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TOSHIO ITO ET AL: "Evaluation of Acoustic Imaging System Using Correlation Division in Synthetic Transmit Aperture with Multicarrier Signals", IEICE TRANSACTIONS ON FUNDAMENTALS OF ELECTRONICS, COMMUNICATIONS AND COMPUTER SCIENCES, vol. E94-A, no. 10, October 2011 (2011-10) , pages 1907-1919, XP001570643, ISSN: 0916-8508, DOI: 10.1587/TRANSFUN.E94.A.1907 [retrieved on 2011-10-01]

DESCRIPTION

TECHNICAL FIELD

[0001] This patent document relates to ultrasound imaging.

BACKGROUND

[0002] Ultrasound imaging is an imaging modality that employs the properties of sound waves traveling through a medium to render a visual image. Ultrasound imaging has been used as an imaging modality for decades in a variety of biomedical fields to view internal structures and functions of animals and humans. Ultrasound waves used in biomedical imaging may operate in different frequencies, e.g., between 1 and 20 MHz, or even higher frequencies. Some factors including inadequate spatial resolution and tissue differentiation can lead to less than desirable image quality using conventional techniques of ultrasound imaging, which can limit its use for many clinical applications.

[0003] Toshio Ito et al., "Evaluation of Acoustic Imaging System Using Correlation Division in Synthetic Transmit Aperture with Multicarrier Signals", IEICE Transactions on Fundamentals of Electronics, Communications and Computer Science, vol. E94-A, no. 10, October 2011, pages 1907-1919, discloses an acoustic imaging system that uses multicarrier signals for correlation division in synthetic transmit aperture.

[0004] US 2010/280379 A1 discloses an ultrasonic diagnostic apparatus in which an image generation time can be reduced and a frame rate can be improved even in a color mode in which a two-dimensional color Doppler image obtained due to Doppler effect is combined with a B-mode image.

SUMMARY

[0005] The invention is defined by the independent claims. The dependent claims define advantageous embodiments. Techniques, systems, and apparatuses are disclosed for ultrasound imaging using spread spectrum, coherent, frequency- and/or phase-coded waveforms that can exhibit wide instantaneous bandwidth.

[0006] In one aspect of the disclosed technology, a method of creating an image from an acoustic waveform in an acoustic imaging device includes setting a transmit/receive switch in the acoustic imaging device into a transmit mode to transmit an acoustic waveform toward a target, in transmitting the acoustic waveform, synthesizing, in one or more waveform synthesizers, a plurality of substantially orthogonal coded waveforms that form a composite

waveform as the transmitted acoustic waveform toward the target, in which each waveform corresponds to a distinct frequency band and the coded waveforms include at least one of frequency-coded waveforms or phase-coded waveforms, setting the transmit/receive switch in the acoustic imaging device into a receive mode to receive a returned acoustic waveform that returns from at least part of the target, converting the received returned acoustic waveform from analog format to digital format as a received composite waveform comprising information of the target, and processing the received composite waveform to produce an image of at least part of the target.

[0007] In another aspect, an acoustic waveform imaging system is provided to include waveform generation unit comprising one or more waveform synthesizers coupled to a waveform generator, wherein the waveform generation unit synthesizes a composite waveform comprising a plurality of substantially orthogonal coded waveforms corresponding to frequency bands that are generated by the one or more waveform synthesizers according to waveform information provided by the waveform generator, the coded waveforms including at least one of frequency-coded waveforms or phase-coded waveforms; a transmit/receive switching unit that switches between a transmit mode and a receive mode; an array of transducer elements in communication with the transmit/receive switching unit that transmits an acoustic waveform based on the composite waveform toward a target and receives a returned acoustic waveform returned from at least part of the target; an array of analog to digital (A/D) converters to convert the received returned acoustic waveform received by the array of transducer elements from analog format to digital format as a received composite waveform comprising information comprising information of the target; a controller unit in communication with the waveform generation unit and the array of A/D converters comprising a processing unit that processes the received composite waveform to produce an image of at least part of the target; and a user interface unit in communication with the controller unit.

[0008] In another aspect, a method of creating an image from an acoustic waveform is provided to include setting a transmit/receive switch into transmit mode; selecting a mode of operation from a plurality of operating modes; synthesizing, in one or more waveform synthesizers, a plurality of substantially orthogonal coded waveforms that form a composite waveform, wherein each waveform corresponds to a distinct frequency band, the coded waveforms including at least one of frequency-coded waveforms or phase-coded waveforms; transmitting an acoustic waveform based on the composite waveform toward a target; setting the transmit/receive switch into receive mode; receiving a returned acoustic waveform returned from at least part of the target; converting the received returned acoustic waveform from analog format to digital format as a received composite waveform comprising information of the target; and processing the received composite waveform to produce an image of at least part of the target.

[0009] In another aspect, a method of creating an image from an acoustic waveform is provided to include combining a plurality of coded waveforms corresponding to different frequency bands to produce a composite waveform comprising substantially orthogonal wave signals at the different frequency bands, the coded waveforms including at least one of

frequency-coded waveforms or phase-coded waveforms; using the composite waveform to produce an acoustic probe wave that includes the different frequency bands toward a target; receiving acoustic energy returned from at least part of the target after the acoustic probe wave is sent to the target; converting the received returned acoustic energy into a digital composite waveform comprising information of the target; and processing the received composite waveform to produce an image of at least part of the target.

[0010] In yet another aspect, a device for creating an image from an acoustic waveform is provided to include means for combining a plurality of coded waveforms corresponding to different frequency bands to produce a composite waveform comprising substantially orthogonal wave signals at the different frequency bands, the coded waveforms including at least one of frequency-coded waveforms or phase-coded waveforms; means for using the composite waveform to produce an acoustic probe wave that includes the different frequency bands toward a target; means for receiving acoustic energy returned from at least part of the target after the acoustic probe wave is sent to the target; means for converting the received returned acoustic energy into a digital composite waveform comprising information of the target; and means for processing the received composite waveform to produce an image of at least part of the target.

[0011] The subject matter described in this patent document can provide one or more of the following features and be used in many applications. For example, the disclosed technology can be used during routine primary care screenings to identify and locate early stage malignancies, as well as later stage cancers, which can potentially raise survival rates of hard to diagnose asymptomatic patients. The disclosed technology can be used by board certified radiologists to diagnose neoplasms as benign or malignant prior to any surgical biopsy or resection intervention, which may also improve patient survival rate while reducing unnecessary biopsies. The disclosed technology can, when integrated with a fine needle biopsy instrument, be used in medical procedures to confirm noninvasive diagnoses, which can reduce the level of invasiveness of such biopsy procedures. The disclosed technology can, when integrated with minimally invasive surgical high definition video instrumentation, fuse optical and ultrasound images, which can further give surgeons added abilities to locate and surgically excise diseased tissue without excising excessive healthy tissue. The disclosed technology can, when integrated with specialized surgical instrumentation, fusing ultrasound images with other data, can give surgeons added abilities to locate and manipulate anatomic areas of interest while minimizing unnecessary damage to nearby structures. The disclosed technology can reduce the amount of time for the brachytherapy treatment of malignant neoplasms by, for example, precisely guiding the insertion of catheters and sealed radioactive sources into the proper location. Similarly, the disclosed technology can aid insertion of high dose, localized pharmaceuticals for treatments of diseases.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012]

FIG. 1A shows a block diagram of an exemplary ultrasound imaging system using spread spectrum coded waveforms.

FIG. 1B shows a chart for operation of an exemplary ultrasound imaging system using spread spectrum coded waveforms.

FIG. 2 shows a graph of an exemplary spread spectrum, wide instantaneous bandwidth, frequency- and/or phase-coded waveform featuring a plurality of waveforms.

FIG. 3 shows ambiguity function characteristics of an exemplary spread spectrum coded waveform.

FIGS. 4A-4C show an exemplary diagram for beam steering, dynamic focusing, and forming.

FIG. 5 shows an exemplary block diagram for correlation processing of a spread spectrum coded waveform.

[0013] Like reference symbols and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0014] Techniques, systems, and apparatuses are described for generating, transmitting, receiving, and processing coherent spread spectrum frequency- and/or phase-coded waveforms used in ultrasound imaging.

[0015] Ultrasound imaging can be performed by emitting a time-gated, single frequency or narrow instantaneous bandwidth acoustic waveform (pulse), which is partly reflected from a boundary between two mediums (e.g., biological tissue structures) and partially transmitted. The reflection can depend on the acoustic impedance difference between the two mediums. Ultrasound imaging by some techniques may only use amplitude information from the reflected signal. For example, when one pulse is emitted, the reflected signal can be sampled continuously. In biological tissue, sound velocity can be considered fairly constant, in which the time between the emission of a waveform and the reception of a reflected signal is dependent on the distance the waveform travels in that tissue structure (e.g., the depth of the reflecting structure). Therefore, reflected signals may be sampled at multiple time intervals to receive the reflected signals being reflected from multiple depths. Also, different tissues at the different depths can partially reflect the incident waveform with different amounts of energy, and thus the reflected signal from different mediums can have different amplitudes. A corresponding ultrasound image can be constructed based on depth. The time before a new waveform is emitted can therefore be dependent of the maximum depth that is desired to image. Ultrasound imaging techniques employing pulsed monochromatic and/or narrow instantaneous bandwidth waveforms can suffer from poor resolution of image processing and production. Yet,

waveforms with spread spectrum, wide instantaneous bandwidth characteristics that can be coded (e.g., by frequency and/or phase) can enable real-time control of ultrasound imaging and higher quality resultant images.

