US007850611B2

(12) **United States Patent**
Davies et al.

(10) **Patent No.: US 7,850,611 B2**
(45) **Date of Patent: Dec. 14, 2010**

(54) **SYSTEM AND METHODS FOR IMPROVED ULTRASOUND IMAGING**

(75) Inventors: **Timothy J. Davies**, Calgary (CA); **Richard Evans**, Bristol (GB)

(73) Assignee: **InnerVision Medical Technologies Inc.**, Calgary (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1478 days.

(21) Appl. No.: **10/945,459**

(22) Filed: **Sep. 20, 2004**

(65) **Prior Publication Data**

US 2006/0064015 A1 Mar. 23, 2006

(51) **Int. Cl.**
A61B 8/00 (2006.01)

(52) **U.S. Cl.** **600/447**; 600/437; 600/441; 600/443; 73/596; 73/628

(58) **Field of Classification Search** 600/437, 600/439, 440, 441, 443, 444, 447, 459, 472; 73/596, 602, 606, 607, 618–629, 632, 633, 73/641

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,895,381 A		7/1975	Kock	
4,325,257 A		4/1982	Kino et al.	
4,452,084 A	*	6/1984	Taenzer	73/609
4,669,482 A	*	6/1987	Ophir	600/449
4,817,434 A		4/1989	Anderson	
5,161,536 A	*	11/1992	Vilkomerson et al.	600/443
5,269,309 A	*	12/1993	Fort et al.	600/447
5,299,576 A		4/1994	Shiba	
5,345,426 A	*	9/1994	Lipschutz	367/103
5,465,722 A		11/1995	Fort et al.	
5,526,815 A	*	6/1996	Granz et al.	600/439
5,558,092 A	*	9/1996	Unger et al.	600/439
5,570,691 A	*	11/1996	Wright et al.	600/447

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0 812 005 A2 12/1997

(Continued)

OTHER PUBLICATIONS

Morten H. Pedersen, Kim L. Gammelmark, and Jorgen A. Jensen; Preliminary In-Vivo Evaluation of Convex Array Synthetic Aperture Imaging; SPIE 2004.

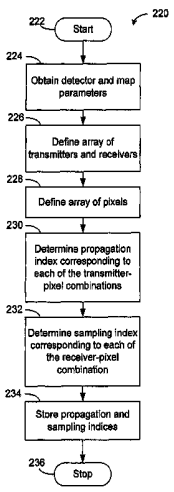
(Continued)

Primary Examiner—Ruth S Smith
Assistant Examiner—Mark Remaly
(74) *Attorney, Agent, or Firm*—Oyen Wiggs Green & Mutala LLP

(57) **ABSTRACT**

Systems and methods are disclosed for improving the resolution and quality of an image formed by signals from an array of receivers. Multiple receivers introduce variations in arrival times that can be less than the period of an operating signal, and also less than the period associated with a sampling operation. Thus, multiple receivers allow sampling of fine features of reflected signals that would be considered beyond the resolution associated with the operating signal. Use of multiple receivers also provides an effective sampling rate that is greater than the sampling rate of an individual receiver. Similar advantages can be obtained using multiple transmitters. Such advantageous features can be used to obtain high resolution images of objects in a medium in applications such as ultrasound imaging.

11 Claims, 36 Drawing Sheets



U.S. PATENT DOCUMENTS

5,628,320	A *	5/1997	Teo	600/443
5,920,285	A	7/1999	Benjamin	
5,969,661	A	10/1999	Benjamin	
6,007,499	A *	12/1999	Martin et al.	601/3
6,049,509	A *	4/2000	Sonneland et al.	367/49
6,050,943	A *	4/2000	Slayton et al.	600/439
6,135,960	A *	10/2000	Holmberg	600/447
6,166,384	A *	12/2000	Dentinger et al.	250/370.09
6,231,511	B1 *	5/2001	Bae	600/447
6,264,609	B1 *	7/2001	Herrington et al.	600/443
6,436,046	B1 *	8/2002	Napolitano et al.	600/447
6,526,163	B1	2/2003	Halmann et al.	
6,547,732	B2 *	4/2003	Jago	600/437
6,672,165	B2 *	1/2004	Rather et al.	73/603
6,692,450	B1 *	2/2004	Coleman	601/3
6,719,693	B2 *	4/2004	Richard	600/437
2002/0065466	A1 *	5/2002	Rather et al.	600/447

FOREIGN PATENT DOCUMENTS

EP	0812005	A2 *	12/1997
EP	0812005	A2 *	12/1997
FR	2 851 662		8/2004

OTHER PUBLICATIONS

William D. Richard, A Scalable Architecture For Real-Time Synthetic-Focus Imaging, Ultrasonic Imaging 25, pp. 151-161, 2003.

