between i) the correlation between hydrophone pairs and ii) their displacement in the x and y directions, where "x" and "y" correspond to the fore/aft and athwart-ship directions, respectively. The location of the correlation peak provides "maximum-correlation distance" components in the fore/aft and athwart-ship directions. The velocity is determined at task **218** by dividing the maximum-correlation distance for each directional component by twice the time differential between the pulses.

Method **200** is repeated, periodically or sporadically, in order to provide successive velocity measurements.

FIG. **3** depicts prior-art receiving hydrophone array pairs for peak correlation of a first pulse on one receiver and a later pulse on another receiver in the array illustrated in FIG. **1**, all as a function of the velocity being measured (magnitude, forward and athwart components). The receiver pairs depicted in FIG. **3** are those that are important for forward motion; receiver pairs for backward motion are not depicted.

For example, for forward speed of x knots and athwart speed 0 knots (x,0), peak correlation will be measured between a first pulse from receiver **1** and a later pulse from receiver **14**. The ellipse in FIG. **3** depicts receiver pairs which yield highest correlation for (x,0) velocity.

FIG. **4** depicts typical correlation magnitude for (x,0) case in which each value corresponds to a position in the receiver pairs array of FIG. **3**.

Up to this point in the Detailed Description, the discussion has summarized conventional spatial correlation SONAR methodology for velocity measurement. FIG. **3** depicts receiver pairs for each velocity vector position. A variable number of "back-up" hydrophone pairs are, however, generally available for most or all such positions. For example, the pair (**1**,**14**) has back-up pairs (**13**,**16**), (**5**,**8**), (**6**,**9**), as can be readily seen with reference to FIG. **1**.

In accordance with a method in accordance with the illustrative embodiment, some or all back-up hydrophone pairs are used to provide improved correlations for some or all of the velocity-vector positions. This benefit accrues due to a reduction in random and bias velocity errors at each velocity-vector position. These velocity errors result from many sources, including, without limitation:

Mechanical hydrophone installation errors;

Hydrophone acoustic center errors;

Noise effects (all noise sources, sea noise, biologics, ship's self noise, electronics self noise);

Hydrophone beam-pattern variations;

Deleterious effects of any failing or otherwise marginal components in each hydrophone receive channel processing chain (e.g., hydrophone, connections, electronics).

Details of a Method for Velocity Measurement in accordance with the Illustrative Embodiment of the Present Invention.

FIG. **5** depicts method **500** for a velocity-measuring spatial correlation SONAR in accordance with the illustrative embodiment of the present invention. Method **500** is similar to conventional method **200**; it departs therefrom at tasks **310** and **312** by developing a complex data array D(i, m, n) of I and Q data, wherein i=time sample number, m=receiver number, and n=echo number.

With respect to method **500**, pulses are transmitted toward the ocean floor, an echo received by a hydrophone is amplified, analog-to-digital converted, band-pass filtered, frequency translated to baseband, and represented by In-Phase (I) and Quadrature (Q) components (tasks **202** through **206**). The I and Q data contains all information about the echo (amplitude and phase) except for its known carrier frequency and is sufficient to execute correlation velocity estimation processing. The leading edge of each pulse is identified in task **208**.

In accordance with task **502**, two or more pairs of hydrophones for each of the various possible ship's velocity vectors are identified. In some embodiments, all available pairs of hydrophones are identified for each possible velocity vector.

In accordance with task **504**, I/Q data from an early pulse on one receiver is correlated with I/Q data from a later pulse and modulated components from the clutter source and EM tagging device only. A first coherent receiver may detect a time-average of un-modulated components of the first sample received reflected signals using the second sample of the transmit test signal as the reference signal, wherein the reference signal is un-modulated. A second coherent receiver may be provided to detect a time-average of modulated components of the second sample received reflected signals using the second sample tagging signal. A module is provided to determine the radar cross section of the target with reflected signals from the clutter source removed by monitoring the time-average of the modulated components of the received reflected signals, adjusting the time-average of a contribution of the clutter source and EM tagging surface to the un-modulated components, and subtracting these adjusted components of the received reflected signals from the received reflected signals. An output device may present the radar cross section of the target with reflected signals from the clutter source and EM tagging device removed.