[0016] FIG. 1A shows a block diagram of an exemplary ultrasound system (100) that can produce acoustic waveforms with enhanced waveform properties that include a spread-spectrum, wide instantaneous bandwidth, coherency, pseudo-random noise characteristics, and frequency- and/or phase-coding. System (100) can be configured in one of many system designs. In one example, system (100) can include a Master Clock (101) for time synchronization. The Master Clock (101) can be interfaced with a System Controller (102). System Controller (102) can include a processing unit, e.g., a central processing unit (CPU) of RISC-based or other types of CPU architectures. System Controller (102) can also include at least one input/output (I/O) unit(s) and/or memory unit(s), which are in communication with the processing unit, to support various functions of the System Controller (102). For example, the processing unit can be associated with a system control bus, e.g., Data & Control Bus (103). System Controller (102) can be implemented as one of various data processing architectures, such as a personal computer (PC), laptop, tablet, and mobile communication device architectures.

[0017] The memory unit(s) can store other information and data, such as instructions, software, values, images, and other data processed or referenced by the processing unit. Various types of Random Access Memory (RAM) devices, Read Only Memory (ROM) devices, Flash Memory devices, and other suitable storage media can be used to implement storage functions of the memory unit(s). The memory unit(s) can store pre-stored waveforms and coefficient data and information, which can be used in the implementation of generating a waveform, e.g., such as a spread-spectrum, wide instantaneous bandwidth, coherent, pseudo-random noise, and frequency and/or phase-coded waveform. The memory unit(s) can store data and information obtained from received and processed waveforms, which can be used to generate and transmit new waveforms. The memory unit(s) can be associated with a system control bus, e.g., Data & Control Bus (103).

[0018] The I/O unit(s) can be connected to an external interface, source of data storage, and/or display device. The I/O unit(s) can be associated with a system control bus, e.g., Data & Control Bus (103). Various types of wired or wireless interfaces compatible with typical data communication standards, such as but not limited to Universal Serial Bus (USB), IEEE 1394 (FireWire), Bluetooth, IEEE 802.111, Wireless Local Area Network (WLAN), Wireless Personal Area Network (WPAN), Wireless Wide Area Network (WWAN), WiMAX, IEEE 802.16 (Worldwide Interoperability for Microwave Access (WiMAX)), and parallel interfaces, can be used to implement the I/O unit. The I/O unit can interface with an external interface, source of data storage, or display device to retrieve and transfer data and information that can be processed by the processor unit, stored in the memory unit, or exhibited on an output unit.

[0019] System Controller (102) can control all of the modules of system (100), e.g., through connection via Data & Control Bus (103). For example, Data & Control Bus (103) can link

System Controller (102) to one or more attached digital signal processors, e.g., Digital Signal Processor (104), for processing waveforms for their functional control. Digital Signal Processor (104) can include one or many processors, such as but not limited to ASIC (application-specific integrated circuit), FPGA (field-programmable gate array), DSP (digital signal processor), AsAP (asynchronous array of simple processors), and other types of data processing architectures. Data & Control Bus (103) can also link System Controller (102), as well as Digital Signal Processor (104), to one or more display units with modules for user interfaces, e.g., Display (105) with a module User Interface (106) to provide information to a user or operator and to receive input/commands from the user or operator. Display (105) can include many suitable display units, such as but not limited to cathode ray tube (CRT), light emitting diode (LED), and liquid crystal display (LCD) monitor and/or screen as a visual display. Display (105) can also include various types of display, speaker, or printing interfaces. In other examples, Display (105) can include other output apparatuses, such as toner, liquid inkjet, solid ink, dye sublimation, inkless (such as thermal or UV) printing apparatuses and various types of audio signal transducer apparatuses. User Interface (106) can include many suitable interfaces including various types of keyboard, mouse, voice command, touch pad, and brain-machine interface apparatuses.

[0020] The exemplary system (100) can include Waveform Generator (107), which can be controlled by System Controller (102) for producing one or more digital waveforms. The one or more digital waveforms can be generated as analog electronic signals (e.g., analog waveforms) by at least one element in an array of waveform synthesizers and beam controllers, e.g., represented in this example as Waveform Synthesizer and Beam Controller (108). Waveform Generator (107) can be at least one of a function generator and an arbitrary waveform generator (AWG). For example, Waveform Generator (107) can be configured as an AWG to generate arbitrary digital waveforms for Waveform Synthesizer and Beam Controller (108) to synthesize as individual analog waveforms and/or a composite analog waveform. Waveform Generator (107) can also include at least one memory unit(s) that can store pre-stored waveforms and coefficient data and information used in the generation of a digital waveform.

[0021] The exemplary system (100) shown in FIG. 1A includes Waveform Synthesizer and Beam Controller (108) comprising I number of array elements. In one example, Waveform Synthesizer and Beam Controller (108) can be configured to include at least one waveform synthesizer element on each line of the I number of array waveform synthesizers. In another example, Waveform Synthesizer and Beam Controller (108) can include at least one beam controller element on each line of the I number of array beam controllers. In another example, Waveform Synthesizer and Beam Controller (108) can include at least one waveform synthesizer element and beam controller element on each line of the I number of array waveform synthesizers and beam controllers. Waveform Synthesizer and Beam Controller (108) can include a phase-lock loop system for generation of an electronic signal, e.g., a radio frequency (RF) waveform. An exemplary RF waveform can be synthesized by Waveform Synthesizer and Beam Controller (108) from individual waveforms generated in the array elements of Waveform Synthesizer and Beam Controller (108), e.g., one individual RF

waveform can be generated in one array element substantially simultaneously to all other individual waveforms generated by the other array elements of Waveform Synthesizer and Beam Controller (108). Each individual RF waveform can be defined for a particular frequency band, also referred to as a frequency component or 'chip', and the waveform properties of each individual waveform can be determined by Waveform Generator (107), which can include at least one amplitude value and at least one phase value corresponding to the chip. Waveform Generator (107) can issue commands and send waveform data including information about each individual waveform's properties to Waveform Synthesizer and Beam Controller (108) for generation of individual RF waveforms that can be composited into a composite RF waveform.

[0022] The individual RF waveforms and/or the composite RF waveform generated by Waveform Synthesizer and Beam Controller (108) can be modified by Output Amplifiers (109), which includes an array of I number of amplifiers, e.g., by amplifying the gain and/or shifting the phase of a waveform. Output Amplifiers (109) can be used as transducer drivers. The individual RF waveforms and/or the composite RF waveform can be passed to Transmit/Receive (T/R) switch (110), e.g., an N-pole double-throw transmit/receive switch. T/R Switch (110) that can be interfaced with a transducer module. A generated RF waveform, e.g., the composite RF waveform and/or at least one individual RF waveform, that is to be transmitted into a target medium can be transduced into, for example, an acoustic wave by the transducer module that can include an array of transducer elements, e.g., Transducer Array (111) comprising I number of elements. For example, the transduced acoustic wave can be emitted in the form of an acoustic waveform pulse. Each array element of the Transducer Array (111) may generate one or more acoustic waveforms that correspond to the individual waveform chips determined by the Waveform Generator (107).

[0023] The exemplary transduced transmitted acoustic waveform can be transmitted toward a target area, e.g., biological tissue, and form a spatially combined acoustic waveform. The transmitted waveform can propagate into the target medium, which for example, can have one or more inhomogeneous mediums that partially transmit and partially reflect the transmitted acoustic waveform. Exemplary acoustic waveforms that are partially reflected, also referred to as returned acoustic waveforms, can be received by Transducer Array (111). For example, each array element of I array elements of Transducer Array (111) can be configured to receive a returned acoustic waveform corresponding to the frequency chip and convert it to an analog RF waveform. The individual received (analog) RF waveforms can be modified by Pre-Amplifier module (112), which includes an array of I number of amplifiers, e.g., by amplifying the gain and/or shifting the phase of a waveform. The individual received waveforms can be converted from analog format to digital format by analog to digital (A/D) Converter module (113), which includes an array of I number of A/D converters. A/D Converter module (113) can include A/D converters that have low least significant bit (LSB) jitter, spurious-free dynamic range (SFDR) and waveform dependency, such that the exemplary waveforms can be adequately decoded. The converted digital representations of the individual received waveforms can be processed by a processor, e.g., Digital Signal Processor (104), in manner that creates and forms a representative image of the target medium.

[0024] The exemplary system (100) can be operated in one of many operation modes. In one example, Master Clock (101) can provide the time base for synchronizing the system (100), e.g., as a time base for the Waveform Synthesizers (108). Master Clock (101) can be configured as a low phase noise clock such that the exemplary waveforms can be phase encoded. An operator can select the mode of operation at User Interface (106). Exemplary modes of operation provided for the user to select at the User Interface (106) include Conventional A-Mode (e.g., 1D Depth only image), Conventional B-Mode (e.g., 2D Plane image - transverse vs. depth), Conventional C-Mode (e.g., 2D Plane image at selected depth), and Conventional D-Modes (e.g., Doppler Modes). Exemplary Doppler modes include Color Doppler (e.g. superposition of color coded Doppler and B-mode images), Continuous Doppler (e.g., 1D Doppler profile vs. depth), Pulsed Wave Doppler (e.g., Doppler vs. time for selected volume), and Duplex/Triplex Doppler (e.g., superposition of Conventional B-Mode, Conventional C-Mode or Color Doppler, and Pulsed Wave Doppler). Some other exemplary modes of operations can include Conventional 3D and 4D ("real time" 3D) volume renderings of the previously described modes of operations. The exemplary system (100) can implement new modes of operation that can generate spread spectrum, wide instantaneous bandwidth, frequency- and/or phase-coded waveforms. For example, a user can select exemplary ATS-Modes (Artificial Tissue Staining Modes) that can comprise a B-Mode, a C-Mode, a D-Mode, or other mode combined with image color coding to aid tissue differentiation - analogous to tissue staining for microscopic histological studies; and exemplary CAD-Modes (Computer Aided Diagnostic Modes) that differentiate and identify tissue type. ATS-Modes can employ the use of features for image color coding in image processing based on one or more of a number of measured properties that are obtained from the returned echo waveform from the target area, e.g., the returned echo from an exemplary transmitted spread spectrum, wide instantaneous bandwidth, coded acoustic waveform. CAD-Modes can use classifiers (algorithms) to classify, for example, tissue types based on features of the measured properties of the returned echo from the target area, e.g., the returned echo from an exemplary spread spectrum, wide instantaneous bandwidth, coded acoustic waveforms. The features properties can include differing impedances, amplitude reflections (as a function of wavelength), group delay, etc. Some exemplary classifiers that can be employed using CAD-Modes can include deterministic classifiers, stochastic classifiers (e.g., Bayesian classifiers), and neural network classifiers.