Mark A. Franklin, Abhijit Mahajan and R. Martin Arthur; Parallel Implementations of an Ultrasonic Image Generation Algorithm using MPI; Parallel and Distributed Computing and Systems, pp. 589-596, Nov. 3-6, 1999.

Stephen W. Smith, Henry G. Pavy, Jr., and Olaf T. von Ramm; High-Speed Ultrasound Volumetric Imaging System—Part I: Transducer Design and Beam Steering; IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 38, No. 2, pp. 100-108, Mar. 1991.

Peter Cheesman, Bob Kanefsky, Richard Kraft, John Stutz and Robin Hanson; Super-Resolved Surface Reconstruction from Multiple Images; NASA Ames Research Center, Dec. 14, 1994.

Jorgen Arendt Jensen, Ole Holm, Lars Joost Jensen, Henrik Bendsen, Henrik Moller Pedersen, Kent Salomonsen, Johnny Hansen and Svetoslav Nikolov; Experimental Ultrasound System for Real-Time Synthetic Imaging; IEEE International Ultrasonics Symposium, Lake Tahoe, 1999.

Yiming Pi, Hui Long and Shunji Huang; A SAR Parallel Processing Algorithm and its Implementation; Conference Proceedings FIEOS 2002.

Donald Bailey; Image Resolution Improvement from Multiple Images; Massey University, available online at www.poly.edu/Podium/eef2001.cfm, Nov. 2001.

Steven R. Broadstone and R. Martin Arthur; An Approach to Real-Time Reflection Tomography Using the Complete Dataset; pp. 829-831, 1986 Ultrasonics symposium.

Catherine H. Frazier and William D. O'Brien, Jr.; Synthetic Aperture Techniques with a Virtual Source Element; IEEE Transactions on Ultrasonics.., vol. 45, No. 1, pp. 196-207, Jan. 1998.

D.K. Peterson and Gordon S. Kino; Real-Time Digital Image Reconstruction; A Description of Imaging Hardware and an Analysis of Quantization Errors; IEEE Transactions on Sonics and Ultrasonics, vol. SU-31, No. 4, pp. 337-351, Jul. 1984.

P.D. Corl, P.M. Grant and G.S. Kino; A Digital Synthetic Focus Acoustic Imaging System for NDE; IEEE Ultrasonics Symposium Proceedings; pp. 263-268, 1978.

Svetoslav I. Nikolov, Jorgen A. Jensen, Remi Dufait and Armin Schoisswohl; Three-Dimensional Real-Time Synthetic Aperture Imaging Using a Rotating Phased Array Transducer; IEEE International Ultrasonics Symposium, 2002.

Mark A. Franklin, Abhijit Mahajan, and R. Martin Arthur; Parallel Implementations of 3D Synthetic-Focus Ultrasonic Image Generation Using MPI; Parallel and Distributed Computing and Systems; vol. I, pp. 239-246, Nov. 6-9, 2000.

Daryl G. Beetner and R. Martin Arthur; Generation of Synthetic-Focus Images from Pulse-Echo Ultrasound Using Difference Equations; IEEE Transactions on Medical Imaging, vol. 15, No. 5, pp. 665-672, Oct. 1996.

William D. Richard and R. Martin Arthur; Real-Time Ultrasonic Scan Conversion via Linear Interpolation of Oversampled Vectors; Ultrasonic Imaging 16, 109-123, 1994.

An Introduction to the Sampling Theorem; National Semiconductor Application Note 236, Jan. 1980.

Samuel H. Gray; The Bleeding Edge of Seismic Imaging; CSEG Recorder, Dec. 2003.

Steven D. Glaser and Mi Kyong Hand; Imaging of Rock Fractures with Low-Frequency Ultrasonic Reflection/Diffraction; American Society for Testing Materials, Geotechnical Testing Journal, vol. 21, No. 4, pp. 317-327, Dec. 1998.

Samuel H. Gray; Nuts and Bolts of Beam Migration; CSEG National Convention 2004.

