

HYDROACOUSTIC RANGING SYSTEM

TECHNICAL FIELD

1 This invention relates to apparatus for transmitting and receiving
hydroacoustic pulses used to determine the spatial separation between pairs
of such apparatus. More particularly, the invention in a preferred embodiment
relates to high-frequency hydroacoustic transceivers using digital-signal-
5 processing devices and deployed at known positions along the lengths of towed
hydrophone streamers for the purpose of determining their shapes and geodetic
positions.

BACKGROUND OF THE INVENTION

In search of geologic formations likely to trap oil or gas, the offshore
seismic exploration industry surveys the outer layers of the earth's crust
10 beneath the ocean by towing an array of hydrophones behind a boat,
periodically firing a source of acoustic energy, recording the responses of
the hydrophones to reflections of the acoustic energy from geologic
formations, and processing the seismic hydrophone data. The hydrophone array
is linearly arranged in a streamer whose depth is controlled. The streamer,
15 which may be a few kilometers long, may also include a head buoy tethered to
the head end of the streamer and a tail buoy to the tail end as surface
references.

1 Historically, only one streamer containing the hydrophone array was
deployed from the exploration boat during a survey. The accuracy of the
survey depended on, among other things, the accuracy of the estimate of the
shape of the hydrophone streamer and the accuracy of the positioning of a
5 known point on the streamer.

One way the shape can be estimated is by mechanically modeling the
streamer and computing its dynamic performance under various towing speeds
and ambient conditions. The accuracy of the estimation is, of course, only
as good as the model. Placing magnetic compasses and depth sensors along the
10 streamer represented an improvement in streamer shape estimation. Data
representing the depth and magnetic heading of sections of the streamer are
sent from the distributed compasses and depth sensors to a controller on
board the tow boat for immediate computation of streamer shape and for
storage of the raw data for later detailed processing. Accurate shape
15 estimation is achieved in this way.

As important as estimating the streamer's shape is tying its position to
a geodetic reference. Typically, radiopositioning receivers aboard the boat
are used to tie a spot on the boat to a geodetic reference. Accurate optical
positioning systems, such as a laser, are then used to tie the front buoy to
20 the geodetic reference. It is also common to have a radiopositioning receiver
aboard the tail buoy to fix its position. The positions of the distributed
compasses and depth sensors with respect to the buoys is then estimated based
on a model of the streamer and the buoy tethers. Inaccuracies in the model
result in absolute errors in transferring the geodetic reference from the
25 buoys to the streamer. Furthermore, the performance of optical positioning
systems degrades with inclement weather.

1 An important advance in the exploration for oil and gas is the development
of the three-dimensional seismic survey, often using more than one hydrophone
streamer. With multiple streamers towed behind one or more boats, more
seismic hydrophone data can be gathered in much less time than with a single
5 streamer, resulting in a significant reduction in exploration costs. With
multiple streamers, accurate estimations of the positions of the hydrophone
streamers with respect to each other and to the acoustic source are
essential. Fortunately, multiple streamers towed more or less in parallel
provide a geometry favorable for determining the positions of the streamers
10 with respect to each other, to the boat, to the acoustic source, or gun, and
to the buoys by means of acoustic ranging. With individual hydroacoustic
transceivers positioned along the streamers, on the acoustic source, on the
boat or boats, and on the buoys, acoustic transit times of pulses transmitted
by the transceivers and received by neighboring transceivers can be
15 telemetered to the controller on the boat where a position solution can be
performed and the raw data stored for further processing. Using the speed of
sound through the water, the controller converts the transit times into
spatial separations between pairs of transceivers in developing the position
solution. With information from a radiopositioning system and from depth
20 sensors and compasses positioned along the array, the position solution is
complete.

In a typical three-dimensional survey run using more than one streamer,
the towing boat or boats follow a more or less constant heading at a more or
less constant speed through the survey field. Waves, wind, current, and
25 inevitable variations in boat speed and heading continuously affect the
shapes of the streamers. Periodically, for example, every ten seconds, the

1 acoustic source, or gun, is fired. An impulse of compressed air is forced
into the water creating a bubble. The collapse of the bubble causes an
acoustic pulse that radiates through the water and into the earth.
Reflections of the pulse off geologic structures are picked up by the
5 hydrophones and data representing these reflections are sent to the
controller on the boat. Each firing of the gun and the associated interval
during which the acoustic echoes are detected is known as a shot point. It
is important that data sufficient to perform a complete position solution for
each shot point be available. For a group of long streamers with acoustic
10 transceivers distributed along each, many acoustic ranges must be measured.
In theory, it would be best if all of the ranges to be measured could be
determined simultaneously before the streamer has a chance to change its
shape and position. Unfortunately, that is not possible in practice. The
idea, then, is to measure all the acoustic ranges in as little time as
15 possible, which requires a high throughput for each transceiver.

The separation between a pair of transceivers is generally measured by
either one-way or two-way ranging. In one-way ranging, the first transceiver
transmits a hydroacoustic pulse at time t_s . The pulse propagates through the
water where it is received by the other transceiver at time t_r . The time
20 difference $t_r - t_s$ is proportional to the spatial separation of the two
transceivers. For an accurate one-way ranging measurement, the timers of both
transceivers must be closely synchronized because the value t_s is determined
by the transmitting transceiver while the value t_r is determined by the
receiving transceiver. In two-way ranging, each transceiver transmits a
25 pulse, the first at time t_{1s} and the second at t_{2s} . The first receives the
second's pulse at time t_{1r} , and the second receives the first's pulse at time

1 t_{2r} . Even if the timers of both transceivers are not synchronized, the
 5 spatial separation is proportional to $[(t_{1r}-t_{1s})+(t_{2r}-t_{2s})]/2$, because the
 offset between the timers is removed by the subtraction. Consequently, the
 precise synchronization required for one-way ranging is not needed in two-
 way ranging systems.

Although a two-way ranging system avoids the synchronization problem in
 one-way ranging, each transceiver in a two-way ranging scheme must do more
 processing, that is, each transceiver must receive a pulse for each range it
 is involved in measuring. The times of arrival of the received pulses and
 10 time of transmission of the transmitted pulse or their differences must be
 telemetered to the controller aboard the boat for each shot point. For a
 transceiver involved in the measurement of many ranges, a lot of data must
 be processed. Consequently, only a transceiver with a high throughput can
 be used effectively in a two-way ranging system.

15 Therefore, one aim of this invention is to provide a hydroacoustic
 transceiver capable of the high throughput rates required for two-way
 acoustic ranging without the need for accurate time synchronization.

If all the transceivers on a ranging system transmit on only one
 frequency, the only way to measure the various ranges is by time-division
 20 multiplexing, i.e., staggering the transmissions in such a way that no two
 pulses transmitted by different transceivers can arrive at any receiver
 simultaneously. Such a requirement, in addition to causing a transmit
 scheduling nightmare, results in a long time to measure many ranges, which
 causes errors in the position solution.

25 Another aim of the invention is to provide a transceiver capable of
 transmitting and receiving hydroacoustic pulses having selected

1 characteristics.

5 A further problem with acoustic ranging is errors caused by multipath interference. The straight-line path from transmitting transceiver to receiving transceiver is the direct path, which is the path defining the actual spatial separation. Other paths are due to reflections of the transmitted pulse off the ocean surface or floor. Depending on the differences in the lengths of the reflected paths with respect to the direct path, the reflected pulses may interfere with the direct pulse. Such interference can be destructive, preventing or distorting the detection of the pulse, resulting in an error in determining the time of arrival of the direct pulse. In addition, the shorter the transmitted pulse the less susceptible it is to multipath interference and the greater is its spatial resolution. It is well known in the art that the narrower the pulse, the wider the transmitter and receiver bandwidths must be. In other words, there is a tradeoff between resolution (pulsewidth) and bandwidth.