[0025] FIG. 1B shows an exemplary operation process (150) for operating the system (100) for ultrasound imaging. For each time epoch, process (150) can begin by implementing process (151) to switch system (100) in transmit mode. For example, the System Controller (102) can command an N-pole double-throw T/R switch, e.g., T/R Switch (110), to transmit position. Process (150) includes a process (152) to check a user-defined mode of operation. For example, mode of operation can be selected by a user using User Interface (106), or the mode of operation can be selected by another entity or internally within system (100). Based on the selected operation mode, System Controller (102) can command Waveform Generator (107) to issue a digital message (data) to one or more elements in Waveform Synthesizers and Beam Controllers (108) that defines the frequency, amplitude and phase of each of the frequency chips that form a desired wideband composite RF waveform commanded, e.g.,

implemented in a process (153). Process (152) can occur anywhere and implemented in multiple instances during process (150). Process (150) includes a process (153) to issue waveform data (e.g., the exemplary digital message/data) to waveform synthesizers and beam formers, such as the Waveform Synthesizers and Beam Controllers (108). The issued waveform data can include the frequency, amplitude and phase information of the desired frequency chips that are synthesized as frequency- and/or phase-coded waveforms, in which each coded waveform corresponds to a distinct frequency band. Process (150) includes a process (154) to generate individual analog RF waveforms that correspond to defined frequency chips. For example, each element in the array of Waveform Synthesizers and Beam Controllers (108) can convert the digital message/data from the Waveform Generator (107) into individual analog waveforms that can make up a coherent analog wideband composite waveform. Process (150) includes a process (155) to amplify the individual analog waveforms that can make up a coherent analog wideband composite waveform. For example, each analog waveform and/or wideband composite waveform can be amplified by an array element in Output Amplifier (109). The amplified analog wideband composite waveform can then pass through the T/R Switch (110) and excite its respective array element of the Transducer Array (111) (e.g., in an ultrasound probe). Process (150) includes a process (156) to transduce the composite analog waveform to an acoustic waveform that can propagate throughout the scanned volume. For example, each element of the Transducer Array (111) can provide an acoustic waveform from each of the individual analog waveform corresponding to the frequency chip generated in Waveform Synthesizer and Beam Controller (108) that makes up the wideband composite acoustic waveform. Transducer Array (111) can form the acoustic beam that propagates into the target medium, e.g., biological tissue volume under study.

[0026] At the end of process (156), process (150) can implement process (157) to switch system (100) in receive mode. For example, the System Controller (102) can command the N-pole double-throw T/R Switch (110) to receive position. Process (150) includes a process (158) to receive a returned acoustic waveform, which can be in the form of one or more returned acoustic waveforms (also referred to as acoustic waveform echoes). Process (158) can also include transducing the returned acoustic waveform echo(es) into individual received analog waveforms, e.g., corresponding to the frequency chips of the generated individual waveforms. For example, the returned acoustic waveform propagates back to and is received by Transducer Array (111). Each element of Transducer Array (111) can convert the received acoustic waveform it receives into an analog signal (waveform). Process (150) includes a process (159) to amplify the individual received analog waveforms. For example, each received analog waveform can be amplified by its respective low noise pre-amplifier element in Pre-Amplifier module (112). Process (150) includes a process (160) to convert the individual received analog waveforms into digital waveform data. For example, each received (and amplified) analog waveform signal can be converted into a digital word by each respective A/D element in A/D Converter module (113). The digital format data can be sent to Digital Signal Processor (104) for signal processing. Process (150) includes a process (161) to process the digital waveform data into image frames representative of the target medium. Process (161) can also include compositing the digital waveform data into a composite digital signal representing the individual and composite received analog waveform. For example, Digital

Signal Processor (104) can detect the amplitude and phase of each of the frequency chips that comprise the wideband composite acoustic waveform received by each of the transducer array elements. Digital Signal Processor (104) can form the received beam and separate the amplitude and Doppler components of each resolution element of the beam, and can form an image frame associated with mode previously selected by operator. The image frame formed by Digital Signal Processor (104) can be displayed on Display (105) to the user. For other subsequent time epochs, System Controller (102) can repeat this exemplary process, e.g., by commanding Waveform Generator (107) to issue to each element in Waveform Synthesizers (108) another digital message that defines the amplitude and phase of each of the frequency chips that comprise the wideband composite waveform and by commanding T/R Switch (110) back to transmit position, etc.

[0027] The system (100) can be implemented to produce spread-spectrum, wide instantaneous bandwidth (e.g., up to 100% or more of fractional bandwidth), coherent, pseudo-random noise (PRN), frequency- and/or phase-coded waveforms for ultrasound imaging. There are limitless embodiments of such waveforms. One example is featured in FIG. 2, which shows an exemplary plot of a generated composite waveform (200) that is comprised of a plurality of individual waveforms (e.g., frequency chips). In some implementations, the individual waveforms of the composite waveform (200) can be PRN waveforms including a sequence of pulses for each frequency chip that repeats itself after a sequence or code period (T), e.g., such that the sequence has a very low correlation with any other sequence in the set of frequency chips, or with the same sequence at a significantly different time frame, or with narrow band interference or thermal noise. For example, the system (100) can generate exactly the same sequences of the exemplary PRN waveforms at both the transmitter and the receiver ends, so a received signal sequence (based on the transmitted signal sequence) can exhibit a high correlation for signal processing to produce an acoustic image of the target.

[0028] As shown in FIG. 2, an exemplary individual waveform or chip (201) of the composite waveform (200) corresponds to the frequency chip f_{N-2} that is transmitted during a transmit period T beginning at time frame t_0, e.g., as described in the process (156) in FIG. 1B. As shown in FIG. 2, following the transmit period T, a receive time interval T_R is exhibited, in which returned acoustic waveform echoes are received as described in the process (158) in FIG. 1B. The transmit period T and the receive time interval T_R form a frame period T_f, which can be repeated in subsequent time frames (t_1, t_2, t_3, ...).

[0029] According to the invention, the exemplary composite waveform (200) is represented by an equation for waveform, W, which is represented in the time domain as a complex number, given by Equation (1):

$$W(t) = \sum_k \sum_n A_{nk} e^{j(2\pi n f_0 t + \phi_{nk} + C_n)} U(t - kT) \qquad (1)$$

[0030] W is comprised of M individual orthogonal waveforms (e.g., orthogonal frequency chips), where

$j = -\sqrt{-1}$

. In Equation (1), T represents the chip duration or period of the coded sequence, and f_0 represents the fundamental chip frequency, such that f_0 = 1/NT, and in which Nf_0 is the maximum frequency and $(M-N+1)f_0$ is the minimum frequency, n represents a sequence of positive integers from N-M+1 to N. The waveform repetition frequency is $1/T_f$, with T_f being the duration of a frame or epoch, and U(x) = 1 for 0 <_ x <_ T. Φ_{nk} represents the frequency chip phase term of the n^{th} chip in the k^{th} time epoch, and A_{nk} is the amplitude of the n^{th} chip in the k^{th} time epoch. The frequency chip phase term Φ_{nk} can be a pseudo-random phase term, in which a pseudo-randomly scrambled starting phase Φ_{nk} is a random number in the set $\{I_{nk}2\pi/N\}$, where I_{nk} is a sequence of random, positive integers selected without replacement from the series I = 0, 1, 2, 3, ..., N, with N being a large number. According to the invention, the amplitude A_{nk} or the phase φ_{nk} for a particular frequency chip is determined as a single value for that frequency chip during a particular time epoch and assigned a different single value in subsequent time epochs. C_n, which is an additive phase term, is a number between 0 and 2π. For example, the frequency chip phase pseudo-random values Φ_{nk} can be pre-stored in an exemplary database within a memory unit of System Controller (102) and/or Waveform Generator (107).

