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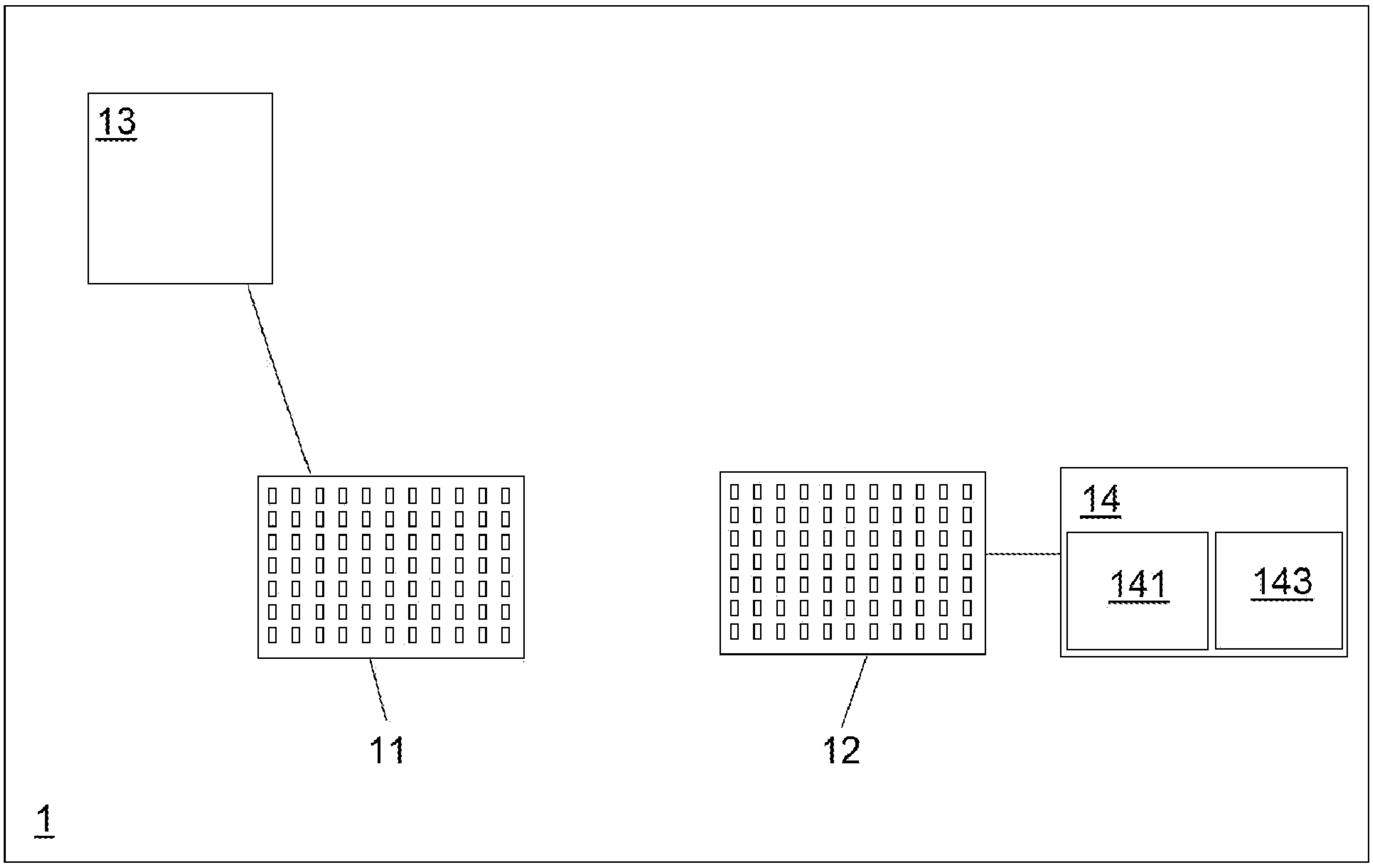