15 Wider bandwidths for each pulse of a given carrier frequency require that each channel in a frequency-division-multiplexed system be separated further. Accommodating a wide range of carrier frequencies is difficult in typical hydroacoustic transducers.

20 One way of squeezing more channels in a given transducer's bandwidth is by synthesizing narrow transmit pulses and detecting them using a matched-filter receiver. With a matched-filter receiver, it is possible to achieve a lower pulsewidth-bandwidth product than with ordinary receivers. A true matched-filter receiver, however, cannot be realized in the linear analog transceivers typically used. Consequently, analog transceivers must sacrifice resolution to enjoy the flexibility afforded by more channels or must

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sacrifice frequency flexibility to improve resolution.

One technique used with analog transceivers to avoid the multipath problem is to sequentially transmit pulses on different channels and analyze the transit times measured on each channel. The idea is that, for the same reflected paths, the interference between the direct and reflected pulses is different at different frequencies and that, at one of the frequencies, the interference will not be destructive and the range measurement can be made. This use of frequency diversity to solve the multipath problem takes more time, because more than one pulse must be transmitted by each transceiver to get a valid range measurement.

Therefore, it is a further aim of this invention to provide a hydroacoustic transceiver operating on a number of efficiently packed channels and transmitting hydroacoustic pulses sufficiently narrow to minimize multipath interference.

SUMMARY

Accordingly, the present invention provides a hydroacoustic ranging system for determining acoustic ranges between individual hydroacoustic transceiver locations on a plurality of underwater objects, characterized by: a plurality of hydroacoustic

transceivers attached at different locations to said
underwater objects, each of said transceivers including
a hydroacoustic energy to electrical energy transducer
adapted for underwater transmission and reception of
5 hydroacoustic pulses; an electronic system coupled to
the transducer for transmitting and receiving
hydroacoustic pulse energy including means for
processing pulses within a predetermined range of
characteristic shapes and frequencies; pulse shape
10 detection filtering means in said electronic system for
identifying the shape of pulses received by the
transducer; means for assigning times of arrival to the
pulses having characteristics within a predetermined
shape and carrier frequency received by the transducer;
15 pulse synthesising means in the electronic system for
producing a waveform of said predetermined shape and
carrier frequency for transmission from said transducer
at a time different from the arrival of pulses; clock
means for producing periodic time counts; means for
20 synchronizing the clock means of said plurality of
hydroacoustic transceivers to each other; and scheduling
means in each transceiver for scheduling a sequence of
pulse transmission and reception events and for
initiating said sequence of events in response to a
25 synchronizing pulse from said means for synchronizing,
said system being coupled to a similar system at a
different underwater location and means being provided
for determining the separation distance between the two
systems by measuring the time by the formula
30 $\{(t_{1r}-t_{1s})+(t_{2r}-t_{2s})\}/2$, where the transceiver in a
first said system transmits at time t_{1s} and the
transceiver in a second said system transmits at time
 t_{2s} and the subscript r identifies the reception time of
the corresponding pulses transmitted at times t_{1s} and
35 t_{2s} .

In such a

1 ranging system, individual transceivers may be attached at various points
along hydrophone streamers, on the gun, on the head buoy, on the tail buoy,
on submerged towfish trailed from the buoys, or on the hull of the tow boat.
A controller, some sort of processing device, on board the boat controls the
5 operation of the system and collects data from the transceivers over
communications links.

The invention teaches a transceiver having a transducer for converting
hydroacoustic energy into electrical energy and vice versa. In a preferred
embodiment, the transducer is a ceramic sphere having a bandwidth ranging
10 from about 50kHz to about 100kHz. The transducer is alternately connected to
either the transceiver's electrical transmission path or its reception path
by means of a transmit/receive switch.

With the switch in the receive position, the transceiver is listening for
pulses from other transceivers. The reception path conducts the electrical
15 energy representative of the hydroacoustic energy impinging on the transducer
to conversion means such as a sampling analog-to-digital converter, which
converts the electrical energy at its input into a sequence of digital words,
or samples, at its output. In a preferred embodiment, the reception path
includes a highpass filter for attenuating the low frequency noise that can
20 be significant in a marine environment. From the sequence of digital samples,
detection means detect the presence of pulses transmitted from other similar
transceivers, the pulses having known characteristics. In a preferred
embodiment, the known characteristics are the shape of the pulse and its
carrier frequency and the detection means is a multiple-channel digital
25 filter realized in a digital-signal-processing (DSP) integrated circuit.
Coefficients of the digital filter, stored in memory means such as an EPROM

1 or RAM, are configured to detect pulses of the known shape on one of five
known carrier frequencies, or channels, from about 50kHz to about 100kHz. The
digital filter detects pulses on each channel by correlating the sequence of
digital samples with the filter's coefficients. Relative maximum correlation
5 values from the filter represent detected pulses, the magnitudes of the
correlation values indicating their signal strengths. The time count of timer
means at the detection of a pulse, representing the time of arrival of the
pulse, is saved in memory. The detection means similarly saves the signal
strength of each of the received pulses. The times of arrival and signal
10 strengths of up to eight pulses can be saved.

While the transducer is connected to the transceiver's electrical
transmission path, the transceiver outputs a hydroacoustic pulse of known
shape and carrier frequency. In a preferred embodiment, one pulse is
transmitted for each shot point on one of five carrier frequencies. The pulse
15 is digitally synthesized in synthesizer means at the shot point rate. Count
comparison means in cooperation with the timer determine the transmission
interval by comparing the timer count with the value stored in a register.
In a preferred embodiment the count of the timer is reset to zero when its
count matches the count in the register. The times of arrival of received
20 pulses are referenced to the time of transmission. The digitally synthesized
pulse is converted into an analog signal by a 12-bit digital-to-analog
converter and conducted to the transducer through the switch over an
electrical transmission path including a bandpass filter for attenuating
digital switching noise and a power amplifier for increasing the pulse's
25 power to a level sufficient to be detected by other transceivers. The pulse
is coupled into the water by the transducer. In a preferred embodiment, the

transmit/receive switch is in the transmit position for about 500 microseconds for each shot point interval. To save power, the power amplifier is turned on only during the brief transmit time.

5 In a preferred embodiment, the timer, comparison means, detection means and synthesizer means less the digital-to-analog converter are realized by a DSP chip, its support circuitry, and its operating machine code. A DSP chip is used because it is capable of quickly
10 performing the many arithmetic and logical operations, such as those required in implementing a multiple-channel digital matched filter. With the DSP chip, high-throughput, near-simultaneous two-way acoustic ranging with good multipath rejection on two or more
15 streamers is possible.

The present invention also provides a method for determining acoustic ranges between individual hydroacoustic transceiver locations on a plurality of underwater objects, characterized by the steps of:
20 affixing a plurality of individual hydroacoustic transceivers to different locations on underwater objects, said hydroacoustic transceivers having timing clocks and storage means and being operable to transmit and receive acoustic pulses having a predetermined
25 characteristic shape and carrier frequency through the water; establishing pulse characteristics including pulse shapes, transmission times, carrier frequencies, and reception windows open during predetermined time periods for reception of said pulses on individual
30 carrier frequencies in the transceivers; composing a schedule of pulse transmission times and pulse reception windows for the plurality of transceivers; storing an individual schedule for each transceiver in the storage means of the corresponding transceiver; synchronizing

the timing clocks in the transceivers periodically at predetermined times; transmitting after each periodic synchronization pulse of said predetermined shapes and associated carrier frequencies according to the schedule of pulse transmission times to corresponding pulse reception windows to enable detection of the shapes of the scheduled pulses having the predetermined carrier frequencies arriving during the opening of the pulse reception windows; determining reception times of detected pulses of predetermined shapes and carrier frequencies according to the clocks in the receiving transceivers; and measuring the separation in water of two transducer locations by clocking the transit times of the hydroacoustic pulses from each transducer to the other and averaging the two transit times.