[0031] The composite waveform, W, is formed by synthesizing substantially orthogonal coded waveforms (e.g., frequency chips), in which each coded waveform corresponds to a distinct frequency band, and the coded waveforms includes at least one of frequency-coded waveforms or phase-coded waveforms, e.g., the coded waveforms synthesized in the Waveform Synthesizers (108). The coded waveforms are synthesized as frequency-coded waveforms by selecting two or more frequencies that define the carrier frequencies of the frequency chips (e.g., including selecting the minimum and maximum frequency) and determining the A_{nk} amplitude values of the frequency chips. The synthesis of the frequency-coded can also include determining a time-bandwidth product (Mf_0T) parameter of each waveform of the coded waveforms. In some implementations, the amplitude for a particular frequency chip can be determined as a single value for that frequency chip during a particular time epoch and repeated in subsequent time epochs for the particular frequency chip. In other implementations, the amplitude for a particular frequency chip can be determined as a single value for that frequency chip during a particular time epoch and assigned a different single value in subsequent time epochs for the particular frequency chip. And in other implementations, the amplitude for a particular frequency chip can be determined to include multiple amplitude values for that frequency chip during a particular time epoch, in which the multiple values of the A_{nk} can be repeated or varied in subsequent time epochs for the particular frequency chip. The selection of the range of frequencies from the maximum frequency (Nf_0) to the minimum frequency ($(M-N+1)f_0$) plus the set of individual waveform amplitude terms (A_{nk}) can utilize one of many known code sequences (e.g. including pushing sequences, Barker Codes, etc.) or, for example, utilize a numerical search on pseudo-random codes or any other codes for minimum ambiguity sidelobes.

[0032] The coded waveforms are additionally synthesized as phase-coded waveforms by determining individual waveform phase terms (Φ_{nk}) of each waveform of the coded waveforms. For example, to provide variation of the composite waveform, W, the phase Φ_{nk} can include one or more phase values for a frequency chip within the transmit period T. In some implementations, the phase Φ_{nk} for a particular frequency chip can be determined as a single value for that frequency chip during a particular time epoch and repeated in subsequent time epochs for the particular frequency chip. In other implementations, the phase Φ_{nk} for a particular frequency chip can be determined as a single value for that frequency chip during a particular time epoch and assigned a different single value in subsequent time epochs for the particular frequency chip. And in other implementations, the phase Φ_{nk} for a particular frequency chip can be determined to include multiple values for that frequency chip during a particular time epoch, in which the multiple values of the Φ_{nk} can be repeated or varied in subsequent time epochs for the particular frequency chip. For example, the waveform (201) in the first time epoch (t_0) can include a first phase Φ_A, for example, as its phase shift for the beginning portion of the transmit period T and a second phase Φ_B, for example, as its phase shift for the latter portion of the transmit period T. The waveform (201) in the next time epoch (t_1) can repeat the exemplary phases Φ_A and Φ_B as its beginning and latter phase shifts or include another phase shift sequence (e.g., such as Φ_A, Φ_B, Φ_C, or such as Φ_B and Φ_A, or other configurations). The synthesis of the frequency-coded can also include determining a time-bandwidth product (Mf_0T) parameter of each waveform of the coded waveforms.

[0033] An exemplary transmitted waveform, W, can be comprised of the set of M individual waveforms that are orthogonal and completely span the frequency range f_{N-M+1} to f_N, as seen in FIG. 2. The parameter N can be chosen to be a large number to give W a wide instantaneous bandwidth. In the special case when the lowest frequency $f_{N-M+1} = 1/T$, then W can describe any wideband waveform that may be contained within this range of frequencies. For any waveform among the M individual waveforms, one or more phases (e.g., Φ_{nk}) can be encoded in a single waveform during the interval T. Additionally, any waveform among the M individual waveforms can include multiple amplitudes encoded in a single waveform. This can be implemented by amplitude weighting and phase weighting.

[0034] The family of individual waveforms described by Equation (1) can form a coherent, pseudo-random noise, frequency- and/or phase-coded, spread spectrum composite waveform. Based on the selection of parameters, the individual waveforms can be made to be statistically orthogonal to any degree desired. For example, the sidelobe levels of the ambiguity function, described later in Equation (2), for a given waveform represents the degree of orthogonality of that waveform. By determining particular parameters of the waveforms, medical ultrasound image resolution can be significantly improved. For example, parameters that affect the resolution of medical ultrasound images include the time-bandwidth product (Mf_0T) parameter, which determines the inherent combined axial range (e.g., Doppler resolution) and the speckle reduction ability of the waveform, and the individual waveform phase terms (Φ_{nk}), which

determine the statistical degree of orthogonality, e.g., which in turn determines the degree that the waveform can function in inhomogeneous media of biological tissues. For example, the lower the sidelobes, the greater the orthogonality and greater the resolution (less noise). The selection of the set of individual waveform phase terms (Φ_{nk}) can utilize one of many known code sequences (e.g. including Barker, Frank, Golay, etc.) or, for example, utilize a numerical search on pseudo-random codes or any other codes for minimum ambiguity sidelobes.

[0035] In some implementations, the composite waveform (200), e.g., described by Equation (1), can be a single wideband, coherent, frequency- and/or phase-coded waveform. For example, based on the selection of parameters, the single waveform can be made to be statistically orthogonal to any other signal waveform or noise signal present in the target medium.

[0036] The parameter A_{nk}, which is the amplitude of the n^{th} chip in the k^{th} time epoch, and C_n, which is an additive phase term, in combination can provide pre-emphasis of the analog signal that excites each individual element of Transducer Array (111) to produce a transmitted acoustic waveform that has the desired amplitude and phase characteristics over the frequency range of W. Pre-emphasis of the transmitted waveform can compensate for both the non-constant amplitude and phase response of transducer elements as a function of frequency, and the non-uniform propagation characteristics of intervening tissue layers. For example, the pre-emphasis terms can provide an acoustic waveform that has equal amplitude chips with constant (e.g., flat) amplitude and a known phase versus frequency characteristic. Such constant amplitude versus frequency acoustic waveforms can be referred to as 'white' waveforms. Alternatively, if pre-emphasis is not provided, then the transmitted acoustic waveform can replicate the frequency response of the transducer, and such waveforms are referred to as 'colored' waveforms. De-emphasis of the received waveform can permit determination of the reflection characteristic of the target medium's volume, e.g., biological tissue volume.

[0037] By inspection, single frequency modes (e.g., Conventional A-, B- and C-Mode), due to their monochromatic nature, do not need pre-emphasis. Such single frequency waveforms may require amplitude control, for example, to ensure biologically safe sound intensity limits.

[0038] If the phase of each chip is random, the transmitted waveform, W, can have random noise-like characteristics. If the phases ($\Phi_{nk} + C_n$) of each chip are uniquely determined, repeatable and synchronized to the Master Clock (as shown in FIG. 1A), the transmitted waveform, W, can be classified as pseudo-random noise. Such pseudo-random noise waveforms are coherent permitting implementation of coherent receivers.

[0039] Image processing advantages of wide instantaneous bandwidth, pseudo-random noise waveforms can include reduction, with proper waveform selection, and potential elimination of speckle, e.g., speckles / speckle patterns, which are random intensity patterns produced by the mutual interference waveforms, which are commonly associated with conventional medical

ultrasound images. This exemplary reduction in speckle can be an analogous comparison of a scene illuminated by wide band, Gaussian noise-like white light, which has no observable speckle to narrow band laser illumination with exhibits strong speckle of the same scene.

[0040] Signal processing advantages of coherent, pseudo-random noise, frequency- and phase-coded waveforms can include waveforms having very low time and Doppler sidelobes. For example, an ambiguity function, A(τ,υ), can be a two-dimensional representation that shows the distortion of a received waveform processed by a matched filter in the receiver due to the effect of Doppler shift (o) or propagation delay (τ). Specifically, the exemplary ambiguity function A(τ,υ) is defined by Equation (2) and is determined solely by the waveform properties and the receiver characteristics and not by the scenario. The ambiguity function of A(τ,υ) is defined by

$$A(\tau,\upsilon)=\int_{-\infty}^{+\infty} X_a(t)X_b^*(t-\tau)e^{j2\pi\upsilon t} \qquad (2)$$

where

$$X_k(t)=\frac{1}{\sqrt{T}}e^{j[2\pi f_k(t-t_k)+\Phi_k]}$$

, for $0 \le t \le T$, $X_k(t) = 0$ otherwise.

[0041] For waveforms of the type described by Equation (1), the following equation can be obtained:

$$A(\tau,\upsilon,t,f_n,\Phi_n,f_m,\Phi_m,T)= \left(1-\frac{|\tau-(\Delta t)|}{T}\right)\frac{Sin[2\pi(\Delta f)(T-|\Delta t|)]}{[2\pi(\Delta f)(T-|\Delta t|)]}e^{j2\pi[\Delta f(T+\Delta t)-f_n\Delta t+\upsilon t+\Delta\Phi]} \qquad (3)$$

where $\Delta t = \tau - t$, $\Delta f = \upsilon - (f_n - f_m)$, and $\Delta\Phi = \Phi_n - \Phi_m$, which can result in the complete ambiguity equation shown in Equation (4):

$$x(\tau,\upsilon)=\frac{1}{M}\sum_n\sum_m A(\tau,\upsilon,t,f_n,\Phi_n,f_m,\Phi_m,T) \qquad (4)$$

where both n and m are a sequence of positive integers from N-M+1 to N.

[0042] FIG. 3 shows exemplary ambiguity function characteristics of a pseudo-random noise, frequency-coded waveform (301), represented by an equation for waveform, W. The exemplary coded waveform (301) includes a code length of 128. As shown in FIG. 3, the sidelobes (302) of this ambiguity function are due to chip-to-chip phase interactions and have a plateau level below the peak that is a function of N^2.

[0043] By inspection, many waveforms (W) are possible depending on the specific random number codes (I_{nk}) selected. However, the sidelobe performance cannot be guaranteed for every waveform defined, and therefore only those codes which give sufficiently low sidelobes as determined by a numerical search of a set of possible codes should be used.