Figure 1

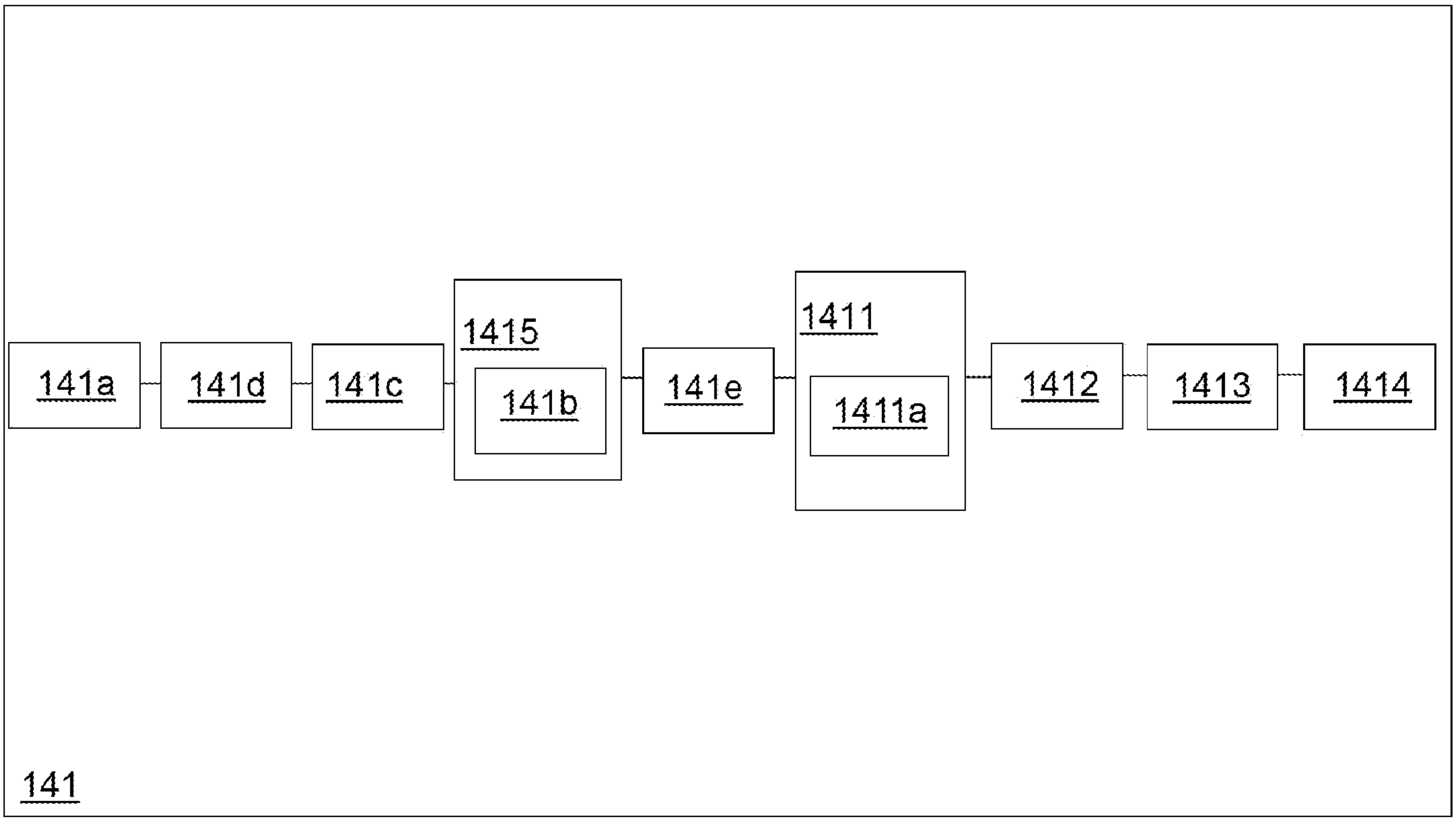

Figure 2

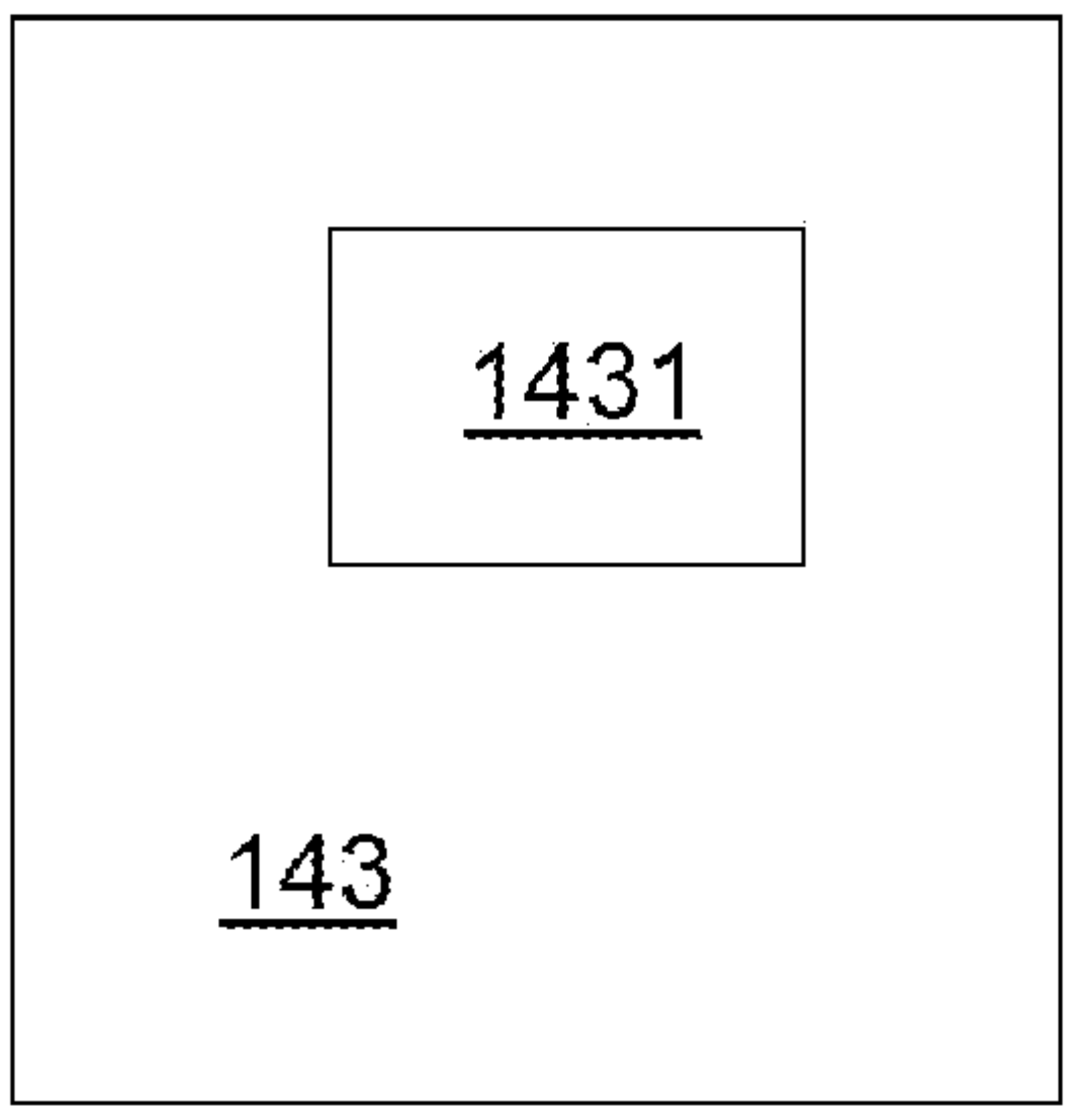

Figure 3

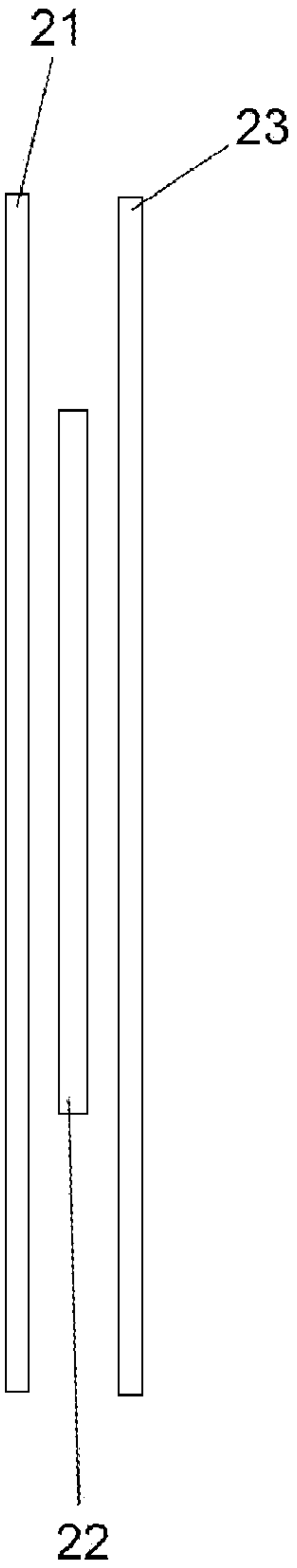

Figure 4

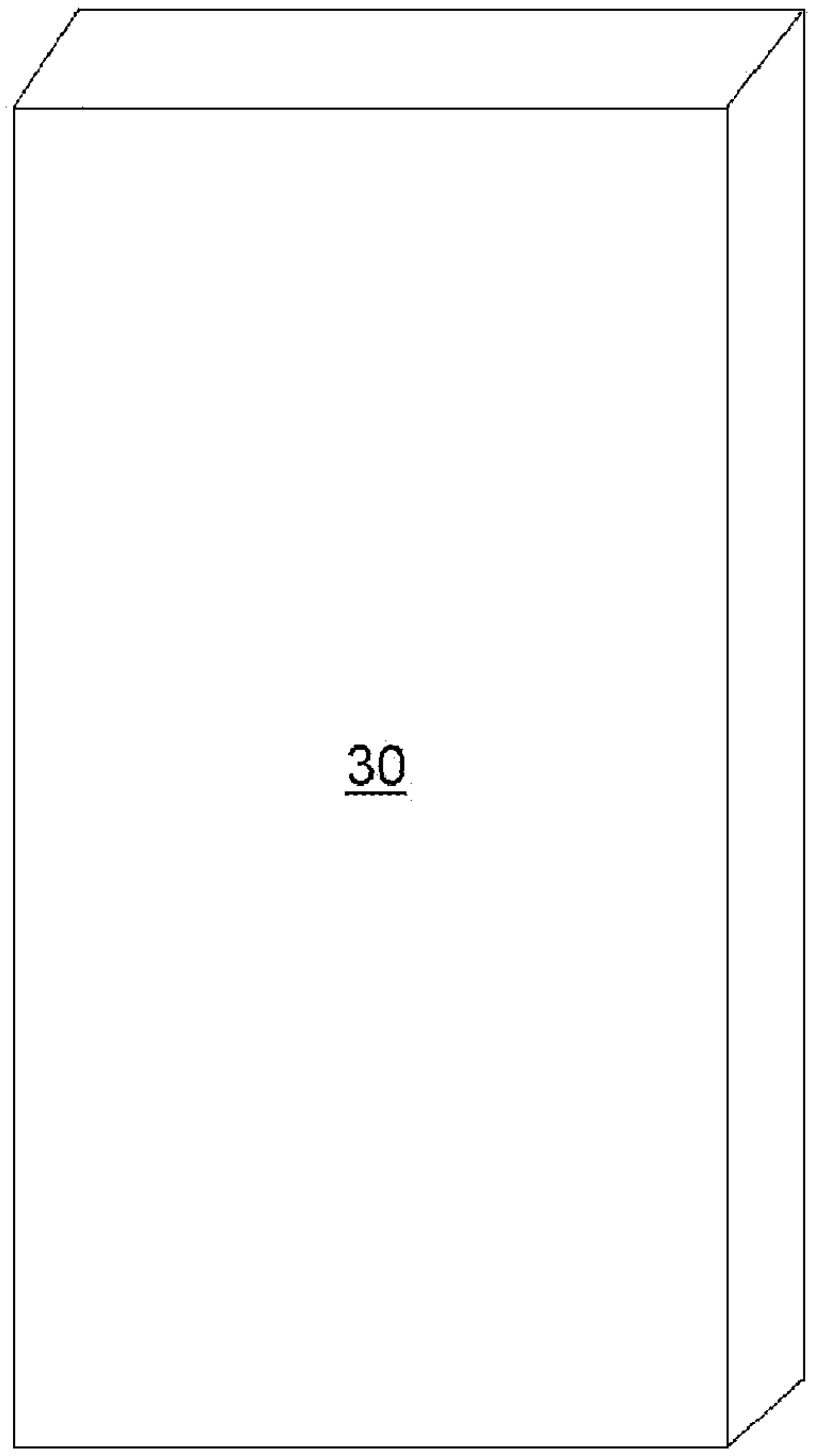

Figure 5

# Title: Aspects of a Sonar System

## Description of Invention

Embodiments of the present invention relate to sonar systems and components thereof. More particularly, aspects of the present invention relate to receive circuitry for a sonar system.

Sonar (Sound Navigation And Ranging) systems were developed in the early 1900s and active sonar systems are now commonly used for detecting objects underwater – for example, for performing underwater surveys, locating fish or submarines, and for general range finding as part of a navigation system.

An active sonar system operates by outputting a pulsed sound wave into a body of water from a transmitter of the system. The sound wave travels through the water as a compressional wave – i.e. a series of pressure fronts. The wave travels through the body of water until it encounters a change in the body of water, that change may be for example an object (such as the seabed if the body of water is the sea, fish, a submarine, etc). A portion of the sound wave will be reflected, a portion will be transmitted into the object, and a portion of the sound wave will be scattered generally in all directions. By detecting the time at which the reflected portion of the sound wave is received by a receiver of the system (relative to the time at which the wave was transmitted) and knowing the speed of the sound wave through the body of water, it is possible to determine the distance the sound wave has travelled between the transmitter and the receiver. The positions of the transmitter and receiver being known, it is then possible to generate an image of the object encountered by the sound wave.

As will be appreciated, the energy of the sound wave will dissipate as the distance the wave has travelled increases.

Modern sonar systems use transmitters and receivers which are in the form of an array of transmitters and receivers. The arrays of transmitters allow beamforming techniques to be used such that the sound waves output by the array of transmitters comprise a number of narrow beams or lobes, which are created by the constructive and destructive interference of the sound waves from the transmitters in the array. Similarly, the array of receivers can also be used to receive reflected sound waves within narrow beams.

With such modern arrays it is possible to provide a multibeam sonar system in which the system is configured to output sound waves in beams across a swath of the body of water. This allows fast and accurate surveys of the objects in that body of water to be performed.