In accordance with another embodiment, a system for performing radar cross section measurements of a target may include a coherent signal generator to generate a test signal at a selected test frequency. A power divider may be provided to split the test signal into an un-modulated transmit test signal to be transmitted by the system and a sample of the transmit test signal. A radio frequency (RF) pulse forming switch may form the un-modulated transmit test signal into pulses for transmission to the target. A pulse generator may control timing of the RF pulse forming switch. A counter may receive pulse signals from the pulse generator to provide a modulated tagging signal that changes state with each pulse at a predefined modulation frequency. The modulated tagging signal is useable to toggle an EM tagging device between a first radar cross section state and a second radar cross section state to spectrally tag a clutter source. A coherent receiver may be used to detect reflected signals received by the system. A signal processor may process the reflected signals to provide a radar cross section of the target with reflected signals from the clutter source and EM tagging device removed. The system may also include an output device to present the radar cross section of the target with reflected signals from the clutter source and EM tagging device removed.

In accordance with another embodiment, a method for performing radar cross section measurements of a target may include transmitting a predetermined signal to the target and transmitting a spectral tagging signal to an EM tagging device located proximate to a clutter source to spectrally tag the clutter source. The EM tagging device may spectrally tag the clutter source by causing changes in an electromagnetic signal reflected by the clutter source when the predetermined signal is transmitted to the target, the clutter source and the EM tagging device. The method may also include receiving reflected signals from the target, the clutter source and the EM tagging device. Contributions of the clutter source and the EM tagging device to an un-modulated component of the received reflected signals may be determined by monitoring variations in a modulated component of the received reflected signals. The method may further include adjusting for the variations in the un-modulated component to remove contributions of the clutter source and the EM tagging device and any interactions with the target from the received reflected signals to provide the radar cross section of the target without influence of the clutter source. The radar cross section of target may be presented without influence of the clutter source.

In accordance with another embodiment, a method for performing radar cross section measurements of a target may include transmitting test pulse signals at a selected pulse repetition frequency to the target. The method may also include generating tagging pulses to toggle a spectral tagging device between a first RCS state and a second RCS state with each successive tagging pulse, wherein even numbered pulses correspond to the first RCS state and odd numbered pulses correspond to the second RCS state. The spectral tagging device is placed proximate to a clutter source to spectrally tag the clutter source. The method may also include computing a sum of the even and odd numbered reflected pulses to represent un-modulated reflected signals and computing a difference of the even and odd numbered reflected pulses to represent modulated reflected signals. The radar cross section of the target without interference of the clutter source may be determined by monitoring the modulated reflected signals to detect variations in contributions from the clutter source and EM tagging device to the un-modulated reflected signals. Adjusting for this variation allows the removal of these contributions from the combined reflected signal.

In accordance with another embodiment, a method for performing radar cross section measurements of a target may include transmitting a predetermined signal at a selected frequency with only a clutter source and spectral tagging device in a RCS range. The method may also include driving the spectral tagging device to cause a periodic time varying change of the spectral tagging device between a first RCS state and a second RCS state at a chosen frequency to produce clutter source scattering at the selected frequency and a sideband frequency that is a combination of the selected frequency and the chosen frequency. The scattered signals at the selected frequency and the sideband frequency may be measured without the target in the RCS range. A ratio of the scattered signals, without the target in the RCS range, at the selected frequency to the scattered signals at the sideband frequency may be determined. The predetermined signal may again be transmitted at the selected frequency with the target in the RCS range and the EM tagging device may be driven to cause the periodic time varying change of the spectral tagging device between the first RCS state and the second RCS state at the chosen frequency. Scattered signals may be measured at the selected frequency and the sideband frequency. Which scattered signals are from the clutter source at the selected frequency may be determined by multiplying the ratio of the scattered signals at the selected frequency without the target in the RCS range to the scattered signals at the sideband frequency without the target in the RCS range times the scattered signals at the sideband frequency with the target in the RCS range. A radar cross section of the target may be determined by subtracting the scattered signals from the clutter source from an average scattered signal with the target in the RCS range at the selected frequency with the spectral tagging device being driven between the first and second RCS states.

Other aspects and features of the present invention, as defined solely by the claims, will become apparent to those ordinarily skilled in the art upon review of the following non-limited detailed description of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The following detailed description of embodiments refers to the accompanying drawings, which illustrate specific embodiments of the invention. Other embodiments having different structures and operations do not depart from the scope of the present disclosure.

For channel pairs z=1 to y, where y is the number of channel pairs available for this array position, each element is broken down into amplitude (expression [16] below) and phase (expression [17] below) (see also, expressions [10] and [11], above):

$$AMP(I, J) = \frac{\sum_{z=1}^{y} \sqrt{RE(A_z(I, J)^2 + IM(A_z(I, J))^2}}{y} \quad [16]$$

$$PH(I, J) = \frac{\sum_{z=1}^{y} \tan^{-1}\left(\frac{IM(A_z(I, J))}{RE(A_z(I, J))}\right)}{y} \quad [17]$$

The real and imaginary parts of the amplitude and phase averages calculated above are next combined to form the A matrix elements, as per expression [18]:

$$A(I,J)=AMP\,(I,J)*Cos(PH(I,J))+jAMP*(I,J)Sin(PH(I,J)) \quad [18]$$

Where: A(I, J) is the complex correlation over all channel pairs for matrix position (I,J).