[0044] For example, in medical ultrasound applications, living tissue as a propagation medium is inhomogeneous. Propagation medium inhomogeneity can introduce differential time delays,

and living tissue can introduce unwanted motion induced Doppler. Ultrasound transducer arrays also can have undesirable side lobes and grating lobes (e.g., due to physical size limitations) in the off axis portions of ultrasound beam that add unwanted time delay and Doppler returns to the returns of the main lobe. Waveforms that exhibit low ambiguity function sidelobes can significantly improve focusing and target contrast due through the reduction interference from differential time delays, motion induced Doppler, transducer side lobe effects.

[0045] Coherent pseudo-random noise, frequency- and/or phase-coded waveforms can enable higher order cross range focusing techniques to be employed that can improve the lateral resolution of size limited ultrasound transducer arrays, e.g., medical ultrasound transducer arrays.

[0046] For example, each biological tissue type and each diseased tissue types may exhibit their own unique ultrasound echo return as a function of frequency and spatial morphology. Using conventional Elastograph-Mode (E-Mode) modalities, it can be difficult to take advantage of such properties to classify tissues, e.g., due to measurement errors such as the inability to accurately characterize the ultrasound wave propagation through overlaying inhomogeneous media. Exemplary waveforms produced by the exemplary system (100), e.g., wide instantaneous bandwidth, coherent pseudo-random noise, frequency- and/or phase-coded waveforms, can enable tissue differentiation by simultaneously determining the propagation delay for each acoustic ray through intervening tissue layers and accurately determining the spatial echo features of the target volume under investigation. Classifiers, one example being Bayesian inference Classifiers among others, can be applied to the feature data obtained from the measured characteristics of the received echo to automatically classify tissue types observed in the target volume providing a Computer Aided Diagnostic-Mode (CAD-Mode).

[0047] Unlike conventional E-Modes, which inherently have significantly reduced image quality and rely on individual operator technique, the exemplary waveforms described by Equation (1) can inherently provide improved image quality while simultaneously colorizing the resultant image by tissue type in the ATS and/or CAD-Modes. With this advantage, user technique can be mitigated and the margins of a lesion are discernible thus permitting improved diagnoses.

[0048] In addition, Waveform Synthesizers (108) positioned on transmit and Digital Signal Processor (104) positioned on receive (as shown in FIG. 1A), can also perform beam control (e.g., beam steering, dynamic beam focusing, and beam forming) functions. FIGS. 4A-4C show the basics of these digital electronic functions by introducing a differential time delay, or equivalently a phase shift, and amplitude weighting between each of the elements of the phased array. As can be seen in FIG. 4A, the differential phase shift can compensate for the differential change in distance (d) each acoustic ray (r_1, r_2, ... r_i, ...) travels from i^{th} element to the point of focus (p). An angle (θ) is formed as the point of focus (p) is not along the z-axis direction of direct aim/alignment of the Transducer Array (111) toward a target in the target medium. Additionally, a differential amplitude weight can be applied to each element to control the beam shape and suppress side and grating lobes. Also, for one or more chips in an exemplary waveform, Waveform Generator (107) can pre-encode a phase delay to delay the

phase of the one or more chips transmitted at each transducer element in Transducer Array (111). An exemplary result of this feature can be seen in FIGS. 4B and 4C. The exemplary phase delay values for the one or more chips can be communicated to Digital Signal Processor (104) and/or System Controller (102) to incorporate the phase delay values in the signal processing of the received composite waveform.

[0049] For narrow instantaneous bandwidth ultrasound devices, this function can be accomplished by introducing phase shift and amplitude attenuation on the composite analog signal driving each element. However, for the exemplary spread-spectrum, wide instantaneous bandwidth, frequency- and phase-coded waveforms generated by system (100), each individual chip of the waveform (W_i) is individually amplitude weighted (B_{ni}) and phase weighted (D_{ni}) as a function of frequency (n) for each array element (i) individually for all I elements, as indicated by Equation (5).

$$W_i(t) = \sum_k \sum_n A_{nk} B_{ni} e^{j(2\pi n f_0 t + \phi_{nk} + C_n + D_{ni})} U(t - kT) \qquad (5)$$

[0050] On transmit, the amplitude and phase weighting required of each chip can be computed by the System Controller (102) and can be sent as an instruction to the Waveform Generator (107). Waveform Generator (107) can then send the digital words (real and imaginary components) to the Waveform Synthesizers and Beam Controller (108) that produces the analog drive signal that is amplified by Amplifier (109) and sent to each element of the array of Transducer Array (111).

[0051] On receive, the reverse process takes place. The A/D Converter module (113) can send the digital words that represent the amplitude and phase information of each chip for each array element to the Digital Signal Processor (104), which in turn can digitally form the receive beam for each chip.

[0052] A multitude of ways can be used to process the received waveforms, e.g., wide-bandwidth, spread-spectrum, frequency and/or phase-coded waveforms. FIG. 5 shows an exemplary correlation processing technique. For example, an input to the exemplary correlation processing technique can include a digitized received signal, $Y_i(\tau,u)$, which can be multiplied by the complex conjugate replica of the transmitted digital waveform, $W_i^*(\tau)$. The complex conjugate replica $W_i^*(\tau)$ can be time shifted by $1 \cdot \tau_0$ prior to multiplication. This multiplication operation can be repeated multiple times for multiple time shifts, e.g., J times, as seen in FIG. 5. The multiple multiplication operations for the multiple time shifts can be repeated in parallel, but for each operation the replica is shifted in time by an increment, τ_0, from the previous one, as shown in the figure. For each time step, the resultant products can be filtered with a window function, such as a Hann, Hamming, Tukey, Kaiser Bessel, Dolph-Chebyshev, Blackman-Harris window, etc., a fast Fourier Transform (FFT) integrator, and passed through a digital filter. For example, a digital filter of a type that is dependent of the specific waveform, W, can be employed to filter and decimate the inputted signal. The

exemplary process can result in the range-Doppler return for each individual i^{th} element of the transducer array. The output data stream from the exemplary detection algorithm can then be processed using conventional techniques to form an image for display. The processed range and Doppler waveforms can be further processed by partitioning the I number of transducer elements into two or more subarrays. The processed range-Doppler return for the i^{th} element can be weighted in amplitude and/or phase depending on which subarray that i^{th} element belongs. These weighted returns can then be summed and differenced. These sum and differences can then be processed to improve the cross range image resolution of the system.

[0053] Several applications and uses of the disclosed technology can be implemented to exploit the described features of the aforementioned systems, methods, and devices. Some examples are described for clinical use of the disclosed technology.

[0054] In one exemplary application, the resultant image quality, the ATS and CAD modes of an exemplary spread spectrum ultrasound device can enable the primary care physician to incorporate this modality into a routine examination screening protocol to locate early stage malignancies (e.g., Stage 0 or 1), as well as later stage cancers. As the result of this application, the device can potentially, for example, enhance the survival rate of hard to diagnose asymptomatic patients suffering from such malignancies such as stomach, pancreatic, bladder cancers, etc.

[0055] In another exemplary application, the resultant image quality, ATS and CAD modes of an exemplary spread spectrum ultrasound device can permit board certified radiologists to diagnose neoplasms as benign or malignant prior to any surgical biopsy or resection intervention. As a result of this application, the ability of radiologists to locate and diagnose early stage malignancies (e.g., Stage 0 or 1) can potentially improve patient survival rate. Additionally, unnecessary biopsies can potentially be avoided, along with their attendant risk of hard to treat or even lethal complications such as, for example, methicillin resistant staphylococcus aureus (MRSA staph) infections.

[0056] In another exemplary application, the resultant 3D image quality of an exemplary spread spectrum ultrasound device and its 4D imaging capability can be used in fine needle biopsy and other medical procedures. For example, the exemplary spread spectrum ultrasound device can be integrated into an exemplary fine needle biopsy instrument (e.g., with the device's transducer probe), which can permit the fine needle biopsy of very small, early stage (e.g., Stage 0 or 1) neoplasms to confirm noninvasive diagnoses. As a result of this application, the ability of surgeons to avoid open biopsies and the potential for hard to treat and lethal complications that may result is clearly beneficial to the patient.

[0057] In another exemplary application, the integration of this device's spread spectrum transducer probe with minimally invasive surgical high definition video instrumentation can permit the fusing of the optical and ultrasound images. Given the improved 3D image quality of this spread spectrum ultrasound device, its 4D imaging capability, the ATS and CAD modes,

such fused video and ultrasound images can give surgeons the added ability to locate and surgically excise diseased tissue without excising excessive healthy tissue.

[0058] In another exemplary application, given the improved 3D image quality of this spread spectrum ultrasound device, its 4D imaging capability, and its ATS modes, an exemplary spread spectrum ultrasound device can reduce the amount of time for the brachytherapy treatment of malignant neoplasms by precisely guiding the insertion of catheters and sealed radioactive sources into the proper location. The application of this spread spectrum ultrasound device to brachytherapy can be especially useful for the treatment of small, hard to locate neoplasms and their margins.

[0059] In another exemplary application, given the improved 3D image quality of this spread spectrum ultrasound device, its 4D imaging capability, and its ATS modes, an exemplary spread spectrum ultrasound device can enable the effective insertion of high dose, localized pharmaceutical treatments of diseases by precisely guiding the insertion of catheters and pharmaceuticals into the proper location. The application of this spread spectrum ultrasound device to brachytherapy can be especially useful for the treatment of small, hard to locate neoplasms.

[0060] Implementations of the subject matter and the functional operations described in this specification, such as various modules, can be implemented in digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. Implementations of the subject matter described in this specification can be implemented as one or more computer program products, e.g., one or more modules of computer program instructions encoded on a tangible and non-transitory computer readable medium for execution by, or to control the operation of, data processing apparatus. The computer readable medium can be a machine-readable storage device, a machine-readable storage substrate, a memory device, a composition of matter affecting a machine-readable propagated signal, or a combination of one or more of them. The term "data processing apparatus" encompasses all apparatus, devices, and machines for processing data, including by way of example a programmable processor, a computer, or multiple processors or computers. The apparatus can include, in addition to hardware, code that creates an execution environment for the computer program in question, e.g., code that constitutes processor firmware, a protocol stack, a database management system, an operating system, or a combination of one or more of them.