Mark A. Haun; Douglas L. Jones, and William D. O'Brien, Jr; Adaptive Focusing Through Layered Media Using the Geophysical "Time Migration" Concept; Proc. Intl. Ultrasonics Symposium, Munich, Germany, Oct. 8-11, 2002.

Improved Resolution in Infrared Imaging Using Randomly Shifted Images, available online at http://www.ph.tn.tudelft.nl/~cris/MastersProiect.html, Nov. 1998.

George Papanicolaou; Interferometric Imaging in Clutter II; ARO/DARPA MURI, Aug. 15, 2003.

Jorgen Arendt Jensen; Ultrasound Imaging and its Modeling; 84 Imaging of Complex Media with Acoustic and Seismic Waves, pp. 135-165, 2002.

Olaf T. Von Ramm, Stephen W. Smith, and Henry G. Pavy, Jr.; High Speed Ultrasound Volumetric Imaging System—Part II: Parallel Processing and Image Display; IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 38, No. 2, pp. 109-115, Mar. 1991.

John E. Greivenkamp, Sub-Nyquist interferometry, Dec. 15, 1997, vol. 26, No. 24, Applied Optics, Rochester, New York.

Lyons RG: Understanding Digital Signal Processing, 2nd ed. (2004). Section 2.3.

International Search Report for PCT/IB2005/003147, filed Mar. 8, 2005.