In a typical application, the transceivers are attached to the streamer at various positions, to the head and tail buoys, to the gun, to towfish, and to the hull of the boat. Before deployment while the streamers are still on the deck of the boat, each transceiver is configured by the controller over the communications link. Parameters that can be configured include: a) the transmit frequency; b) the interrogate interval, i.e., the rate of transmission; c) the transmit time, i.e., the time to transmit relative to the resetting of the timer to zero, which occurs at the start of the interrogate interval or upon a master sync reset; d) the receive window open times and close times, i.e., the acceptance interval for each receive pulse relative to the start of the interrogate interval; e) the receive channel number (or carrier frequency); f) the receive detection threshold; and g) the receive time calibration value. The configurable parameters are stored in registers. Eight registers are reserved for each of items d-g, permitting the reception of up to eight pulses each shot point that meet the criteria

1 defined by the corresponding settings of items d - g. In addition, each
transceiver can be configured as a responder that transmits a pulse on a
selected channel only upon reception of a pulse on a given channel.
5 Responders are used in locations in the system, such as on the tail buoy,
having no communications link with the controller on the boat. Communications
over the link is between the controller and each transceiver over a party
line. A microcontroller in each transceiver handles the communications and
stores the configuration parameters in registers accessible by the DSP chip.
10 In a preferred embodiment, multipath interference is rejected by ending the
acceptance interval for a given pulse once it is detected.

During deployment and ranging, the controller aboard the boat loosely
synchronizes each transceiver every so often over the communications link.
When two-way ranging is practiced, synchronization to within a few
milliseconds is adequate and can be done over the communications link. For
15 each shot point, the transceiver sends time of arrival and signal strength
data for up to eight pulses back to the controller on the boat, where it is
processed and stored for further in-depth solution of the position and shape
of the hydrophone streamer.

BRIEF DESCRIPTION OF THE DRAWINGS

20 The abovementioned features as well as other features of the present
invention will be more clearly understood from consideration of the following
description in connection with the accompanying drawings in which:

FIG. 1 is a block circuit diagram of one of the multiplicity of the
transceivers used in the positioning apparatus of this invention.

FIGs. 2 through 5 are flow diagrams representing the program of the

1 processor located in the transceivers.

FIG. 6 shows the actual and the desired frequency response of the channel of a transceiver.

5 FIG. 7a shows the idealized frequency spectrum of the transmitted pulses for five channels.

FIG. 7b shows the idealized frequency spectrum of the received pulses for five channels undersampled at a frequency of 100 kHz.

FIG. 8 represents the actual transmitted pulse for a 95 kHz carrier and its envelope.

10 FIG. 9 represents the 50 in-phase and quadrature receiver correlation coefficients for a channel.

FIG. 10 is a block diagram of the pulse detection technique used in the preferred embodiment.

FIG. 11 shows the envelope autocorrelation function of a received pulse.

15 FIG. 12 is an overhead view of the deployment of transceivers used in this invention.

BEST MODE FOR CARRYING OUT THE INVENTION

Referring now to FIG. 1, there is shown a block diagram of the apparatus of this invention. A transducer 20 converts acoustic energy received through water into received electrical energy and reciprocally converts electrical pulses into acoustic pulses and couples them into the water. An example of such a transducer is a ceramic sphere having a fairly flat response from 50kHz to 100kHz and a more or less omnidirectional beam pattern. The transducer 20 is alternately connected to either an electrical transmission path 22 or an electrical reception path 24 by means of a T/R

1 (transmit/receive) switch 26. The T/R switch of the preferred embodiment is an electromechanical single-pole, double-throw relay, although it will be appreciated that other types of switching could be used including solid state switches.

5 With the T/R switch 26 in the receive position as shown in FIG.1, the transducer is connected to the electrical reception path 24. Included in the reception path is an active highpass filter 28 which provides a substantial voltage gain. In the preferred embodiment, the highpass filter 28 is a fourth-order Butterworth filter having a cutoff frequency of about 40kHz, and
10 a voltage gain of about 300. The filter attenuates noise in the 0-50kHz range. Although the preferred embodiment uses an active filter with gain, it is also possible to use a separate preamplifier as a gain stage along with a passive highpass filter. Filtered electrical energy at the output of highpass filter 28 is sampled and converted into a sequence of digital
15 samples by a sampling A/D (analog-to-digital) converter 30 which provides a 12-bit output. The sampling rate is determined by the output frequency f_s of a frequency divider 32. The frequency divider divides the input frequency f_1 applied to it by a source of clock signals from an oscillator 34. In the preferred embodiment, the oscillator frequency f_1 is 20MHz, the frequency
20 divider 32 divides by a factor of 200 for a sampling rate f_s of 100kHz. Thus, the A/D converter 30 provides new samples at a rate of 100000 samples per second.

The 12-bit digital sample from the A/D converter 30 of the preferred embodiment is read by a processor 36 over its bidirectional data bus 38. An
25 end of conversion signal 40 from the A/D converter 30 notifies the processor 36 that a digital sample is ready to be read. The processor then commands

1 the A/D converter to output the digital sample to the bus 38 with an A/D read
control signal 42. The processor as programmed implements a multiple-
channel digital matched filter as a means for detecting the presence of
acoustic pulses having known characteristics from the sequence of digital
5 samples. The details of the detection are described hereinafter.

While the transducer 20 is connected to the electrical transmission path
22 as selected by transmit/receive control line 44 from the processor 36,
electrical pulses synthesized under the control of the processor can be
directed to the transducer for coupling into the water. In synthesizing a
10 pulse to be transmitted, the processor 36 outputs a sequence of 12-bit
digital words over the data bus 38. In the preferred embodiment, the
sequence for a given pulse contains about 200 digital words. With successive
words being output at a rate of 400000 words per second, the entire sequence
spans about 0.5ms, the duration of a transmit pulse. Successive digital words
15 from the sequence are latched from the data bus 38 to the input of a 12-bit
D/A (digital-to-analog) converter 50 at a rate of 400kHz by a D/A latch
signal 46 from the processor. The D/A converter converts the 12-bit digital
word at its input into an analog voltage at its output. Because the analog
output of the D/A converter is undefined during its conversion time, i.e.,
20 the interval commencing with the start of the conversion and ending with its
completion, a deglitcher circuit 52 is used. During the conversion time, the
deglitcher 52 shorts its output to ground. While the output of the D/A
converter 50 is stable, the deglitcher 52 passes the output of the D/A
converter directly to a lowpass reconstruction filter 56. Deglitcher control
25 line 54 under processor control via latch 48 alternately switches the output
of the deglitcher 52 between ground and the output of the D/A converter 50

1 as appropriate. The lowpass filter 56 smooths the output of the deglitcher
52, removing most of the digital switching noise. In the preferred
embodiment, the filter 56 is a passive third-order Bessel filter, giving
minimum phase distortion over the frequency range of the pulses. The
5 waveform at the output of the filter 56 is that of the desired synthesized
pulse.

The synthesized pulse from the filter is conducted to the transducer 20
over the electrical transmission path 22, which includes a driver 58 and a
power amplifier 60. The driver 58 serves to buffer the low-voltage analog
10 section from the high-voltage power amplifier 60. In the preferred
embodiment, the driver 58 also provides a voltage gain of two to the
synthesized pulse. The power amplifier 60, with an operating frequency range
of about 50-100kHz and a gain of about 32dB into a nominal 100-ohm load,
amplifies the pulse to the proper levels for transmission.