Thus, illustrative method **500** performs combining processing over samples and alternative method **600** performs combining processing over channels or receivers. Compared to method **500**, method **600** reduces the amount of averaging required, and, as a result, is faster and more efficient.

These methods can be applied to an existing spatial correlation SONAR system without changes thereto except for software (i.e., no changes to sensors or processing hardware are required).

It is to be understood that the disclosure teaches just one example of the illustrative embodiment and that many variations of the invention can easily be devised by those skilled in the art after reading this disclosure and that the scope of the present invention is to be determined by the following claims.

What is claimed is:

1. A method comprising:

identifying, in processing electronics, at least two pair of receivers for all possible velocity vectors for a moving object;

forming correlations, in the processing electronics, using spatial correlation techniques, for data samples comprising In-phase and Quadrature components for all pairs of identified receivers;

combining the correlations in the processing electronics for each of the velocity vectors;

forming a correlation array element in the processing electronics by summing over all correlations for each velocity vector;

forming a correlation array in the processing electronics from all of the correlation array elements; and

determining velocity of the moving object using the correlation array.

2. The method of claim **1** wherein all available pairs of receivers are identified in the processing electronics for each possible velocity vector.

3. The method of claim **1** further comprising:

receiving a signal at a receiver;

processing the signal, whereby the processing comprises sampling the signal and representing each sample in terms of the In-Phase (I) and the Quadrature (Q) components.

4. The method of claim **3** wherein the task of processing the signal further comprises:

amplifying the signal;

digitizing the signal;

bandpass filtering the signal; and

frequency translating the signal to baseband.

5. The method of claim **3** wherein the receiver is a hydrophone.

6. The method of claim **3** wherein the receiver is an antenna element.

7. The method of claim **3** further comprising transmitting a pulse, wherein the signal is an echo of the pulse.

8. The method of claim **7** wherein the pulse is transmitted through water.

9. A method for determining velocity of a moving object via spatial correlation techniques, wherein the method comprises:

transmitting a series of pulses from the moving object and detecting echoes of the pulses at a plurality of receivers;

generating, in processing electronics, in-phase and quadrature data from data pertaining to the echoes;

identifying, in the processing electronics, at least two pairs of receivers for all possible velocity vectors for a moving object;

forming, in the processing electronics, a correlation array comprising correlation array elements developed from data obtained from the at least two pairs of receivers for all the velocity vectors; and

determining velocity of the moving object using the correlation array.

10. The method of claim **9** wherein the operation of identifying at least two pairs of receivers further comprises identifying all available receiver pairs for each velocity vector and wherein the operation of forming a correlation array further comprises forming, in the processing electronics, a correlation array comprising correlation array elements developed from data obtained from all available receiver pairs for each velocity vector.

11. The method of claim **9** wherein the operation of forming a correlation array further comprises:

correlating, in the processing electronics, using spatial correlation techniques, data from the at least two receiver pairs;

combining, in the processing electronics, the correlated data for each velocity vector; and

forming, in the processing electronics, a complex correlation element by summing, for each velocity vector, the correlated data.

12. The method of claim **9** wherein the operation of forming a correlation array further comprises:

correlating, in the processing electronics, using spatial correlation techniques, data from the at least two receiver pairs;

forming complex correlation sums by summing, in the processing electronics, the correlated data for each velocity vector; and

forming a complex correlation element, in the processing electronics, by combining the complex correlation sums for the at least two receiver pairs for each velocity vector.

13. A method comprising:

identifying, in processing electronics, at least two pairs of receivers for all possible velocity vectors for a moving object;

forming correlations, in the processing electronics, using spatial correlation techniques, for data samples comprising In-Phase and Quadrature components for the at least two pairs of identified receivers;

forming a plurality of complex correlation sums for the at least two pair of identified receivers by summing, in the processing electronics, all correlations for each velocity vector;

forming a correlation array element by combining, in the processing electronics, for the at least two pairs of identified receivers for each given velocity vector, the complex correlation sums;

forming a correlation array in the processing electronics from all of the correlation array elements; and

determining velocity of the moving object using the correlation array.

14. The method of claim **13** wherein all available pairs of receivers are identified, in the processing electronics for each possible velocity vector.

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