* cited by examiner

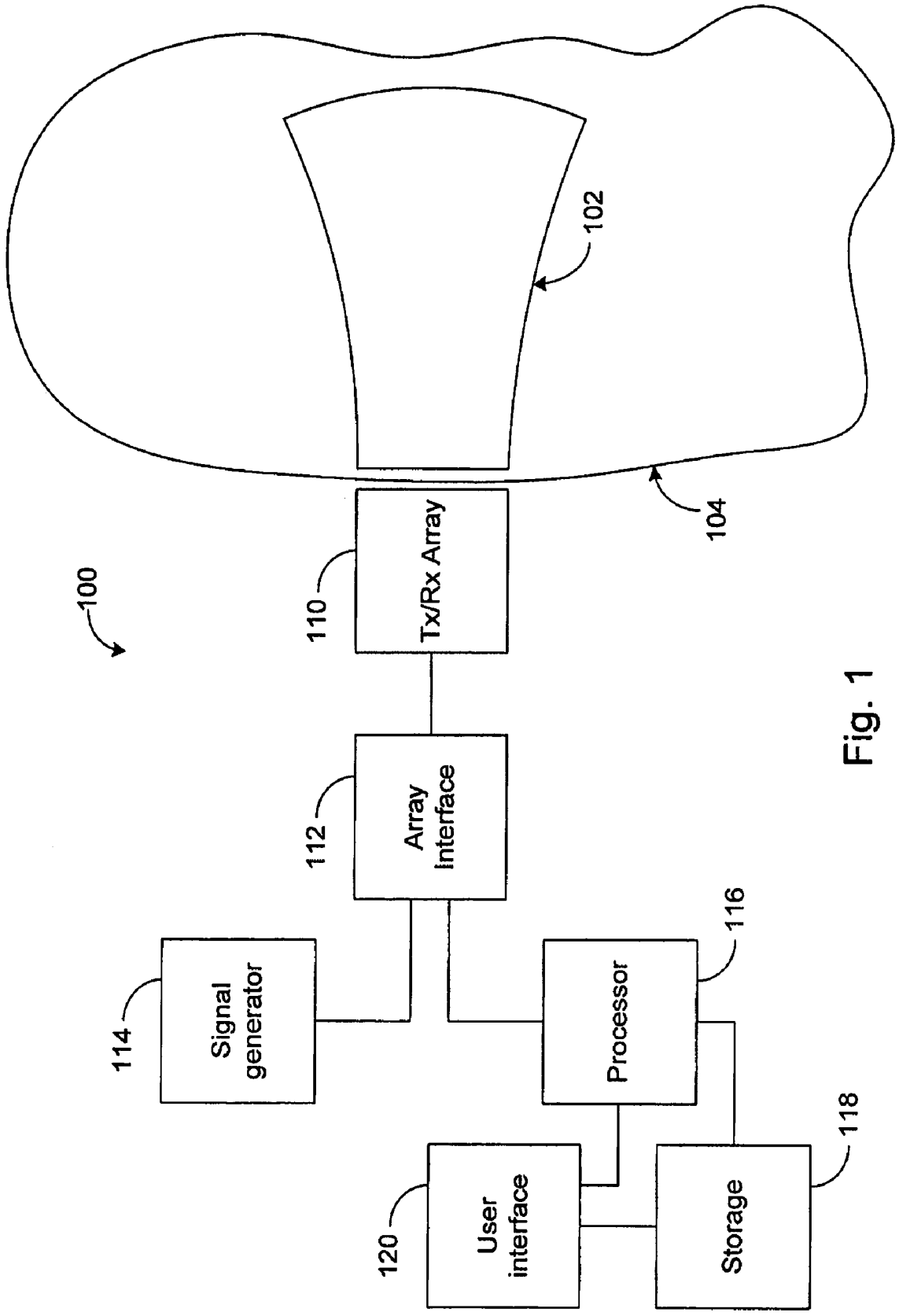

100
102
104
110
Tx/Rx Array
112
Array Interface
114
Signal generator
116
Processor
118
Storage
120
User interface