15 By means of the communications interface 37, the processor 36 is able to
communicate with an external controller 59 by means of line 61A. Parameters
defining the transmitter and receiver configurations can be selected at the
controller and then sent to the processor 36 and stored in its memory. The
controller can also synchronize processor 36 with the processors in a
20 multiplicity of similar circuits by parity lines on 61A or separate lines 61B
through 61N over the interface. Furthermore, the times of arrival of
received pulses and their signal strengths are sent to the external
controller 59 over the interface 37. The processor 36 also reads data
gathered by a data acquisition module 35 that may contain sensors such as
25 pressure transducers for measuring the depth and temperature transducers for
measuring the temperature of the sea water. The data from the data

1 acquisition module can be sent to the external controller over the
communications interface 37.

5 The synthesis of the transmit pulses is controlled by the processor 36 of
FIG.1 and the operating program stored in its memory. The flowchart of FIG.2
describes the transmit subroutine used to synthesize a transmit pulse. When
it is time to transmit a pulse, the transmit subroutine is called and program
execution jumps to step 62 of FIG.2. First, the sequence of digital words,
or transmit coefficients, $c_N(i)$ corresponding to the carrier frequency, or
channel N, over which the pulse is to be transmitted is selected based on the
10 value in a transmit configuration register. The transmit configuration
register is a location in the processor's memory that can be programmed over
the communications interface 37 in FIG.1. The transmit configuration
register contains, in the preferred embodiment, one of six possible values.
Values of one through five define channels $N = 1$ through 5, or respective
15 carrier frequencies of 55kHz, 65kHz, 75kHz, 85kHz, and 95kHz. The sixth
possible value, which is 0, disables the transmission of pulses. If, for
example, the transmit configuration register contains a value of 3, a pulse
with a carrier frequency of 75kHz is synthesized.

20 Once the correct sequence of transmit coefficients is selected, the data
pointer 1 is zeroed in step 64, pointing to the first member of the selected
sequence $c_N(0)$. Next, according to step 66, the deglitcher 52 in FIG.1 is
shorted via the latch 48 and the control line 54 in anticipation of a D/A
conversion. The i th transmit coefficient $c_N(i)$ is put on the bus 38 and
latched into the input of the D/A converter 50 via the latch 48 and D/A
25 control line 46, and the conversion is begun. The processor then delays,
step 70, for a time sufficient for the conversion to finish. After the

1 delay, the short at the output of the deglitcher is disconnected and the
output connected to the output of the D/A converter as shown in step 72.
According to step 74, the data pointer i is then compared to the total number
of coefficients XMTCNT in the sequence. In the preferred embodiment, XMTCNT
5 = 203. If the data pointer is less than the total number, execution
continues to step 76. Otherwise, indicating that the entire sequence has
been converted and pulse synthesis is completed, execution continues with
steps 80 and 82, which short out the deglitcher and return execution to the
main calling program. The data pointer i is incremented in step 76, pointing
10 to the next consecutive transmit coefficient. Another processor delay is
interposed by step 78, before execution resumes with step 66. The delays of
steps 70 and 78 are chosen such that, during pulse synthesis, the deglitcher
is shorted half the time and connected to the stable output of the D/A
converter for the other half of the time. The delays are further chosen such
15 that, in the preferred embodiment, one traversal of the loop defined from
step 66 through step 78 and back to 66 takes 2.5 microseconds for an output
sample rate of 400kHz. The five sequences $c_N(i)$ are stored in the memory of
the processor 36. To change to another set of synthesized signals requires
only that the values in the memory be changed. Such a change could even be
20 done over the communications interface 37. In an analog system, hardware
would have to be replaced.

Means for detecting the presence of acoustic pulses from the sequence of
digital samples from the A/D converter 30 in FIG.1 are realized by a
correlation routine executed by the processor 36. The A/D converter 30
25 produces new digital samples at a rate of 100kHz as set by oscillator 34 and
frequency divider 32. Upon the completion of each conversion, the A/D

1 converter signals the processor 36 over the end of conversion line 40, which
causes the processor to immediately execute an interrupt service routine.
The routine, called A/D READ in FIG.4, forces the A/D converter to put the
digital sample on the data bus 38 by a signal on the A/D read line 42. The
5 processor then reads the sample and saves it at the next available location
in a circular buffer 83 in its memory. The circular buffer 83 of the
preferred embodiment holds 50 samples. Once the buffer is filled, the next
sample replaces the oldest of the 50 samples, so that the buffer always holds
the 50 most recent samples. Step 124 in FIG.4 performs this operation before
10 returning to former program execution, as shown by step 126. At this point,
it should be remembered that transmit pulses are synthesized by about 200
coefficients at a 400kHz rate, creating a 0.5ms pulse. Because the A/D
converter in the receiver samples at only 100kHz, 50 consecutive samples span
a 0.5ms interval, the width of a pulse. More transmit coefficients are used
15 in order to simplify the hardware required to realize the lowpass
reconstruction filter 56.

The correlation detector is implemented in the processor 36 by a detect
routine flowcharted in FIG.3. To simplify the drawing, the flowchart of
FIG.3 is drawn for detection of a pulse on a single channel. In fact, the
20 detect routine can be performed simultaneously on up to five channels. The
first step 84 of the routine zeroes the receive data pointer j, which is used
as a count index relative to the start of the detection routine. At step 86,
the processor waits for a timer interrupt, which occurs every 0.1ms, or at
a rate of 10kHz. The timer interrupt routine is flowcharted in FIG.4. Once
25 the timer interrupt occurs and the A/D converter is read, execution continues
to steps 88 and 90, which zero the correlation pointer k and the correlation

1 accumulators $y_i(j)$ and $y_q(j)$. Iteratively executed steps 92, 94, 96, and 98
perform the in-phase and the quadrature correlations of the 50 most recent
input samples $x(j)$, $j = -49$ through 0, with the sequence of 50 in-phase
correlation coefficients $h_i(k)$ and 50 quadrature coefficients $h_q(k)$ for the
5 given channel. The coefficients are stored in the memory of the processor.
A total of 500 coefficients are stored to cover the five channels. Just as
the transmit coefficients c_N could be modified without significant hardware
changes, so could the correlation coefficients. As will be explained in
detail hereinafter, the coefficients represent the known shape of the
10 transmitted pulses for each channel. The iteration through steps 92, 94, 96,
and 98 continues until the correlation pointer k , which is incremented each
iteration, reaches one-fourth the number of values in the transmit pulse
sequence. In the preferred embodiment $XMTCNT = 203$ and $XMTCNT/4 = 50$.
Consequently, each correlation accumulator represents the sum of 50 terms.
15 In standard mathematical terms, the in-phase correlation is given by $y_i(j)$
 $= \sum [x(j-k)h_i(k)]$, and the quadrature correlation is given by $y_q(j) = \sum [x(j-$
 $k)h_q(k)]$, where the summation is over k from 0 to 49.

Once the correlation computations are completed, execution continues with
step 100, which computes the net correlation value $y(j)$, the vector sum of
20 the in-phase and quadrature correlation values, or the square root of the
sums of the squares of $y_i(j)$ and $y_q(j)$. In step 102, the net correlation
value is compared with a receive threshold value $THLD$, which is a selectable
value in a receive configuration register in the memory of the processor.
If the net correlation value is less than the threshold value, the net
25 correlation value $y(j)$ is set to zero in step 104. In either case, execution
continues to step 106, which determines the maximum correlation value. In

1 step 106, the most recent net correlation value $y(j)$ is compared to the previous maximum peak value $p(j-1)$. If the most recent value is greater, it replaces the previous value in $p(j)$. Otherwise, the previous value $p(j-1)$ is put in $p(j)$. Thus, $p(j)$ contains the maximum correlation yet computed.