[0061] A computer program (also known as a program, software, software application, script, or code) can be written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a stand alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program does not necessarily correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program

in question, or in multiple coordinated files (e.g., files that store one or more modules, sub programs, or portions of code). A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

[0062] The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed by, and apparatus can also be implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit).

[0063] Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, such as, for example, digital signal processors (DSP), and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read only memory or a random access memory or both. The essential elements of a computer are a processor for performing instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto optical disks, or optical disks. However, a computer need not have such devices. Computer readable media suitable for storing computer program instructions and data include all forms of non volatile memory, media and memory devices, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0064] While this patent document contains many specifics, these should not be construed as limitations on the scope of any invention or of what may be claimed, but rather as descriptions of features that may be specific to particular embodiments of particular inventions. Certain features that are described in this patent document in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[0065] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments.

[0066] Only a few implementations and examples are described and other implementations, enhancements and variations can be made based on what is described and illustrated in this patent document.

REFERENCES CITED IN THE DESCRIPTION

Cited references

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- **TOSHIO ITO et al.**Evaluation of Acoustic Imaging System Using Correlation Division in Synthetic Transmit Aperture with Multicarrier SignalsIEICE Transactions on Fundamentals of Electronics, Communications and Computer Science, 2011, vol. E94-A, 101907-1919 [0003]

Patentkrav

1. Fremgangsmåde til at skabe et billede fra en akustisk bølgeform i en akustisk billeddannelsesindretning, omfattende:

indstilling (151) af en sende/modtage-omskifter (110) i den akustiske billeddannelsesindretning til en sendetilstand for at transmittere en akustisk bølgeform mod et mål;

ved transmission af den akustiske bølgeform, syntetisering (153, 154), i en eller flere bølgeformsynthesizere, af en flerhed af i det væsentlige ortogonalt kodede bølgeformer, der danner en sammensat bølgeform (200) som den transmitterede akustiske bølgeform mod målet, hvor den sammensatte bølgeform (200) er repræsenteret i tidsdomænet som et komplekst tal, givet ved

$$W(t) = \sum_{k}\sum_{n} A_{nk} e^{j(2\pi n f_0 t + \phi_{nk} + C_n)} U(t - kT)$$

hvor W består af M individuelle ortogonale bølgeformer, T repræsenterer sendeperioden inden for en tidsepoke, f_0 repræsenterer den grundlæggende chipfrekvens, således at $f_0=1/NT$, Nf_0 er den maksimale frekvens, og $(M-N+1)f_0$ er minimumsfrekvensen, n repræsenterer en sekvens af positive heltal fra N-M+1 til N, bølgeformens gentagelsesfrekvens er $1/T_f$, hvor T_f er varigheden af en tidsepoke, $U(x)=1$ for $o \leq x \leq T$, Φ_{nk} repræsenterer frekvenschipfaseleddet for n^{te} chip i den k^{te} tidsepoke, og A_{nk} er amplituden af den n^{te} chip i den k^{te} tidsepoke, og C_n er et additivt faseled, der er et tal mellem o og 2π, hvor amplituden A_{nk} eller fasen φ_{nk} for en bestemt frekvenschip bestemmes som en enkelt værdi for den frekvenschip under en bestemt tidsepoke og tildeles en anden enkelt værdi i efterfølgende tidsepoker;

indstilling (157) af sende/modtage-omskifteren (110) i den akustiske billeddannelsesindretning til en modtagetilstand for at modtage (158) en returneret akustisk bølgeform, der returnerer fra i det mindste en del af målet;

konvertering (160) af den modtagne returnerede akustiske bølgeform fra analogt format til digitalt format som en modtaget sammensat bølgeform omfattende information om målet; og

behandling (161) af den modtagne sammensatte bølgeform for at frembringe et billede af i det mindste en del af målet.

2. Fremgangsmåde ifølge krav 1, hvor hver kodet bølgeform af flerheden af kodede bølgeformer inkluderer en eller flere amplituder og en eller flere faser, og hvor (i) den ene eller flere amplituder er individuelt amplitudevægtet for mindst en bølgeform af flerheden af kodede bølgeformer, eller (ii) den ene eller flere faser fasevægtes individuelt for mindst én bølgeform af flerheden af kodede bølgeformer, hvorved der tilvejebringes mindst én af styring, fokusering eller dannelse af den transmitterede akustiske bølgeform.

3. Fremgangsmåde ifølge krav 1, hvor faseparameteren bestemmes ud fra et sæt af deterministiske tal.

4. Akustisk bølgeformsbilleddannelsessystem (100), omfattende:

en bølgeformsgenereringsenhed (108) omfattende en eller flere bølgeformssynthesizere, der er koblet til en bølgeformgenerator (107), hvor bølgeformsgenereringsenheden syntetiserer en sammensat bølgeform (200), der omfatter en flerhed af i det væsentlige ortogonalt kodede bølgeformer svarende til frekvensbånd, der genereres af den ene eller flere bølgeformsynthesizere ifølge bølgeformsinformationer, der tilvejebringes af bølgeformsgeneratoren, hvor den sammensatte bølgeform (200) er repræsenteret i tidsdomænet som et komplekst tal, givet ved

$$W(t) = \sum_{k} \sum_{n} A_{nk} e^{j(2\pi n f_0 t + \phi_{nk} + C_n)} U(t - kT)$$

hvor W består af M individuelle ortogonale bølgeformer, T repræsenterer sendeperioden inden for en tidsepoke, f_0 repræsenterer den grundlæggende chipfrekvens, således at $f_0=1/NT$, Nf_0 er den maksimale frekvens, og $(M-N+1)f_0$ er minimumsfrekvensen, n repræsenterer en sekvens af positive heltal fra N-M+1 til N, bølgeformens gentagelsesfrekvens er $1/T_f$, hvor T_f er varigheden af en tidsepoke, $U(x)=1$ for $0 \leq x \leq T$, φ_{nk} repræsenterer frekvenschipfaseleddet for den n^{te} chip i den k^{te} tidsepoke, og A_{nk} er amplituden af den n^{te} chip i den k^{te} tidsepoke, og C_n er et additiv faseled er et

tal mellem 0 og 2π, hvor amplituden A_{nk} eller fasen φ_{nk} for en bestemt frekvenschip bestemmes som en enkelt værdi for den frekvenschip i løbet af en bestemt tidsepoke og tildeles en anden enkelt værdi i efterfølgende tidsepoker;

en sende/modtage-omskiftningsenhed (110), der skifter mellem en sende- og modtagetilstand;

et array af transducerelementer (111) i kommunikation med sende/modtage-omskifterenheden, der transmitterer en akustisk bølgeform baseret på den sammensatte bølgeform (200) mod et mål og modtager en returneret akustisk bølgeform returneret fra i det mindste en del af målet;

et array af analog-til-digital-(A/D)-konvertere (113) til at konvertere den modtagne returnerede akustiske bølgeform modtaget af arrayet af transducerelementer fra analogt format til digitalt format som en modtaget sammensat bølgeform med informationer omfattende informationer om målet;

en styreenhed (102) i kommunikation med bølgeformgenereringsenheden og arrayet af A/D-konvertere, hvor styreenheden omfatter en behandlingsenhed, der behandler den modtagne sammensatte bølgeform for at frembringe et billede af i det mindste en del af målet; og

en brugergrænsefladeenhed (105, 106) i kommunikation med styreenheden.

5. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, hvor brugergrænsefladeenheden (106) omfatter et display (105), der viser billedet.

6. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, hvor bølgeformgenereringsenheden (108) yderligere omfatter en eller flere forstærkere (109), der er konfigureret mellem sende/modtage-omskifterenheden (110) og den ene eller flere bølgeformsynthesizere, der modificerer den sammensatte bølgeform (200).

7. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, yderligere omfattende et array af en eller flere forforstærkere (112), der er konfigureret mellem sende/modtage-omskifterenheden (110) og arrayet af mindst én A/D-konverter (113), der modificerer den modtagne returnerede akustiske bølgeform.

8. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, hvor behandlingsenheden omfatter en digital signalprocessor (DSP).

9. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, hvor styreenheden (102) yderligere omfatter et masterur (101), der synkroniserer tid i mindst et af elementerne i det akustiske bølgeformsbilleddannelsessystem.

10. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, hvor brugergrænsefladeenheden (106) yderligere omfatter en eller flere brugergrænsefladeindretninger i kommunikation med styreenheden (102), som modtager input fra en bruger.

11. Akustisk bølgeformsbilleddannelsessystem ifølge krav 10, hvor inputtet indbefatter en driftstilstand.

12. Akustisk bølgeformsbilleddannelsessystem ifølge krav 11, hvor driftstilstanden indbefatter mindst én af ATS-tilstand (kunstig vævfarvingstilstand) til billeddannelse af biologisk væv, der muliggør billedfarvekodning baseret på mindst én egenskab af en eller flere målte egenskaber, som opnås fra den returnerede akustiske bølgeform.

13. Akustisk bølgeformsbilleddannelsessystem ifølge krav 11, hvor driftstilstanden indbefatter mindst én af CAD-tilstand (computerstøttet diagnosticeringstilstand) til billeddannelse af biologisk væv, der anvender en eller flere algoritmiske klassifikatorer til at klassificere biologiske vævstyper ved anvendelse af mindst én funktion af en eller flere målte egenskaber, der opnås fra den returnerede akustiske bølgeform.