Fig. 1

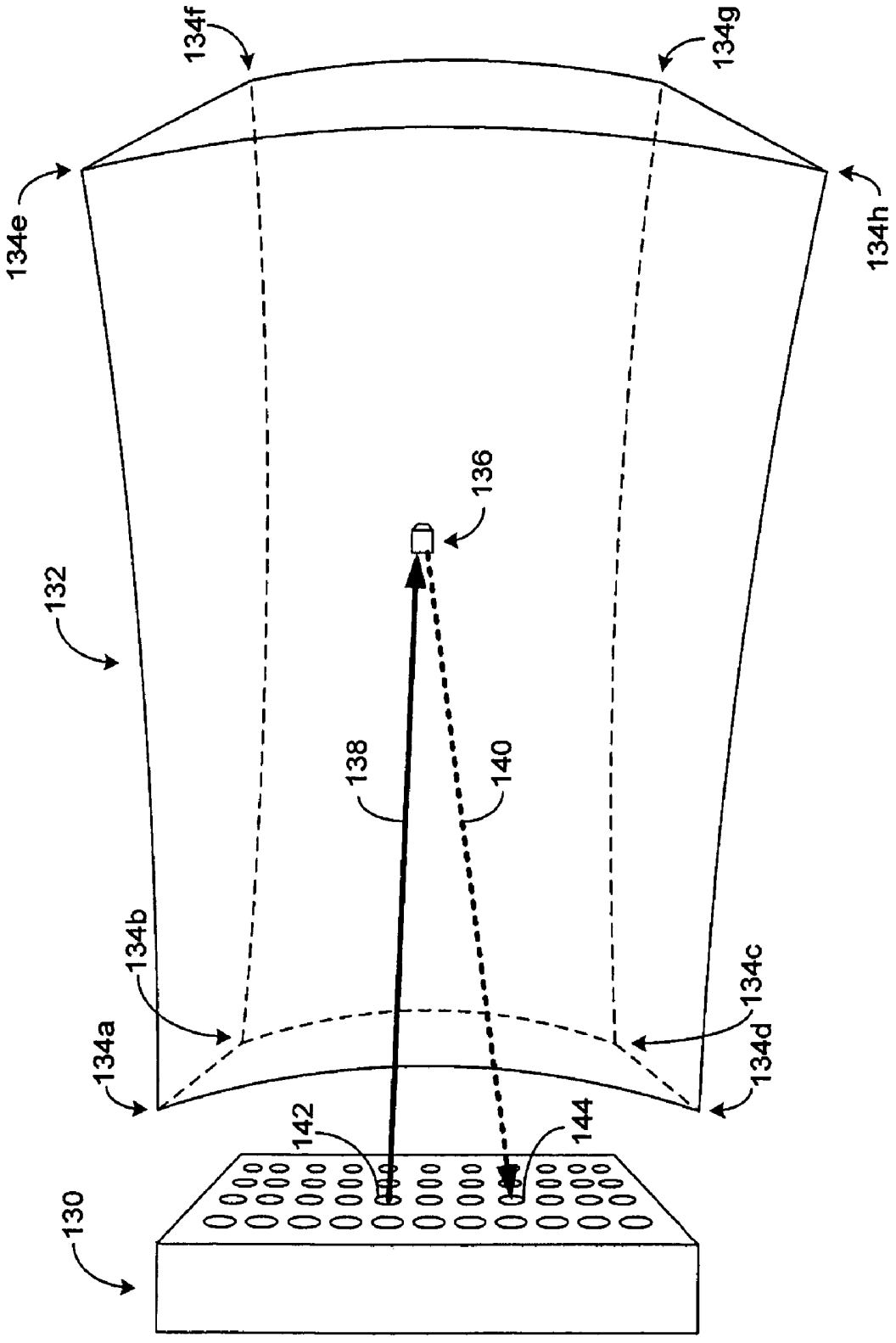

134f
134g
134e
134h
136
132
138
140
134b
134c
134a
134d
142
144
130

Fig. 2

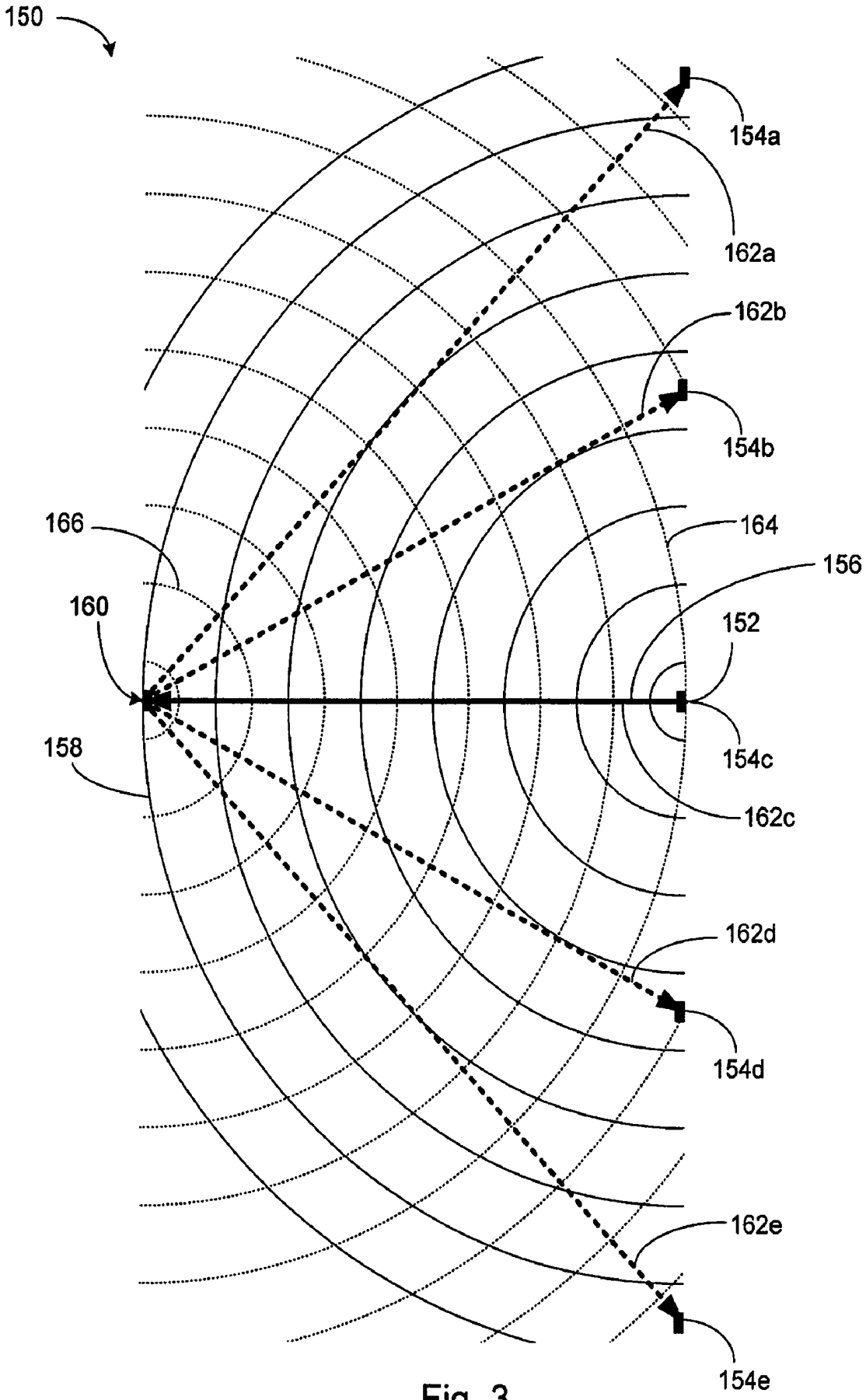

150
154a
162a
162b
154b
166
164
156
160
152
154c
158
162c
162d
154d
162e
154e

Fig. 3

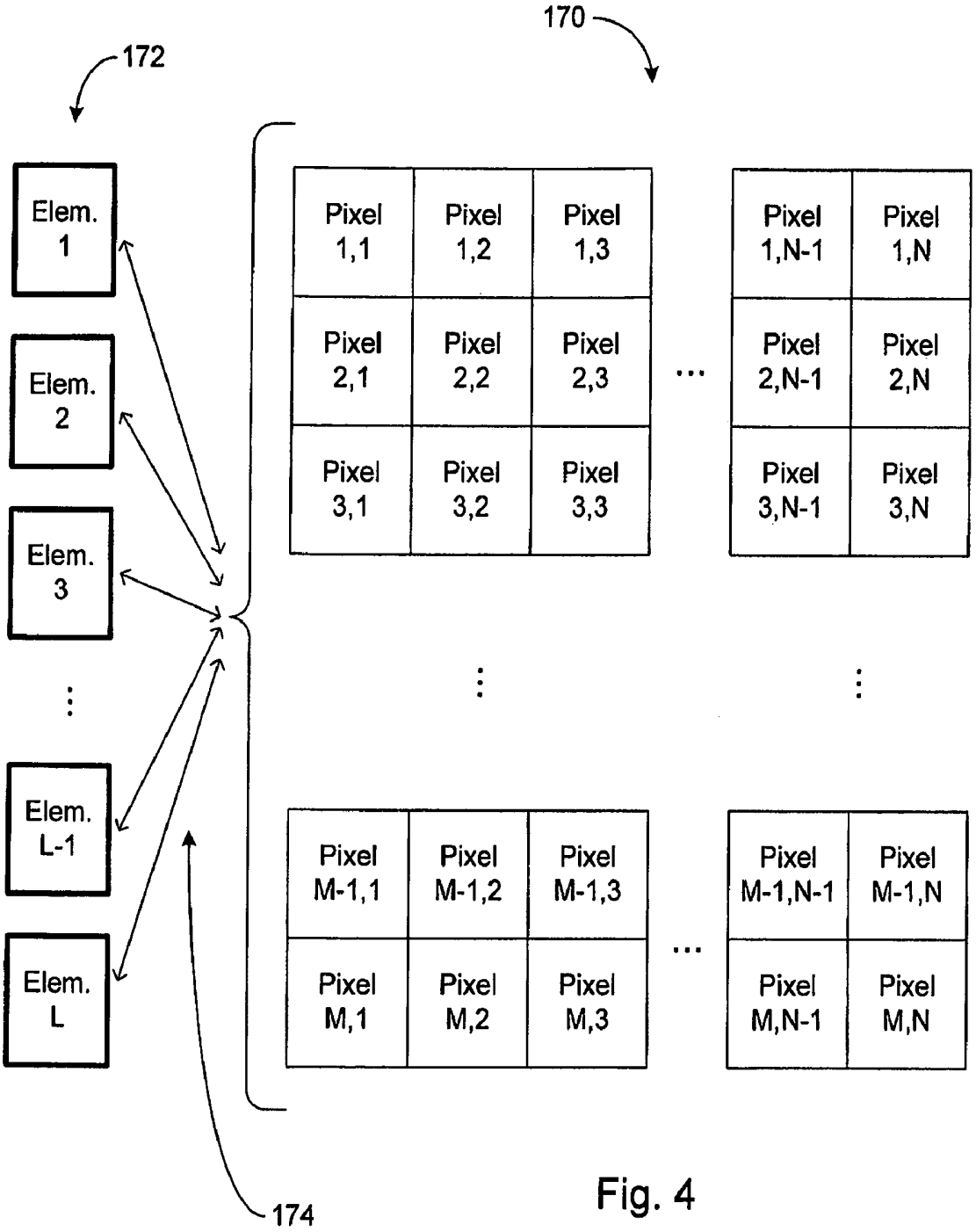

170
172
Elem. 1
Elem. 2
Elem. 3
Elem. L-1
Elem. L
Pixel 1,1
Pixel 1,2
Pixel 1,3
Pixel 1,N-1
Pixel 1,N
Pixel 2,1
Pixel 2,2
Pixel 2,3
Pixel 2,N-1
Pixel 2,N
Pixel 3,1
Pixel 3,2
Pixel 3,3
Pixel 3,N-1
Pixel 3,N
Pixel M-1,1
Pixel M-1,2
Pixel M-1,3
Pixel M-1,N-1
Pixel M-1,N
Pixel M,1
Pixel M,2
Pixel M,3
Pixel M,N-1
Pixel M,N
174