5 Step 108 causes execution to bypass the peak detector implemented in steps 110, 112, 114, and 116 if the peak net correlation value has already been detected. If the peak net correlation value has not yet been detected, execution advances to step 110, which compares the most recent net correlation value $y(j)$ with the maximum correlation value thus far $p(j)$. If

10 $y(j)$ is less than $p(j)$, the correlation values are beginning to decrease and the current $y(j)$ is the first value beyond the peak. If the peak is detected and the apparatus is being operated as a responder, the time count of the timer is reset to zero and execution returns to the calling routine, as shown in steps 111, 113, and 122. If the peak is detected and operation is

15 standard, execution advances to step 112, which saves the value of the data pointer coinciding with the peak ($j-1$) in a location in the processor's memory called PLSTIM. Because the data pointer is incremented each time a new correlation value is computed, i.e., every 0.1ms, the data pointer serves as a timer producing periodic time counts. Step 112 provides a means for

20 assigning a time count to the maximum correlation value, indicating the time of arrival of a pulse relative to the start of the detection routine. The signal strength of the received pulse, which is its peak correlation value $p(j)$, is stored at location PLSLVL in the processor's memory in step 114. Step 116 sets the SKIP flag, which indicates that the peak has been

25 determined. Regardless of the results of the decisions of steps 108 and 110, execution resumes with step 118, which determines whether pulse detection on

1 the given channel is completed. A receiver configuration register in the
processor's memory contains a value RCVCNT defining an acceptance interval
relative to the start of the detection routine during which the correlation
detection routine is operating on a given channel. When the data pointer j
5 reaches the value of RCVCNT, program execution returns to its formerly
running routine through step 122. Otherwise, the data pointer j is
incremented in step 120, and execution loops back to step 86 to compute the
next correlation value. It should be appreciated that the square-root
function performed by step 100 could be eliminated without affecting the
10 determination of times of arrival. If the step is eliminated, the net
correlation values are merely the squares of the correlation values and the
threshold values would have to be similarly squared. The purpose of the
square-root step 100 of the preferred embodiment is to scale the net
correlation value to the same units as the input samples.

15 A software timer is implemented by the timer interrupt routine flowcharted
in FIG.4. The routine runs every 0.1ms, or at a rate of 10kHz. The
oscillator 34 of FIG.1 is the source of clock signals to which the rate of
execution of the timer routine is referenced. Each time the timer routine
runs, a time count stored in the processor's memory at a location labeled
20 TIMER is incremented as shown in step 130. If the time count reaches a
maximum time count TCNT, the time count is reset to zero as shown in steps
128 and 136. Furthermore, if a master sync command is received, the time
count is reset to zero and the master sync is cleared so that the timer
routine does not keep resetting the time count to zero as indicated by steps
25 132 and 134. A master sync command sent over the communications interface
37 in FIG.1 is used to synchronize apparatus to each other, usually once each

shot point. If the apparatus are not synchronized each shot point, TCNT defines an interrogate interval setting the transmission rate.

The scheduling of the transmit and detection routines is handled by a main routine shown in FIG.5. The main routine runs upon a reset and continues running in a loop unless reset again. First, according to step 140, a digital word representing zero is put onto the data bus 46 of FIG.1 and latched to the input of the D/A converter 50 by means of the latch control line 46 through latch 48. Next, step 142 resets the T/R switch 26 to its receive position via the control line 44. Program execution then enters the start of the loop, step 144. When a timer interrupt occurs (every 0.1ms), the loop is executed one time. First, the routine determines in step 146 if it is time to set the T/R switch 26 to the transmit position and, if so, does so in step 148. In step 150 the time count TIMER is compared to the time to begin synthesis and transmission of a pulse XMTTIM. If there is a match, the transmit subroutine, shown in FIG.2, is called to execute in step 152. If it is not time to transmit or if the transmit routine is finished executing, step 154 determines if it is time to reset the T/R switch 26 to the receive position. If so, step 156 resets the switch. In the preferred embodiment, the T/R switch 26 is maintained in the transmit position only long enough to ensure that the synthesized pulse can get through, or just over 0.5ms. The T/R switch is in the receive position the rest of the time. In step 158, the time count TIMER is compared to a value RCVTIM representing the opening of an acceptance interval on a given receive channel. If there is a match, the detect subroutine, shown in FIG.3, is called to execute by step 160. Otherwise or after the detect subroutine has finished, the loop is restarted at step 144.

1 For simplicity, the flowcharts discussed thus far are drawn depicting
detection on a single channel. In fact, in the preferred embodiment,
simultaneous detection on up to five channels is possible. Moreover, up to
8 pulse detection events can be captured for each shot point. The eight
5 pulse detection events are defined by values in eight receiver configuration
registers representing preset conditions. The eight registers are in the
processor's memory. In the preferred embodiment, each of the eight receiver
configuration registers contains:

- 10 a) a receive channel number, selecting the in-phase and quadrature
correlation coefficients to be used in the detection routine;
- b) a receive threshold (THLD), defining the minimum correlation value to be
used in peak detection;
- c) a receive window open time (RCVTIM), defining the start of an acceptance
window during which the detection routine runs;
- 15 d) a receive window close time (RCVCNT), defining the end of the acceptance
window of c) relative to RCVTIM; and
- e) a bit defining that the apparatus is to operate as an autonomous responder
by transmitting only in response to reception of the pulse defined by the
foregoing a) - d).

20 Other presettable registers used in the preferred embodiment include:

- 1 a) the transmit configuration register, selecting the transmit channel N and
the corresponding coefficients $c_N(1)$;
- b) an interrogate interval register, containing a value (TCNT), which is the
timer count modulus, so that whenever TIMER equals TCNT, TIMER is reset
5 to zero, restarting a transmission interval;
- c) an offset time register, containing a value (XMTTIM), which determines
the time of transmission relative to the start of the transmission
interval (TIMER = 0); and
- d) a calibration register, containing a calibration value (CALTIM) that
10 corrects the time of arrival of pulses for delays otherwise unaccounted
for.

Upon detection of each of up to eight pulses according to the conditions
set by each of the eight receiver configuration registers, the time of
arrival (PLSTIM) and the signal strength (PLSLVL) of each are stored in
15 memory. The time of arrival is stored in one of eight reception time
registers; the signal strength is stored in one of eight signal strength
registers. The eight reception time and signal strength registers correspond
to the eight receive configuration registers. The time of arrival is
computed with respect to the time of transmission XMTTIM by (RCVTIM + PLSTIM
20 - XMTTIM + CALTIM).

Because the direct acoustic path is shorter than the reflected paths, the

1 pulse over the direct path arrives at the detector earlier than pulses over
reflected paths. By selecting the first net correlation peak within each
acceptance interval, the detection routine solves the multipath problem.

5 The presettable registers are configured by an external controller over
the communications interface 37 in FIG.1. The values in the reception time
and the signal strength registers are sent to the controller over the
communications interface 37 to be used in solving acoustic ranges.