Whilst there have been considerable developments in sonar technology, there is a general need to reduce the cost of the sonar systems so that they are more affordable and, therefore, more accessible. There is also a need to reduce the power consumption of such sonar systems, and reduce the amount of heat generated by such systems. Increasing the frequency range of operation of the systems is also desirable, particularly if there are no significant cost increases associated with the frequency range increase. There is also a desire to make the systems as small and robust as possible.

The present invention seeks to ameliorate one or more problems associated with the prior art.

An aspect of the present invention provides receive array circuitry for a sonar system, comprising: a plurality of inputs, each input being configured to receive an analogue signal from a receiver of a sonar receive array, wherein the plurality of inputs may be a plurality of inputs from a substantially planar sonar receive array; an analogue-to-digital converter configured to sample and convert analogue signals into corresponding digital signals; beamforming circuitry configured to receive the digital signals from the analogue to digital converter and to generate a sonar image from the digital signals, wherein the analogue-to-digital converter is configured to sample the analogue signals at a sample rate which is determined based on a predetermined required bandwidth of the analogue signal, wherein the predetermined required bandwidth of the analogue signal may be selected based on the required range resolution for the sonar system, and wherein the sample rate is less than the Nyquist sample rate determined based on an operating frequency of the analogue signal; and multiplexing circuitry configured to sequence the delivery of a plurality of the analogue signals to the analogue-to-digital converter in accordance with a multiplexing scheme and wherein the beamforming circuitry is configured to compensate for relative delays between samples captured by the analogue-to-digital converter.

The analogue-to-digital converter may be further configured to receive a user selected range resolution.

The sample rate may be substantially equal to or greater than twice the predetermined bandwidth of the analogue signal.

The sample rate may be a fraction of the operating frequency of the sonar system.

The receive array circuitry may further comprise an I/Q demodulator configured to receive the digital signals from the analogue to digital converter, to perform I/Q demodulation, and to pass the I/Q demodulated digital signals to the beamforming circuitry.

The I/Q demodulator may use an FIR Hilbert Transform filter.

The beamforming circuitry may be configured to use a spectral decomposition of the aperture field technique to generate the sonar image.

Another aspect provides a sonar system including receive array circuitry.

The sonar system may further comprise a receive array.

The sonar system may further include a transmit array.

Another aspect provides a vessel including a sonar system.

Another aspect provides an installation including receive array circuitry.

Another aspect provides a vessel including an installation.