14. Akustisk bølgeformsbilleddannelsessystem ifølge krav 13, hvor brugergrænsefladeenheden (106) omfatter et display (105), der viser et farvekodet billede af det biologiske væv baseret på de klassificerede biologiske vævstyper.

15. Akustisk bølgeformsbilleddannelsessystem ifølge krav 4, hvor hver i det væsentlige ortogonalt kodet bølgeform af flerheden af i det væsentlige ortogonalt kodede bølgeformer inkluderer en eller flere amplituder og en eller flere faser, og

hvor (i) den ene eller flere amplituder er individuelt amplitudevægtet for mindst én bølgeform af flerheden af i det væsentlige ortogonalt kodede bølgeformer, eller (ii) den ene eller flere faser er individuelt fasevægtet for mindst én bølgeform af flerheden af i det væsentlige ortogonalt kodede bølgeformer, hvorved der tilvejebringes mindst én af styring, fokus eller formning af den akustiske bølgeform, der skal transmitteres.

DRAWINGS

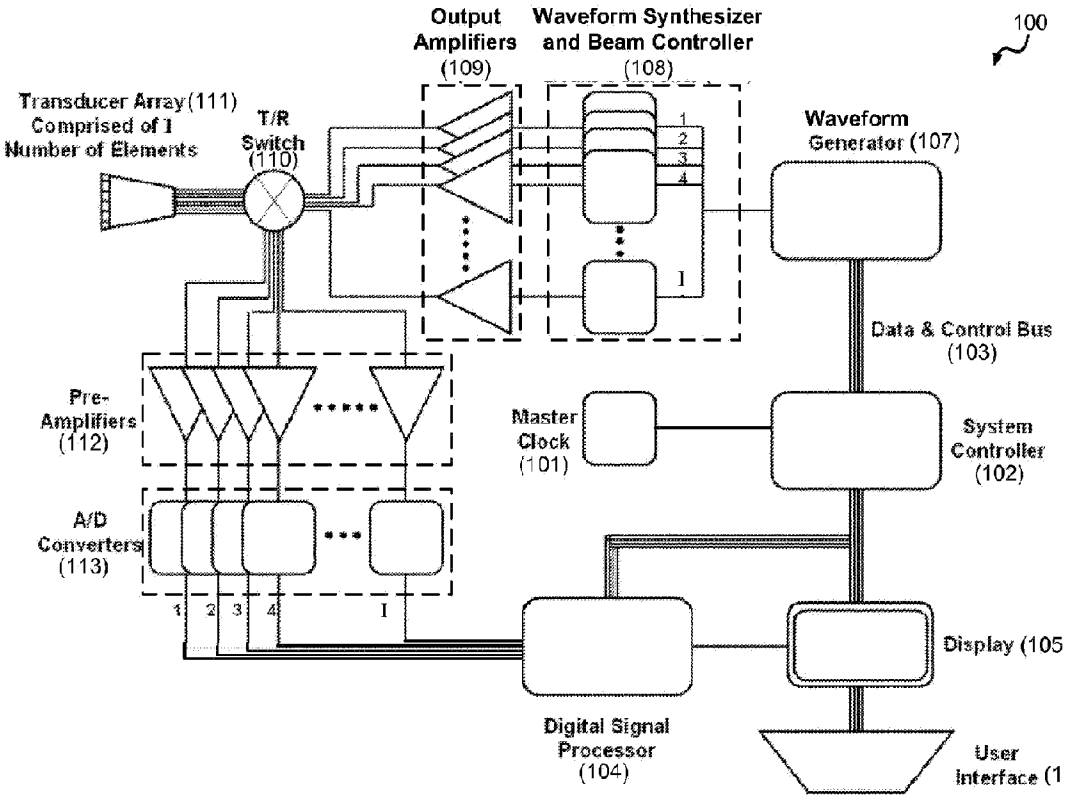

FIG. 1A

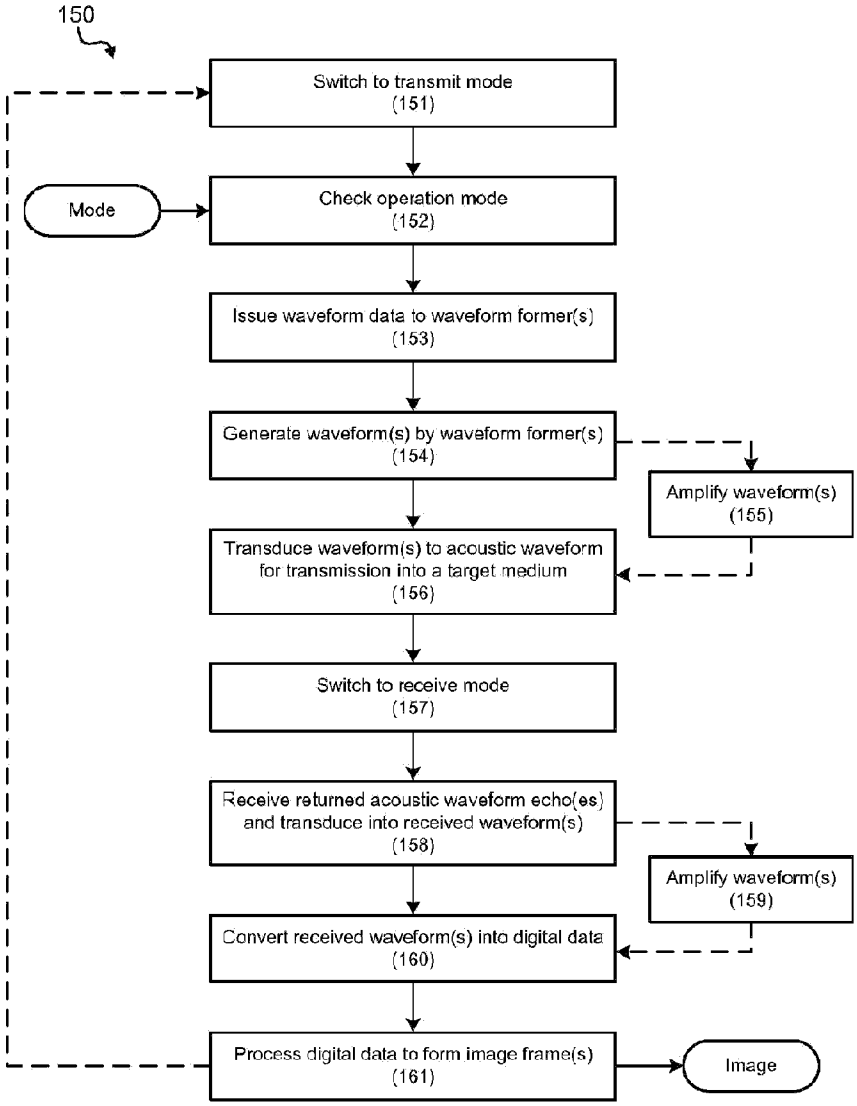
150
Switch to transmit mode
(151)
Mode
Check operation mode
(152)
Issue waveform data to waveform former(s)
(153)
Generate waveform(s) by waveform former(s)
(154)
Amplify waveform(s)
(155)
Transduce waveform(s) to acoustic waveform
for transmission into a target medium
(156)
Switch to receive mode
(157)
Receive returned acoustic waveform echo(es)
and transduce into received waveform(s)
(158)
Amplify waveform(s)
(159)
Convert received waveform(s) into digital data
(160)
Process digital data to form image frame(s)
(161)
Image

FIG. 1B

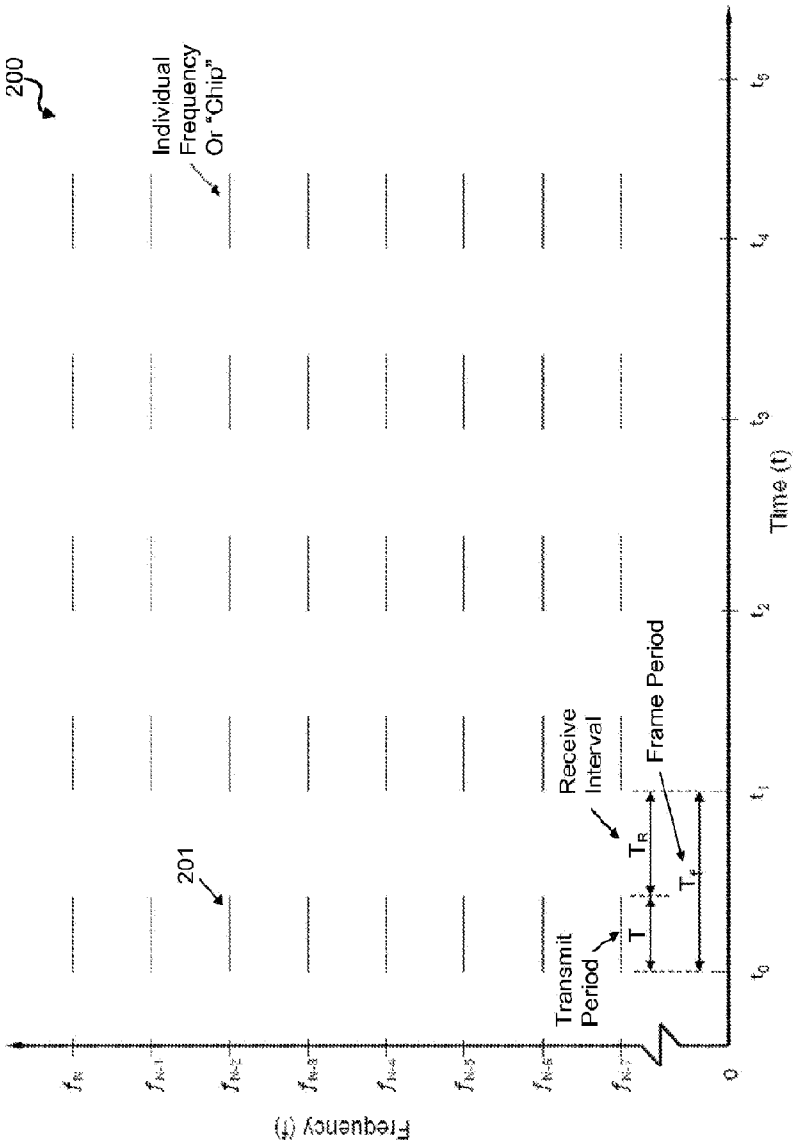
200
Individual Frequency Or "Chip"
201
Receive Interval
Frame Period
Transmit Period
T
T_R
T_f
Frequency (f)
Time (t)
0
t_0
t_1
t_2
t_3
t_4
t_5