10 As discussed hereinbefore, the transmit signal set comprises a 0.5ms pulse
on five carrier frequencies: 55kHz, 65kHz, 75kHz, 85kHz, and 95kHz. The
actual pulse shape was derived by an iterative technique, known as the Parks-
McClellan algorithm and described in the book Digital Signal Processing by
Oppenheim and Schafer, Prentice-Hall 1975. The Parks-McClellan algorithm
derives, for a finite pulse shape, an optimum approximation to a desired
frequency spectrum. The actual output of the algorithm is a set of
15 coefficients representing the magnitude of the pulse at equal intervals.
Several criteria were used in designing the signal set. First, a finite-
length, narrow pulse is desirable to maximize spatial resolution and minimize
multipath interference. Second, the channel spacing required by the receiver
to avoid cross-channel interference should be small to permit a given
20 transducer to handle many channels for more flexible operation of the ranging
system. It is well known in the art that the best receiver for a given set
of transmitted signals is a matched filter receiver. A matched filter is
defined as a filter whose impulse response has the same shape as the signal
to which it is matched, but reversed in time. For a symmetrical transmit
25 pulse, which is identical time-reversed, the impulse response is identical
to the shape of the signal to which it is matched. Likewise for a symmetrical

1 transmit pulse, the matched filter receiver has a frequency response
identical to the frequency spectrum of the pulse. Thus, selecting the
receiver's desired frequency response also sets the frequency spectrum of the
pulse. A further point about matched filters is that they cannot be realized
5 in linear analog systems because the reverse time impulse response cannot be
realized.

In FIG.6 is shown the desired frequency response 170 of a given receive
channel and the actual response 172 approximating the desired for the Parks-
McClellan-generated pulse shape. The desired frequency response 170 can be
10 seen to have a symmetrical triangular shape decreasing from its 0dB peak at
the carrier frequency to 80dB down at the adjacent channels' carrier
frequencies and remaining constant at 80dB down on beyond. The actual
response 172 represents an approximation to the desired that actually yields
a worse-case cross-channel rejection of 60dB. The good cross-channel
15 rejection permits the receiver channels to be separated by only 10kHz,
thereby allowing one high-frequency transducer to be used. The bandwidth of
the actual frequency response 172 of the receiver channel, which is the same
as that of the pulse to which it is matched, is about 10kHz. FIG.7a shows the
overlap of the desired frequency responses of the five channels and the
20 efficient use of the available spectrum from 50kHz to 100kHz. In an analog
implementation, five separate bandpass filters would be required, each
comprising a number of components.

Plots of the transmit pulse envelope 180 and of the transmit pulse on a
carrier frequency of 95kHz 182 are shown in FIG.8. Each of the plots is of
25 about 200 values. In the preferred embodiment 203 are used. If each of the
203 values plotted for the envelope is designated $c_E(i)$, the transmit

1 coefficients for each channel are given by

$$c_N(i) = c_E(i) \cos[2\pi(f_N/f_t)i],$$

where $f_t = 400\text{kHz}$, the transmit sampling frequency, $f_N =$ the carrier frequency for channel N, and i runs from -101 to +101. The processor 36
5 synthesizes a transmit pulse on channel 5, for example, by sending consecutive coefficients $c_5(i)$ to the D/A converter 50 at a rate of 400000 coefficients per second. The result is a transmitted pulse having the shape 182 shown, but further smoothed by the reconstruction filter 56. By synthesizing pulses from digital words converted at a rate four times that
10 of the highest significant transmitted frequency (100kHz), the digital switching noise can be effectively eliminated by a third-order lowpass Bessel filter 56. A Bessel filter is used to minimize phase distortion in the filtering process. Slower conversion rates would require more complex and costly higher order filters.

15 Although the pulse envelope of the preferred embodiment has a total duration of about 0.5ms, most of its energy is within a 0.1ms window bracketing the center of the pulse envelope. Consequently, it is possible to achieve a time resolution of about 0.1ms, which corresponds to a spatial resolution of about 0.15m in sea water. The narrow pulses also make it
20 possible to resolve desired pulses from reflected pulses for differences in path length equivalent to about 0.1ms, allowing the detector to discriminate between direct and reflected pulses, thereby effectively eliminating the multipath problem.

A general rule in designing a sampled data receiver is that the sampling
25 frequency should be at least twice the highest frequency present in the signals to be received in order to avoid what is known as aliasing. Aliasing

1 is the phenomenon whereby a frequency component f_a sampled at another
frequency f_b , where $f_b < 2f_a$, appears to be a component shifted to a
frequency $f_3 = f_b - f_a$. If another frequency component is actually at f ,
it is said to be aliased by the shifted component. It is impossible to
5 distinguish the two separate components. If the general rule were followed
in the preferred embodiment, the sampling frequency f_s of the A/D converter
30 would have to be about 200kHz. Such a high sampling frequency would make
a five-channel receiver difficult to implement. In the preferred embodiment,
the known frequency shifting properties are taken advantage of to permit a
10 slower sampling frequency. The undersampling of signals occupying a band
from 50kHz to 100kHz at a rate of 100kHz shifts those signals into the band
from 0Hz to 50kHz. In fact, the spectrum above 50kHz is folded about 50kHz
(one-half the sampling frequency). For this undersampling technique to work,
highpass filter 28 is used to eliminate pre-sampled energy from the 0Hz to
15 50kHz band to avoid aliasing. A cut off frequency of about 40 kHz minimizes
phase distortion in the passband, while adequately attenuating noise in the
stopband. The 50kHz - 100kHz spectrum of FIG.7a is converted to the 0Hz -
50kHz spectrum of FIG.7b. The transmitted channel 1 carrier frequency of
55kHz, when sampled at 100kHz, appears as a frequency of 45kHz in the shifted
20 spectrum; the carrier frequencies of the other channels appear as: channel
2 - 35kHz, channel 3 - 25kHz, channel 4 - 15kHz, and channel 5 - 5kHz. The
natural filtering of high frequencies by sea water and the 12 dB/octave
transducer roll-off above 100kHz minimize the effects of the aliasing of even
higher noise frequencies into the 0-50kHz band.

25 A transmit pulse synthesized from 203 400kHz coefficients is sampled in
the receiver at a 100kHz rate and correlated against in-phase and quadrature

1 sequences of 50 coefficients each. The in-phase and quadrature receiver
coefficients $h_i(k)$ and $h_q(k)$ are plotted in FIG.9 for channel 5. The in-
phase sequence of coefficients $h_i(k)$ is generated by multiplying the shape
of the envelope 180 by a 5kHz sinusoidal waveform with its peak coincident
5 with the peak of the envelope and selecting 50 samples of the resulting
waveform 190 spaced every 0.01ms. The quadrature coefficients are generated
similarly, except that the envelope 180 is multiplied by a 5kHz sinusoid
shifted by 90° . The plot 192 of the resulting sequence $h_q(k)$ is shown in
FIG.9.

10 The quadrature detection scheme shown in FIG.10 correlates 50 consecutive
samples $x(k)$ from the A/D converter 30 spanning 0.5ms against two sequences
of 50 coefficients $h_i(k)$ and $h_q(k)$ in correlators 200 and 202. (Except for
the A/D converter 30, the remaining blocks of FIG.10 are implemented in
program code.) The resulting correlation values $y_i(j)$ and $y_q(j)$ are squared
15 in squarers 204 and added in summer 206. Finally, the net correlation value
 $y(j)$ is derived by square root block 208. It should be appreciated that the
square-root block 208 is used merely to scale the net correlation value to
the same units as the sampled input. A big advantage with using a matched
filter in the detection scheme is that the $y(j)$ sequence is the
autocorrelation function of the transmit pulse envelope. An interesting
property of the autocorrelation function of a symmetrical pulse is that it
is also symmetrical, but twice as wide. Because the autocorrelation function
defined by the sequence $y(j)$ is twice as wide in time, its frequency spectrum
is about half that of the pulse. It should be remembered that the bandwidth
25 of each of the transmit pulses is about 10kHz, making the bandwidth of the
autocorrelation function about 5kHz. Consequently, the correlation

1 computations need be performed only at a rate f_k of 10kHz to avoid aliasing
of the correlation function. Thus, an advantage with using a matched filter
receiver is that the output of the correlator can be sampled at the same rate
as the bandwidth of the transmitted signals instead of at twice the bandwidth
5 as in non-matched filter receivers. The advantage greatly reduces the number
of correlation computations required.