Another aspect provides a method of retrofitting a sonar system with receive array circuitry comprising: replacing at least one component of a sonar system with at least one component of the receive array circuitry to provide receive array circuitry in the sonar system.

Embodiments of the present invention are described herein, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 depicts a sonar system of an example embodiment;

Figure 2 depicts channel circuitry of an example embodiment;

Figure 3 depicts beamforming circuitry of an example embodiment;

Figure 4 depicts circuit boards of an example embodiment; and

Figure 5 depicts a housing of an example embodiment.

With reference to figure 1, embodiments of the present invention include a sonar system 1. The sonar system 1 includes a transmitter 11 (which may be a plurality of transmitters which may be arranged in an array (known as a transmit array 11)) and an array of receivers (known as a receive array 12).

The receive array 12 may be positioned in a grid-like formation with the receivers in a first plane and the transmitter 11 in a second plane (in some embodiments, the first and second planes are the same plane). The receive array 12, therefore, comprises columns and rows of receivers. Such an array may be referred to as a 2D array because the receivers are in a common plane. In some embodiments, the transmitter 11 also comprises a 2D array of transmitters (e.g. arranged in columns and rows, in the second plane). The first and second planes may be 5-10cm (e.g. 8-10cm) apart in some embodiments. In some described arrangements, one or both of the first and second planes is substantially flat but in other embodiments is curved.

In some embodiments, the receive array 12 comprises a forty eight by forty eight array of receivers giving a total of two thousand three hundred and four receivers in the receive array 12. Each receiver in the receive array 12 may be referred to as a receive element. Other sizes of array are envisaged; however, for ease of explanation, a forty eight by forty eight receive array 12 is used herein as an example. In some embodiments, the receive array 12 has a width of about 20cm and a height of about 20cm. It will be appreciated that the explanation of the operation of aspects of the invention will apply to other sizes of receive array 12 with appropriate scaled modifications to the calculations and hardware requirements.

The transmitter 11 is configured to output a sound wave for use in a sonar technique and the receive array 12 is configured to receive the sound wave (reflected from an object).

The transmitter 11 and receive array 12 are generally spaced apart from each other. In some embodiments the transmitter 11 and receive array 12 are housed as a single unit in one housing (for example, in a transducer head of the sonar system 1). The transmitter 11 and the receive array 12 may be generally located close to each other to reduce parallax errors.

In some embodiments, a plurality of transmitters 11 and receive arrays 12 may be provided. The pluralities may be in respective transmitter-receive array 11,12 pairs – each pair being housed in one housing, for example, but not necessarily the same housing as another pair (which may be in a separate housing).

The sonar system 1 is configured such that the transmitter 11 transmits sound waves into a body of water and the receive array 12 receives reflected sound waves from the body of water. The transmitter 11 may be configured to transmit sound waves in the form of a chirp signal (i.e. using chirp modulation or linear frequency modulation). The transmitter 11 may be configured to transmit sound waves in the form of a continuous waveform signal (i.e. a CW signal).

Accordingly, the sonar system 1 is configured to be at least partially submerged in the body of water during use. For example, at least part of the sonar system 1 (e.g. the transmitter 11 and receive array 12) may secured to a vessel – i.e. a ship, boat, or submarine – or may be towed behind such a vessel. Other parts of the sonar system 1 may be located separately – e.g. at a sonar station within the vessel or at a remote location (which may be another vessel or a land-based facility). At least part of the sonar system 1 may be provided as part of an installation which may be part of a vessel or which may be a land-based installation or which may be located in an aircraft, for example.

The transmitter 11 is coupled in electrical communication with transmitter circuitry 13 of the sonar system 1 and, similarly, the receive array 12 is coupled in electrical communication with receive array circuitry 14.

The transmitter circuitry 13 is configured to drive the operation of the transmitter 11 or transmitters 11 to output a sound wave in a predetermined manner – for example, as a series of pulses or pings. In some embodiments, the transmitter 11 is driven to output an acoustic signal with an operating frequency (i.e. a carrier frequency) which may be an operating frequency of about 375kHz (or any other suitable operating frequency). In other embodiments, the operating frequency is between about 80 and about 500 kHz. As will be appreciated, the transmitter circuitry 13 may be configured to drive the operation of the transmitter 11 or transmitters 11 to output sound in the form of a chirp signal (i.e. using chirp modulation or linear frequency modulation) or a continuous waveform signal.

The receive array circuitry 14 is configured to receive one or more signals from the receivers of the receive array 12 and to pre-process those signals – either for use in their pre-processed form or for further processing to occur. The one or more signals from the receivers are generated by the receivers in response to detected sound waves at the receivers. Accordingly, each of the one or more signals is representative of a sound wave detected by a receiver of the receive array 12. Collectively, the information carried by the one or more signals is referred to herein as receive array data. The one or more signals from the receive array 12 are typically each analogue signals.

The receive array circuitry 14 includes channel circuitry 141 and beamforming circuitry 143 for pre-processing the receive array data.

The or each analogue signal is provided to the channel circuitry (or channel 'boards') 141 which may, in turn, comprise various filters, amplifiers, and other circuit elements including an analogue-to-digital converter 1411. The circuit elements of the channel circuitry 141 form channels for the or each signal on which they act.

The analogue-to-digital converter 1411 may comprise an array of analogue-to-digital converter devices 1411a such that the or each analogue signal may be converted by a respective analogue-to-digital converter device 1411a into a respective digital signal. Each analogue-to-digital converter device 1411a may form part of a respective channel, as mentioned above. As such each digital signal may be described as 'channel data' on which further processing is performed.

The analogue-to-digital converter 1411 is configured to sample the or each analogue signal (the receive array data) for conversion into one or more corresponding digital signals (the channel data).

In some embodiments, following conversion of the or each analogue signal into a respective digital signal, the channel data is then I/Q demodulated in an I/Q demodulator 1412 and the channel data output by the I/Q demodulator 1412 is demodulated channel data in the form of digital output signals which include both complex and real parts. In other embodiments, other signal processing is performed on the channel data output by the analogue-to-digital converter 1411.

In some embodiments, the I/Q demodulator 1412 operates on a first set of samples of signals from the receive array 12 to determine the in-phase component, 'I', and a second set of samples of signals from the receive array 12 to determine the quadrature component, 'Q'.

The demodulated channel data is then passed to a low pass filter 1413 and then to a decimator 1414 which decimates (or sub-samples) the channel data to reduce the effective sampling rate – to reduce computational overheads in the beamforming circuitry 143 and later processing stages (if applicable).

The digital output signals from the channel circuitry 141 are provided from the channel circuitry 141 to the beamforming circuitry 143 (or beamforming 'boards'). The beamforming circuitry 143 is configured to process the digital data it receives from the channel circuitry 141 in accordance with conventional beamforming techniques so as to identify data within the received data which relates to specific narrow beams within the receive array data. This data can then be analysed to determine the location of one or more objects with respect to the sonar system 1 or a part thereof (for example, the seabed, a vessel, or fish). In some embodiments, the beamforming circuitry 143 is configured to process the digital data it receives from the channel circuitry 141 to identify data which relates to a one hundred and twenty eight by one hundred and twenty eight array of beams – although other array sizes are possible in other embodiments.