FIG. 2

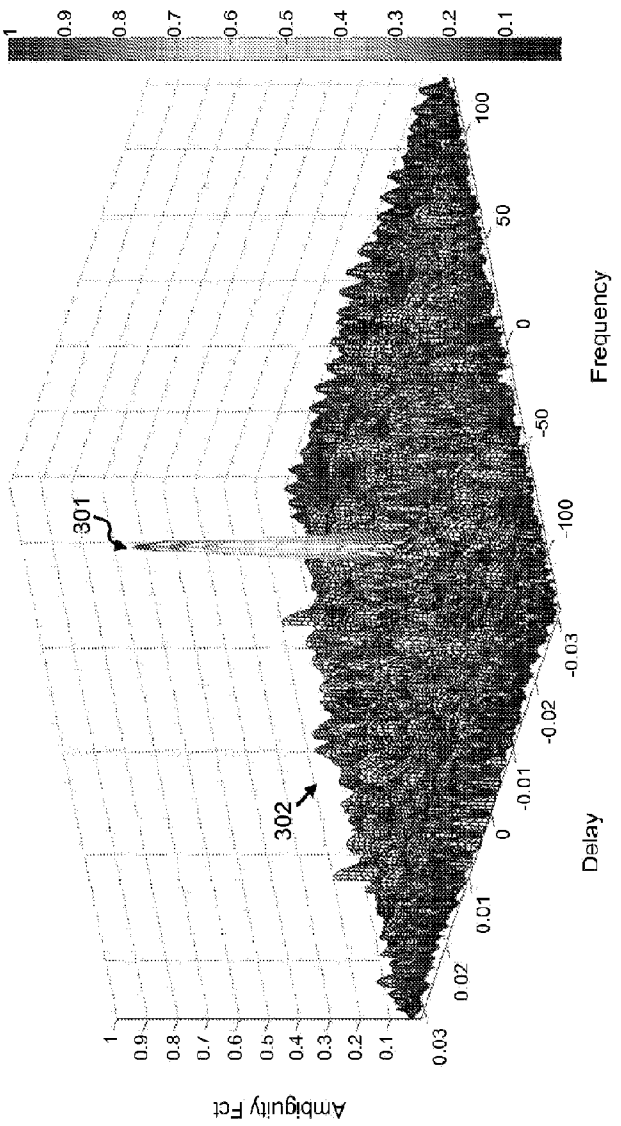
Ambiguity Fct
Delay
Frequency
301
302
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
100
50
0
-50
-100

FIG. 3

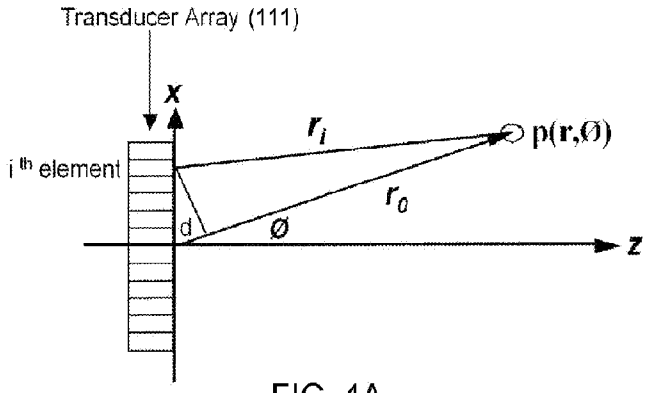

FIG. 4A

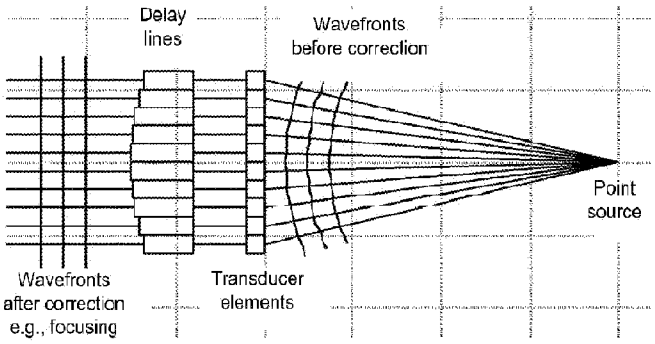

FIG. 4B

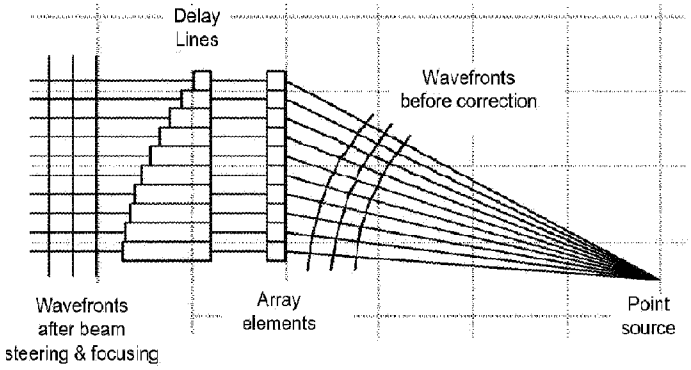

FIG. 4C

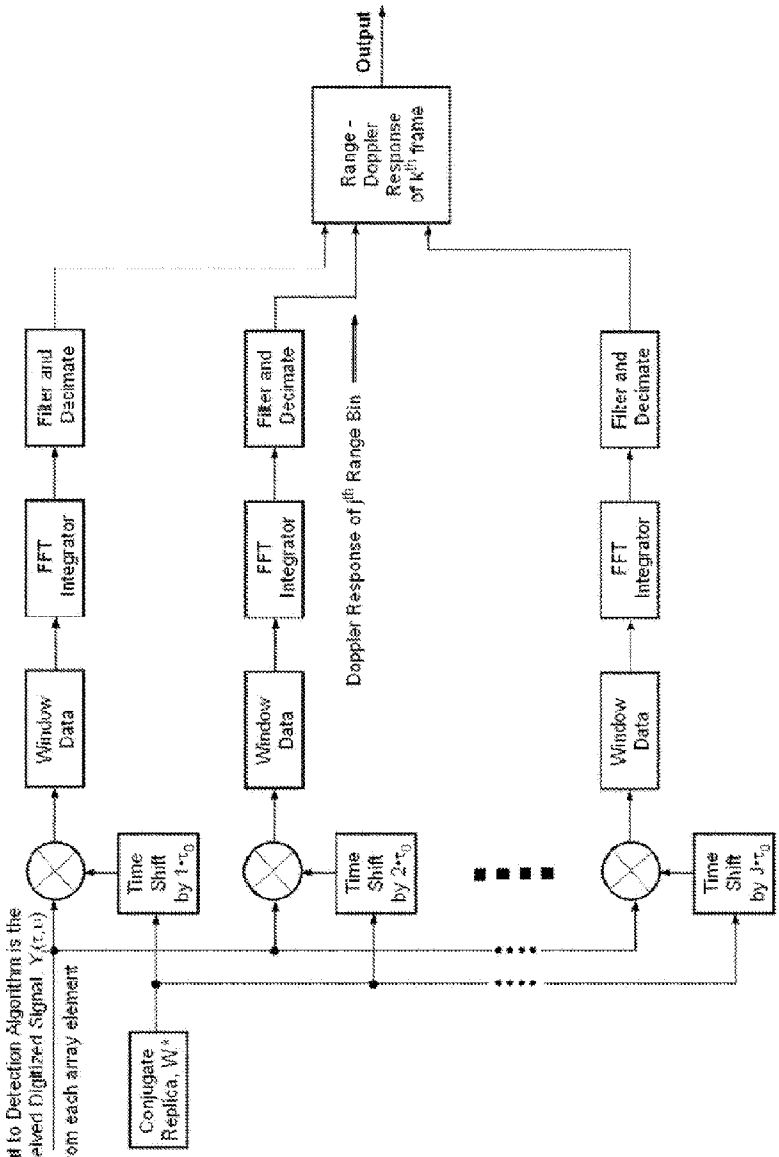
Input to Detection Algorithm is the Received Digitized Signal, Y(τ, u)
from each array element
Conjugate Replica, W*
Time Shift by 1*τ0
Time Shift by 2*τ0
Time Shift by J*τ0
Window Data
Window Data
Window Data
FFT Integrator
FFT Integrator
FFT Integrator
Filter and Decimate
Filter and Decimate
Filter and Decimate
Doppler Response of jth Range Bin
Range - Doppler Response of kth frame
Output

FIG. 5