A typical sequence of net correlation values $y(j)$ spanning the arrival of
a pulse is plotted in FIG.11. It should be noticed that the envelope of the
plotted values in FIG.11 describes the autocorrelation function of the
10 transmit pulse envelope and is twice as wide as the pulse. The peak detector
209 in FIG.10 selects the maximum $y(j)$ from the sequence, which represents
the arrival of a pulse.

Performing the many computations of a multi-channel system requires a
processor capable of high performance. In the preferred embodiment, a
15 digital-signal-processing (DSP) integrated circuit is used to synthesize the
transmitted pulses and to detect the received pulses. An example of such a
DSP chip is the DSP 56000, manufactured by Motorola, Inc., Schaumburg, IL.
To unburden the DSP chip further so that it can perform more efficiently, a
low-cost microcontroller is used to handle other functions, such as timing
20 and communications over the communications interface 37 and reading the data
acquisition module 35. An example of such a microcontroller is the Motorola
MC68HC11A1, also manufactured by Motorola, Inc., Schaumburg, IL. Thus, the
processor 36 of the preferred embodiment comprises a DSP chip for pulse
synthesis and detection, a microcontroller for general input/output, timing,
25 communications, and control, and their associated memories.

Referring to FIG.12, there is shown an overhead view of a seismic tow boat

1 220 trailing two submerged hydrophone streamers 222A and 222B. Head buoy
226A and tail buoy 230A are tethered to streamer 222A at its front and rear
respectively. The floating buoys 226A and 230A are used as surface
references marking the ends of the submerged streamer 222A. Streamer 222B
5 is similarly marked by its head buoy 226B and its tail buoy 230B. Hydro-
acoustic transceiver pods 236A-J, including the apparatus of the invention,
are shown attached to the submerged streamers 222A and 222B at POSITIONS #2-
4, to the head buoys 226A and 226B at POSITION #1, and to the tail buoys 230A
and 230B at POSITION #5. For the purposes of simplifying the illustration
10 of FIG.12, transceivers 236A-J are shown attached to only two streamers 222A
and 222B and to their buoys 226A-B and 230A-B. In a typical seismic survey,
additional transceivers could also be attached to the hull of the tow boat
220 and to the air gun 234. These additional transceivers would typically
be connected by a communications link to the external controller, but could
15 be operated as responders if appropriate. If, moreover, the vertical thermal
profile of the sea excludes an acoustic path between the transceivers on the
buoys and those on the streamer, towfish-mounted transceivers can be towed
beneath the buoys to complete a relay acoustic path. Furthermore, more than
two streamers could be deployed, each with many more transceivers than shown
20 in FIG.12 distributed along its length. A typical 3km streamer may have about
six transceivers along its length.

Transceivers 236B, C, D and 236G, H, I which are attached directly to the
streamer, can communicate with a controller aboard the tow boat 220 through
communication lines in the streamers 222A and 222B. In most applications,
25 the buoys are tethered to the streamers without any electrical connection
along the tether. Consequently, buoy-mounted transceivers usually cannot

1 communicate with the controller. For the purposes of illustration, let us
assume that transceivers 236A, E, F, and J in FIG.12 cannot communicate with
the controller. The buoy-mounted transceivers are configured as responders,
which transmit only upon detection of a pulse on a designated channel. Dashed
5 lines in FIG.12 represent ranges between pairs of transceivers 236. In a
typical deployment, all of the transceivers on streamer 222A are configured
to transmit on the same channel and all those on streamer 222B on another
channel. The responders in the buoys are configured to transmit in response
to reception of a pulse on the same channel as it transmits on. Each
10 transceiver, excluding the responders, is configured to receive pulses from
its neighboring transceivers. For example, transceiver 236B is configured
to receive five pulses: from 236A, C, F, G, and H. The pulse transmission
times are staggered to prevent pulses on the same channel from arriving
simultaneously at the same transceiver. In a typical deployment,
15 transceivers directly across from one another would transmit more or less
together, the one nearest the boat first on through those farthest from the
boat.

The range between a pair of transceivers in the preferred embodiment is
measured by two-way ranging to avoid the need for an accurate sync command.
20 In two-way ranging, each transceiver transmits a pulse, the first at time
 t_{1x} referenced to transceiver #1's timer and the second at time t_{2x}
referenced to transceiver #2's timer. The first receives the second's pulse
at time t_{1r} , and the second receives the first's pulse at time t_{2r} . Even if
the timers of the two transceivers are not synchronized, the range is
25 proportional to $[(t_{1r}-t_{1x})+(t_{2r}-t_{2x})]/2$, because the offset between the two
timers is removed by the subtraction. The time differences $(t_{1r}-t_{1x})$ in

transceiver #1 and $(t_{2r}-t_{2x})$ in transceiver #2 are the values sent over the communications interface 37 to the external controller. The external controller then computes the range as $c[(t_{1r}-t_{1x})+(t_{2r}-t_{2x})]/2$, where c is the speed of sound through the water. The computation described applies to the range 240 in FIG. 12 between transceivers 236D and 236I which can communicate with the external controller aboard the towboat 220.

In determining ranges between a transceiver and a responder, the computation is different. For a range between a transceiver #3 and a responder #4 on the same streamer, where the responder is configured to transmit in response to detection of a pulse from transceiver #3, the range 242 is proportional to $[(t_{3r}-t_{3x})-t_d]/2$. The difference $(t_{3r}-t_{3x})$, which transceiver #3 reports to the external controller, is the interval between transceiver #3's pulse transmission and the reception of the pulse from responder #4. A delay t_d , equivalent to $XMTTIM+CALTIM$, inherent in all responders between a responder's detection of a pulse and its subsequent transmission is known by the controller and taken into account in computing the range. This computation applies to the range 242 between transceiver 236D and responder 236E in FIG. 12.

For the range 244 between transceiver 236D and responder 236J, in which the responder transmits in response to detection of a pulse from a transceiver other than 236D, namely from transceiver 236I, the computation is more complicated. To simplify the format of the range equations used in this case, let us use a subscript of I to refer to transceiver 236I, a subscript of J to refer to responder 236J, and a subscript of D to refer to responder 236D. The range 244 is proportional to:

$$[(t_{DrJ} - t_{Dx}) - (t_{DrI} - t_{Dx}) - t_d]$$

$$-[(t_{IrJ} - t_{Ix}) - t_d]/2$$

$$+[(t_{IrD} - t_{Ix}) + (t_{DrI} - t_{Dx})]/2,$$

where $(t_{IrJ} - t_{Ix})$ is the time of arrival at 236I of the pulse from responder 236J with respect to the time of transmission of the pulse from 236I,

$(t_{IrD} - t_{Ix})$ is the time of arrival at 236I of the pulse from transceiver 236D with respect to the time of transmission of the pulse from 236I,

$(t_{DrJ} - t_{Dx})$ is the time of arrival at 236D of the pulse from responder 236J with respect to the time of transmission of the pulse from 236D,

$(t_{DrI} - t_{Dx})$ is the time of arrival at 236D of the pulse from the transceiver 236I with respect to the time of transmission of the pulse from 236D, and t_d is the inherent delay in a responder between reception and transmission of a pulse.

The terms in parentheses are times of arrival sent to the external controller via the communications interface and t_d is a known value. From these terms, the external controller can compute the range 244.