In some conventional sonar systems, similar channel circuitry is used in which samples of the or each analogue signal are taken at a rate of 2M samples/s. As will be appreciated, in some conventional sonar systems, with a 375kHz operating frequency, and separate samples taken to determine the in-phase and quadrature components, a minimum sampling frequency would be understood to be 1.5M samples/s (i.e. for each of the samples for the in-phase and quadrature components, a sampling rate of 750kHz would be used). In some conventional sonar systems, there is oversampling in order to allow for additional filtering to be performed or to accommodate the possibility of higher operating frequencies (e.g. a rate of 2M samples/s allows an operating frequency as high as 500kHz). The samples are converted by a similar analogue-to-digital converter to output digital words of 12-bit length at a rate of 55.3GBits/s for a forty eight by forty eight receive array 12 (which collects one set of samples for determining the in-phase component and another set of samples for determining the quadrature component), for example. This sampled data is then I/Q demodulated with an effective sampling frequency of 1MHz (which is the Nyquist sampling rate for a signal with a frequency of 500kHz). This data is then low-pass filtered and sub-sampled by a factor of 12 to provide an effective sampling frequency of 75kHz (which is the Nyquist sampling rate for a signal with a frequency of 37.5kHz). In other words, an output from the channel circuitry may be in the form of 12-bit digital words output at a rate of 75k samples/s for each data channel (i.e. 2.07Gbits/s for a forty eight by forty eight receive array 12). This provides a range resolution of 2cm (e.g. for a continuous wave signal or may be greater for a chirp signal). Thus, in such a conventional system, the data output by the channel circuitry is just 1/13 of the data available after the initial sampling and digitisation.

In other words, it was conventionally thought that outputs from the receive array 12 would need to be sampled at, at least, the Nyquist sampling rate (i.e. double the maximum frequency of the analogue signal (i.e. the operating frequency)). So, for example, a sampling rate of 750kHz would be required for a 375kHz operating frequency.

In accordance with described arrangements, however, some such conventional, modified, or novel sonar systems can achieve identical or substantially identical results with a sampling frequency which is determined by the bandwidth of the analogue signal. The bandwidth relates only to the required range resolution. Therefore, for a range resolution of 1cm with a 375kHz operating frequency, there is a required bandwidth of 75kHz and so a Nyquist sampling rate of 150kHz, where the bandwidth required for that range resolution is c/(2d), wherein ‘c’ is the speed of sound in water (about 1500m/s) and ‘d’ is the range resolution in metres. Accordingly, a sampling rate for the outputs from the receive array 12 of 150kHz, in this example, would be sufficient to provide substantially all the useful data to the beamforming circuitry 143 (although, in some embodiments, elements such as the decimator 1414 could be omitted as sub-sampling is not necessarily needed in accordance with embodiments).

In some embodiments, the analogue-to-digital converter 1411 includes one or more multiplexed analogue-to-digital converter devices 1411a which are each configured to convert more than one analogue signal (of the receive array data) into respective corresponding digital signals (the channel data). As such, there may be fewer analogue-to-digital converter devices 1411a than the number of receivers in the receive array 12.

Accordingly, in some embodiments, the channel circuitry 141 may include an array of pre-amplifiers 141a which are each configured to amplify a respective one of the analogue signals.

The channel circuitry 141 may further include an array of switch devices 141b (such as FET switch based devices) which are each configured to provide selectively one of two or more of the analogue signals to one of the analogue-to-digital converter devices 1411a. Accordingly, the array of switch devices 141b provide multiplexing circuitry 1415 configured to provide a plurality of the analogue signals selectively to a single of the analogue-to-digital converter device 1141a.

Thus, for example, in a forty eight by forty eight receive array 12, each of the forty eight receive elements in each row of the receive array 12 may be sampled in turn, from one end of the array to the opposing end of the array – working up (or down) the columns of the receive array 12. Each column, in such an example, may be provided with its own analogue-to-digital converter device 1411a. In some embodiments, such an arrangement is provided but there are a different number of rows and columns of receive elements in the receive array 12. In some embodiments, sampling is performed in a sequence from the centre of the receive array 12 outwards instead.

In some embodiments, the channel circuitry 141 may further include an array of band pass filters 141c which is connected between the pre-amplifiers 141a and the switch devices 141b. Each of the band pass filters 141c is configured to receive a one of the analogue signals (of the receive array data) and to apply a band pass function on that signal which is then passed towards a switch device 141b of the multiplexing circuitry 1415. The positioning of the band pass filters 141c between the pre-amplifiers 141a and the switch devices 141b (rather than between the switch devices 141b and the analogue-to-digital converter devices 1411a) may help to reduce the risk of propagation delays through the band pass filters 141c meaning that there is insufficient setup time for the analogue-to-digital converter devices 1411a – which would lead to interference of the samples and inaccurate digital signals being output by the analogue-to-digital converter devices 1411a.

In some embodiments, each band pass filter 141c may include a plurality of filters arranged in series.

In some embodiments, an array of further switch devices 141d is provided between the pre-amplifiers 141a and band pass filters 141c. The array of further switch devices 141d may be configured to provide selectively one of at least two of the pre-amplified analogue signals to one of the band pass filters

141c – thus allowing two stages of multiplexing in some embodiments. However, in such arrangements, the analogue signals which are multiplexed must be selected to avoid the propagation delay through band pass filters 141c causing errors in the analogue-to-digital conversion by the analogue-to-digital converter devices 1411a. In other words, the further switch devices 141d may be used, in some embodiments, to schedule the outputs of the relatively slow band pass filters 141c to the analogue-to-digital converter devices 1411a. As will be appreciated, in embodiments with further switch devices 141d, there may be fewer band pass filters 141c compared to the number of pre-amplifiers 141a.

In particular, the receive array 12 may be configured as a grid of receivers arranged in rows and columns – as discussed above. The multiplexing may be achieved by sampling the analogue signals from the columns of receivers simultaneously but sampling each the analogue signals from each row of all columns slightly later than the previous one.

In some embodiments, the sampling may start at the centre of the receive array 12 and proceed in an outward direction with successive samples. In some embodiments, the sampling may be performed by rows or columns instead – in a similar manner to the sampling described above by the multiplexing circuitry 1415. Two successive samples provided to the same band pass filter 141c would be selected to ensure that the propagation delay from the receiver to the further switch devices 141d is greater than the propagation delay (or group delay) through the band pass filters 141c.

Sampling may be performed by the channel circuitry 141 as will be apparent.

In embodiments including the multiplexing circuitry 1415 and further switch devices 141d, the multiplex circuitry 1415 and further switch devices 141d (which might be collectively referred to as further multiplexing circuitry) may operate independently of each other.

In other embodiments, the further switch devices 141d are not provided and, instead, an array of band pass filters 141c is provided (each being configured to apply a band pass filter function to a one of the analogue signals). Accordingly, instead of their being fewer band pass filters 141c than receivers in the receive array 12 (as may be achieved using multiplexing as described above), there may be a generally equal number of band pass filters 141c to the number of receivers in the receive array 12.

In embodiments, the channel circuitry 141 may further include an array of time varying gain (TVG) amplifiers 141e. The TVG amplifiers 141e may be located (i.e. connected) between the switch devices 141b (i.e. the multiplexing circuitry 1415) and the analogue-to-digital converter devices 1411a (i.e. the analogue-to-digital converter 1411). Therefore, as will be appreciated, there may be fewer TVG amplifiers 141e than the number of receivers in the receive array 12 (as achieved by the multiplexing described above). The TVG amplifiers 141e are configured to compensate for the attenuation of a sound signal as it passes through the body of water. This attenuation is largely due to the spreading of the signal through the water. For an omnidirectional emitter, the attenuation would typically be -20.logR dB (where R is the distance travelled by the signal). However, reflected signals are, in practice, not omnidirectional. Therefore, although a signal emitted by the transmitter 11 may have an attenuation close to the above, the attenuation of the reflected signal may be different. The TVG amplifiers 141e may, therefore, be configured to receive a user input to fine tune the gain of the TVG amplifiers 141e to accommodate different attenuations when in use.

A variable gain amplifier such as the AD8338 device, by Analog Devices, Inc, is one possible example of a device which could be used to implement each TVG amplifier 141e.

In some embodiments, the array of TVG amplifiers 141e is connected between receive array 12 and the multiplexing circuitry 1415, instead of between the multiplexing circuitry 1415 and the analogue-to-digital converter 1411. The array of TVG amplifiers 141e may be connected to receive signals from the band pass filters 141c (or other component connected between the band pass filters 141c and the array of TVG amplifiers 141e) or may be connected to send signals to the band pass filters 141c (or other component connected between the array of TVG amplifier 141e and the band pass filter 141c). Similarly, in some embodiments, the array of pre-amplifiers 141a may be connected between the multiplexing circuitry 1415 and the analogue-to-digital converter 1411 instead of between receive array 12 and the multiplexing circuitry 1415.

The two stages of multiplexing may be useful in embodiments in which the TVG amplifiers 141e constrain the number of multiplexed signals that can be handled.

Use of TVG amplifiers 141e allow echoes (i.e. reflected sound signals) from distant objects to be amplified more than echoes from closer objects.

In some embodiments, fixed gain amplifiers may be used instead of TVG amplifiers 141e, connected in much the same manner (see 141e in figure 2, for example). In such embodiments, the fixed gain amplifiers may be connected between the switch devices 141b (i.e. the multiplexing circuitry 1415) and the analogue-to-digital converter devices 1411a (i.e. the analogue-to-digital converter 1411) or between the receive array 12 and the multiplexing circuitry 1415. Each of the fixed gain amplifiers is configured to receive a signal from the switch devices 141b or receive array 12, as the case may be, in succession. Each of the fixed gain amplifiers is configured to amplify each received signal in accordance with a fixed gain for that fixed gain amplifier. Accordingly, the fixed gain amplifiers are configured to output a plurality of amplified signals for each received signal, each of the plurality of amplified signals having been amplified by a predetermined amount, i.e. gain, according to which of the fixed gain amplifiers output generated the amplified signal.

The analogue-to-digital converter 1411 is configured to determine which of the amplified signals to use based on the operating range of the analogue-to-digital converter 1411 (e.g. the range of signal voltage that the analogue-to-digital converter 1411 can convert).

The analogue-to-digital converter 1411 may be further configured to output, with the digital signals, an indication of which amplifier of the fixed gain amplifiers was used. This output may be in the form of a scaling factor, which may be a digital word (e.g. a byte) associated with the digital signal or a part of the signal.

Unused amplified signals from the fixed gain amplifiers may be discarded.

For example, for a range of up to 200m, the usual maximum TVG amplification is 40logR dB (where R is the distance travelled by the signal), or about 92dB. If the fixed gain amplifiers had gains of 10dB, 82dB and 154dB respectively, an effective range of about 2m to about 7km would be adequately amplified to be digitised correctly by the analogue-to-digital converter 1411 (assuming an appropriately powerful pulse had been transmitted). In such an example one of the three fixed gain amplifiers would output an amplified signal which can be converted accurately by the analogue-to-digital converter 1411. This may, for example, be the fixed gain amplifier with the 82dB gain.

The dynamic ranges of the fixed gain amplifiers may overlap. Thus, with the information indicating which fixed gain amplifier was used, the analogue-to-digital converter devices 1411a may, in some embodiments, output a digital signal with an effectively larger dynamic range and number of bits.

For a 16 bit analogue-to-digital converter device 1411a the dynamic range may be about 96dB. Therefore, in the above example the ranges of the digital signals output by the fixed gain amplifiers with 82dB and 154dB gains will overlap for 10dB (approximately 2 bits). Similarly, the ranges of the digital signals output by the fixed gain amplifiers with 10dB and 82dB gains will overlap by 24dB (approximately 4 bits).Effectively, the 16 bit analogue-to-digital converter device 1411a has been used to create a 42 bit, 250dB digital signal.

As will be appreciated, each analogue-to-digital converter device 1411a may be associated with (i.e. configured to receive an amplified signal directly or indirectly from) a plurality of fixed gain amplifiers with respective different gains (i.e. a group of fixed gain amplifiers). In some embodiments, each analogue-to-digital converter device 1411a is associated with three such fixed gain amplifiers. The gains of each group of fixed gain amplifiers for a particular analogue-to-digital converter device 1411a may have the same gains as each other group of fixed gain amplifiers.

As will be appreciated, multiplexing as used herein is a reference to the sequencing of the delivery of the analogue signals to another circuit component – be it the analogue-to-digital converter 1411 for sampling or to the band pass filters 141c. The multiplexing (or sequencing) is in accordance with a predetermined scheme – as discussed above.

The I/Q demodulator 1412 may operate, in some embodiments, by using signals from the receive array 12 which are sampled (and converted into digital signals) by the analogue-to-digital converter 1411 at a sampling frequency which is twice the bandwidth of the analogue signal. The I/Q demodulator 1412 may obtain a cos and a sine component of the output sound wave from the transmitter 11 at substantially the moment (i.e. instant) each sample is taken by the analogue-to-digital converter 141. The digital signal output by the analogue-to-digital converter 141 is then used by the I/Q demodulator to determine a value for the in-phase and quadrature components of the signal by multiplying the digital signal by the cos component of the sound wave to give the in-phase component and by the –sine component of the sound wave to give the quadrature component. Thus, in such embodiments, it is not necessary to take separate samples for determining the in-phase and quadrature components – as is the case in other embodiments.

The beamforming circuitry 143 may include a processor 1431 which is configured to perform one or more operations on the digital channel data received from the channel circuitry 141. The processor 1431 may be a dedicated or general purpose processor and may be a Field Programmable Gate Array device or other programmable logic device.

The beamforming circuitry 143 may be configured to use spectral decomposition of the aperture field (SDAF) techniques to generate image data from the digital channel data received from the channel circuitry 141.

The SDAF technique is an example of a pseudo-inverse technique and embodiments of the invention could employ pseudo-inverse techniques other than the SDAF technique.