An essential element in the complete position solution is the depth of each transceiver at the time of a range measurement. For this reason, the data acquisition module 35 in FIG.1 of the preferred embodiment can transfer depth information from a pressure transducer to the processor 36, which sends it on to the external controller over the communications interface 35. Along with depth data, the data acquisition module can provide temperature information from a temperature sensor, which can similarly be sent to the external controller for use in estimating the local speed of sound.

Referring again to FIG. 1, the invention of this system could be used as

1 a one-way ranging system by the use of an external sync signal provided to
the processor 36. The external sync signal is used to reset the time count
of the timer to zero. The sync signal interrupts the execution of the
processor and immediately resets the time count of the timer to zero. In
5 addition, each transceiver would be configured as a dedicated receiver or
transmitter.

Thus there has to this point been described apparatus and methods for a
hydroacoustic positioning system, and although the present invention has been
described with respect to such specific methods and apparatus, it is not
10 intended that such specific references be considered limitations upon the
scope of the invention except insofar as is set forth in the following
claims.

30

CLAIMS



1. A hydroacoustic ranging system for determining acoustic ranges between individual hydroacoustic transceiver locations on a plurality of underwater objects, characterized by:

a plurality of hydroacoustic transceivers attached at different locations to said underwater objects, each of said transceivers including a hydroacoustic energy to electrical energy transducer adapted for underwater transmission and reception of hydroacoustic pulses;

an electronic system coupled to the transducer for transmitting and receiving hydroacoustic pulse energy including means for processing pulses within a predetermined range of characteristic shapes and frequencies;

pulse shape detection filtering means in said electronic system for identifying the shape of pulses received by the transducer;

means for assigning times of arrival to the pulses having characteristics within a predetermined shape and carrier frequency received by the transducer;

pulse synthesising means in the electronic system for producing a waveform of said predetermined shape and carrier frequency for transmission from said transducer at a time different from the arrival of pulses;

clock means for producing periodic time counts;

means for synchronizing the clock means of said plurality of hydroacoustic transceivers to each other; and

scheduling means in each transceiver for scheduling a sequence of pulse transmission and reception events and for initiating said sequence of events in response to a synchronizing pulse from said means for synchronizing; said system being coupled to a similar system at a different underwater location and



means being provided for determining the separation distance between the two systems by measuring the time by the formula $\{(t_{1r}-t_{1s})+(t_{2r}-t_{2s})\}/2$, where the transceiver in a first said system transmits at time t_{1s} and the transceiver in a second said system transmits at time t_{2s} and the subscript r identifies the reception time of the corresponding pulses transmitted at times t_{1s} and t_{2s} .

2. A hydroacoustic ranging system according to claim 1 and further characterized by means responsive to said time of arrival for initiating after a predetermined delay time the synthesization of a pulse by said pulse synthesising means for transmission by said transducer.

3. A hydroacoustic ranging system according to claim 1 or claim 2, and further characterized by a resettable counter register responsive to the periodic time counts produced by the clock means for establishing said time of arrival of said identified pulses.

4. A hydroacoustic ranging system according to any preceding claim and further characterized by pulse shape determination means operable in a digital sampling mode to sample the pulse amplitude for determining the shape of the received pulses.

5. A hydroacoustic ranging system according to claim 4, further characterized by correlation means for comparing a plurality of digital samples of the hydroacoustic pulse amplitude with an established digital model to identify said pulses of predetermined shape.



6. A hydroacoustic ranging system according to any preceding claim, further characterized by received hydroacoustic pulses of a predetermined carrier frequency above about 40kHz and an electronic high pass filter coupled in said electronic system for attenuating received hydroacoustic noise present at frequencies below about 40kHz.

7. A hydroacoustic ranging system according to any preceding claim, wherein a plurality of transducers are provided and wherein means are provided for transmitting hydroacoustic pulses selectively from the transducers on scheduled ones of a plurality of predetermined carrier frequencies within a range of 50kHz to 100kHz.

8. A hydroacoustic ranging system according to any preceding claim and further characterized in that said pulse shape determination means comprises a digital filter responsive to a plurality of digital samples of the amplitude of received hydroacoustic pulses.

9. A hydroacoustic ranging system according to claim 1, further characterized by:

a third said system with associated hydroacoustic transceiver, and wherein the transmission from the first system at said time t_{1s} , and from the second system at said time t_{2s} , further comprises:



means for receiving the first pulse at the second system and digitally processing it to identify and time the first pulse at time t_{2r1} ,

means for receiving the second pulse at the first system and digitally processing it to identify and time the second pulse at time t_{1r2} ,

means for transmitting from the third system a third digitally synthesized pulse after a delay time t_d following the timing of the second pulse,

means for receiving the third pulse in the second system, identifying it and assigning a time of t_{2r3} ,

means for receiving the third pulse in the first system, identifying it and assigning a time of t_{1r3} , and

wherein the means for determining the separation distance between the first and second systems from the foregoing pulses as a function corresponding to $\{(t_{1r} - t_{1s}) + (t_{2r} - t_{2s})\}/2$, with the third system included corresponds to $[t_{2r3} - t_{2s}) - (2t_{2r1} - t_{2s}) - t_d - (t_{1r3} - t_{1s})/2 + t_d/2 + (t_{2r1} - t_{2s})/2 + (t_{1r2} - t_{1s})/2]$.

10. A method for determining acoustic ranges between individual hydroacoustic transceiver locations on a plurality of underwater objects, characterized by the steps of:



affixing a plurality of individual hydroacoustic transceivers to different locations on underwater objects, said hydroacoustic transceivers having timing clocks and storage means and being operable to transmit and receive acoustic pulses having a predetermined characteristic shape and carrier frequency through the water;

establishing pulse characteristics including pulse shapes, transmission times, carrier frequencies, and reception windows open during predetermined time periods for reception of said pulses on individual carrier frequencies in the transceivers;

composing a schedule of pulse transmission times and pulse reception windows for the plurality of transceivers;

storing an individual schedule for each transceiver in the storage means of the corresponding transceiver;

synchronizing the timing clocks in the transceivers periodically at predetermined times;

transmitting after each periodic synchronization pulse of said predetermined shapes and associated carrier frequencies according to the schedule of pulse transmission times to corresponding pulse reception windows to enable detection of the shapes of the scheduled pulses having the predetermined carrier frequencies arriving during the opening of the pulse reception windows;

determining reception times of detected pulses of predetermined shapes and carrier frequencies according to the clocks in the receiving transceivers; and

measuring the separation in water of two transducer locations by clocking the transit times of the hydroacoustic pulses from each transducer to the other and averaging the two transit times.



11. A method according to claim 10 and further characterized by the steps of digitally sampling the shape of received hydroacoustic pulses to determine waveform shape and timing the arrival of pulses of predetermined shape with reference to a digital sampling time.
 12. A method according to claim 10 or claim 11 and further characterized by the steps of transmitting the hydroacoustic pulses at a predetermined carrier frequency in excess of about 40kHz and presenting frequency components of received pulses above 40kHz for digital sampling to determine pulse shape.
 13. A method according to any one of claims 10 to 12 and further characterized by the steps of coupling a plurality of said transducers in each of a plurality of streamers towed behind a vessel, and determining the location of the transducers by comparing the arrival times of identified pulses at the transducers.
 14. A method according to claim 13 and further characterized by the steps of storing historical data regarding the relative transducer and vessel location in a data processing system for analyzing related seismic data from the locations of the transducers.
 15. A hydroacoustic ranging system substantially as described herein with reference to the drawings.
 16. A method for determining acoustic ranges between individual hydroacoustic transceiver locations on a plurality of underwater objects substantially as described herein with reference to the drawings.
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