The pseudo-inverse techniques are advantageous, in relation to embodiments of the present invention, because they do not require assumptions regarding the simultaneity of the samples from the receivers of the receive array 12. As will be appreciated from the above discussion of embodiments of the invention, multiplexing in the manner described means that not all samples are simultaneously collected. By controlling which samples are collected simultaneously as part of the multiplexing process (e.g. all column of receivers being simultaneously sampled but each row of all columns being sampled later than the preceding row) allows the effect of the delays to be predicted, quantified, and (if necessary) compensatory action can be taken accordingly. Indeed, in the multiplexing scheme example given above the effect of the delays will be as if the pitch of the receive array 12 had been altered.

In accordance with the SDAF technique, the vector of the sound waves received at the receive array 12 (s(w, p)) can be defined as:

$$s(w, p) = U(w, p, r)c(w, r)$$

where

s(w, p) is the vector of the received sound waves and is of size Nx1;

U(w, p, r) is a propagation matrix which describes how an acoustic signal reflected, of one of the beams defined by the beamforming circuitry 143, by an object will appear at each receiver of the receive array 12;; and

c(w, r) is a vector of scattering objects (i.e. the objects from which the sound wave has reflected) of size Mx1.

‘c’ is the data representing the image of the object which has reflected the sound waves and is what the beamforming circuitry 143 seeks to determine (i.e. a vector of the scattering elements’ reflectivity of size Mx1). Of course, ‘s’ is what is measured by the receive array 12 and ‘U’ is known from the design of the sonar system 1.

In some embodiments, the vector ‘s’ is composed of N Fourier transforms of the digital channel data. In some instances neither matrix ‘U’ nor vector ‘s’ are required – for example, in embodiments in which a fixed frequency pulse is being transmitted and I/Q demodulation of the received waveform has been performed.

A best estimate, $\tilde{\mathbf{c}}$, for c may be determined from the minimum-norm solution of the above equation:

$$\tilde{\mathbf{c}} = U^H (UU^H)^+ \mathbf{s}$$

where $^H$ is the complex conjugate and transpose, and $^+$ is the pseudo-inverse.

Each element in U can be defined as:

$$u_{l,i} = Q(\omega)e^{j(\omega/c)(r_i+|\mathbf{p}_l-\mathbf{r}_i|)}$$

$U_{l,i}$ is an element of the propagation matrix;
$l$ is the propagation matrix row index;
$i$ is the propagation matrix column index;
$\omega$ is the angular frequency of the transmitted sound signal
$Q(\omega)$ is the Fourier Transform of the transmitted sound signal
$r_i$ is the distance from an origin (e.g. the transmitter 11) to the scattering array element whose properties are being determined
$p_l$ is the location of the receive element in the sonar receiver array.

That is, the propagation matrix elements comprise the Fourier transform of the outgoing sound pulse, and the Fourier transform of the delay incurred by its travel to and from the reflector (in the range cell being sensed). The delay caused by the multiplexing process can, therefore, be taken into account within this equation by adjusting the distance $|p_l-r_i|$ to compensate for the delay (which will appear as an increased distance between the scattering array element and the receive element).

It will be appreciated that the pseudoinverse $(UU^H)^+$ does not need to be calculated as the product of U and $U^H$ is a Hermitian matrix. Therefore, the inverse of $UU^H$ can be taken to be the diagonal eigenvalue matrix of $UU^H$, where each eigenvalue has been inverted.

The multiplexing and the introduced delay also has the effect of decreasing the grating lobe performance – the receivers in the receive array 12 appear further apart and the grating lobes, therefore, are closer together. However, if the multiplexing is designed carefully – e.g. in accordance with the technique described above – then the effect is limited to the rows of receivers. To compensate, therefore, the rows of receivers may be positioned closer together in the receive array 12.

To avoid spatial aliasing, the sample rate may be greater than twice the desired bandwidth of the signal for a given range resolution. Using the example figures given above, the signal bandwidth has been restricted to 37.5kHz to achieve the desired range resolution, so the Nyquist sampling rate to avoid spatial aliasing would be 75kHz.

As will be understood, embodiments of the present invention allow a sampling frequency to be used which is substantially equal to or greater than the required bandwidth of the analogue signals (for the desired range resolution) but which is less than twice the carrier frequency (i.e. the operating frequency) of the sonar system 1.

As will be appreciated the degree of multiplexing which is possible will depend on the desired range resolution – a greater range resolution will mean more bandwidth is required and the degree of multiplexing must be lower.

In some embodiments, the above described I/Q demodulator 1412 may be a FIR Hilbert Transform filter – configured to demodulate the digital channel data into digital output signals which include both complex and real parts. The FIR Hilbert Transform filter (compared to the conventional I/Q demodulator) would allow further reductions in the sampling frequency. This is because both the in-phase and quadrature components can be determined, using the FIR Hilbert Transform filter, from a single set of samples – it is not necessary to obtain a first set to determine the in-phase component and a second set to determine the quadrature component. In embodiments using the FIR Hilbert Transform filter, multiplications by cosine and sine that are part of conventional I/Q demodulation may be avoided.

In accordance with embodiments, elements for the channel circuitry 14 may be provided as on a printed circuit board 21 on which the receiver array 12 is mounted. These elements may include, for example, the pre-amplifiers 1141, and the switches 1141.

The analogue-to-digital converter 141 may be provided on a separate printed circuit board 22 and the beamforming circuitry 13 may also be provided on a separate printed circuit board 23. The circuit boards 21,22,23 may be arranged in a sandwich formation, with the circuit board 22 carrying the analogue-to-digital converter 141 mounted between the circuit board 21 carrying the receiver array 12 and the circuit board 23 carrying the beamforming circuitry 13. This provides a very compact construction. These circuit boards 21,22,23 may then be placed in a single housing 30.

Such housings 30 are conventionally filled with a liquid (such as Fluorinert(RTM)) to provide desirable heat transfer characteristics between the housed components and the housing 30 – to allow heat to be dissipated quickly. Because of the reduced power requirements of embodiments, liquids may be used for this purpose which have lower heat transfer performance – such as vegetable oils or hydraulic fluid.

According to some embodiments of the invention, a method of retrofitting aspects of the invention to an existing sonar system 1 is provided. The method may include the replacement of printed circuit boards of the existing sonar system 1 (or other circuitry) with printed circuit boards 21,22,23 (or other circuitry) according to embodiments of the invention. For example, the channel circuitry of an existing sonar system 1 may be replaced with the above described channel circuitry 14. The modified circuitry could then be housed in the housing 30 of the existing sonar system 1.

In some embodiments, the band pass filters 141c may be replaced by respective low pass filters – which may provide sufficient filtering for some applications. The above description is to be read accordingly and relates equally to such embodiments.

As will be understood, in embodiments, the multiplexing (and therefore delaying) of the signals from the receive array 12 uses a generalisation that each part of the sound wave pulse is reflected exactly the same by any target element – changes in phase caused by a delay may be accommodated during I/Q demodulation.

In some embodiments, the transmitter circuitry 13 may be configured to drive the operation of the transmitter 11 or transmitters 11 to output a sequence of pulses or pings. Accordingly, the or each transmitter 11 may be configured to output a sequence of pulses or pings.

In some embodiments, the sequence of pulses or pings comprises groups of pulses or pings, with each group may include one or more pulses or pings. In some embodiments, at least one group includes at least one pulse or ping which is of a different length (i.e. duration). Accordingly, one group may be different to another group. The difference in groups allows the receive array circuitry 14 to distinguish one group from another group of pulses or pings which are received by the receive array 12.

In accordance with embodiments, therefore, the use of different groups of pulses or pings enables consecutive groups of pulses and pings to be output by the transmitter 11 or transmitters 11 (and/or driven by the transmitter circuitry 13) at a higher rate than would otherwise be possible because the receive array 12 and receive array circuitry 14 can distinguish one group from another group. This, in turn, allows a better range resolution to be achieved.

As such a first group of pulses or pings may comprise a first pulse or ping of half the length normally used for the desired range resolution (a short pulse or ping), followed by a gap of the same length, followed by a pulse or ping of the length normally required for the desired range resolution (a long pulse or ping). A second of the group of pulses or pings, may comprise a single pulse of the length required for the desired range resolution.

The receive array 12 may receive pulses or pings reflected from one or more objects. The receive array circuitry 14 may be further configured to analyse the received pulses or pings. If the first received group comprises two pulses or pings with a gap therebetween, then this is determined to be the first group of pulses or pings. The second received group may comprise a single pulse or ping which is determined to be the second group of pulses or pings. Receipt of the first group of pulses or pings will mean that the range resolution for the range determined by the time of flight (i.e. the time between transmission and reception) will be the range resolution associated with the first group of pulses or pings. Receipt of the second group of pulses or pings gives a time of flight at a higher range resolution than the first group.

If the time between the transmission of the first and second groups of pulses or pings is known (for example, equal to the length of time required for the pulse or ping to travel one metre in water), and only one of the groups is received (e.g. the second group), then this implies that the other group (e.g. the first group) has not been received. If the received group is the second group, then the range resolution may be better than would otherwise be the case even though the first group was not received.

The time (i.e. gap) between the initial short pulse or ping and the later long pulse or ping of the first group, along with the length of the short and long pulse may be varied to achieve different range resolutions for a given sample rate. In some embodiments, the first pulse or ping may be the long pulse or ping and the subsequent pulse or ping may be the short pulse or ping.

The receive array circuitry 14 may be configured to monitor the time between received pings or pulses, the duration of each received ping or pulse, and sequence of received pings or pulses.

The receive array circuitry 14 may be configured to distinguish one group of pulses or pings from another group of pulses or pings based on one or more of the time between received pings or pulses, the duration of each received pulse or ping, and the sequence of the received pulses or pings.

The use of multiple distinguishable groups of pulses or pings, therefore, may allow multiple pings or pulses to be travelling through the water at any one time and to be distinguished from each other by receive array circuitry 14.

If an object from which a group of pings or pulses are reflected is at a range such that a second or subsequent pulse or ping of the group is not detected (i.e. it is reflected but falls between samples), then this gives information about the range of the object. In particular, a sample from which a first pulse or ping of the group may be detected could be a sample of that pulse or ping at any point along the length of the pulse or ping. Whether or not the second or subsequent pulse or ping is detected may allow, in some embodiments, the point of detection along the length of the first pulse or ping to be determined or inferred with greater accuracy – thus giving more information about the range of the object. In other words, the use of a group of pulses or pings may allow not only the time of flight between transmission of a first pulse/ping and the receipt of the reflected first pulse/ping to be used to determine range of an object, but the subsequent pulse(s) or ping(s) may be used to make the measured time of flight to be more accurate (and hence also to refine the determined range) – by determining to a greater accuracy when the first pulse or ping of the group was, in fact, received.

As will be understood, the receive array circuitry 14 and the transmitter circuitry 13 may be configured to communicate such that the receive array circuitry 14 is provided with information identifying the groups of pings or pulses being transmitted – this information may include, for example, transmission times, pulse or ping duration, gap duration, and sequence information for the pulses or pings of each group.

In embodiments, there are more than two groups of pings or pulses. In some embodiments, the groups of pings or pulses are selected substantially at random. In embodiments, the groups of pings or pulses are not predefined – in such embodiments, one or more of the duration of each ping or pulse, the duration of the gap between each ping or pulse, and the sequence of pings or pulses, is varied from group to group by the transmitter circuitry 13.

The use of different groups of pulses or pings may allow for compensation from distortion or interference – i.e. a particular group may suffer from distortion to a greater extent on reflection from a particular object than another group (e.g. because of the form of the object).

When used in this specification and claims, the terms "comprises" and "comprising" and variations thereof mean that the specified features, steps or integers are included. The terms are not to be interpreted to exclude the presence of other features, steps or components.

CLAIMS

1. Receive array circuitry for a sonar system, comprising:

a plurality of inputs, each input being configured to receive an analogue signal from a receiver of a sonar receive array, wherein the plurality of inputs is a plurality of inputs from a substantially planar sonar receive array;

an analogue-to-digital converter configured to sample and convert analogue signals into corresponding digital signals;

beamforming circuitry configured to receive the digital signals from the analogue to digital converter and to generate a sonar image from the digital signals, wherein the analogue-to-digital converter is configured to sample the analogue signals at a sample rate which is determined based on a predetermined required bandwidth of the analogue signal, wherein the predetermined required bandwidth of the analogue signal is selected based on the required range resolution for the sonar system, and wherein the sample rate is less than the Nyquist sample rate determined based on an operating frequency of the analogue signal; and

multiplexing circuitry configured to sequence the delivery of a plurality of the analogue signals to the analogue-to-digital converter in accordance with a multiplexing scheme and wherein the beamforming circuitry is configured to compensate for relative delays between samples captured by the analogue-to-digital converter.

2. Receive array circuitry according to claim 1, wherein the analogue-to-digital converter is further configured to receive a user selected range resolution.

3. Receive array circuitry according to any of claims 1 to 2, wherein the sample rate is substantially equal to or greater than twice the predetermined bandwidth of the analogue signal.

4. Receive array circuitry according to any preceding claim, wherein the sample rate is a fraction of the operating frequency of the sonar system.

5. Receive array circuitry according to any of claims 1 to 4, further comprising an I/Q demodulator configured to receive the digital signals from the analogue to digital converter, to perform I/Q demodulation, and to pass the I/Q demodulated digital signals to the beamforming circuitry.

6. Receive array circuitry according to claim 5, wherein the I/Q demodulator uses an FIR Hilbert Transform filter.

7. Receive array circuitry according to claim 6, wherein the beamforming circuitry is configured to use a spectral decomposition of the aperture field technique to generate the sonar image.

8. A sonar system including receive array circuitry according to any preceding claim.

9. A sonar system according to claim 8, further comprising a receive array.

10. A sonar system according to claim 8 or 9, further including a transmit array.

11. A vessel including a sonar system according to any of claims 8 to 10.

12. An installation including receive array circuitry according to any of claims 1 to 7.

13. A vessel including an installation according to claim 12.

14. A method of retrofitting a sonar system with receive array circuitry comprising:

replacing at least one component of a sonar system with at least one component of the receive array circuitry to provide receive array circuitry according to any of claims 1 to 7 in the sonar system.