Fig. 4

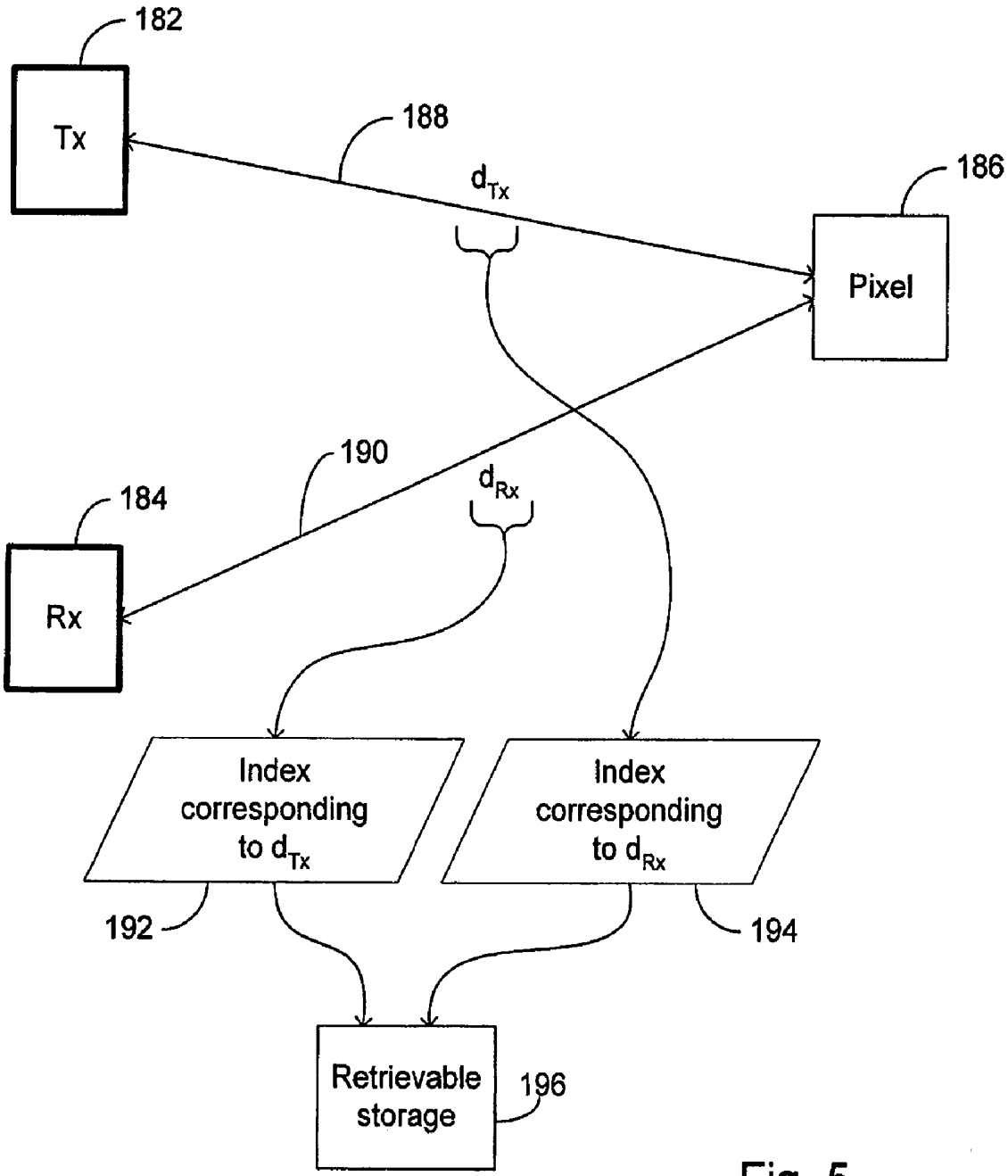

182
Tx
188
d_{Tx}
186
Pixel
190
d_{Rx}
184
Rx
Index corresponding to d_{Tx}
Index corresponding to d_{Rx}
192
194
Retrievable storage
196

Fig. 5

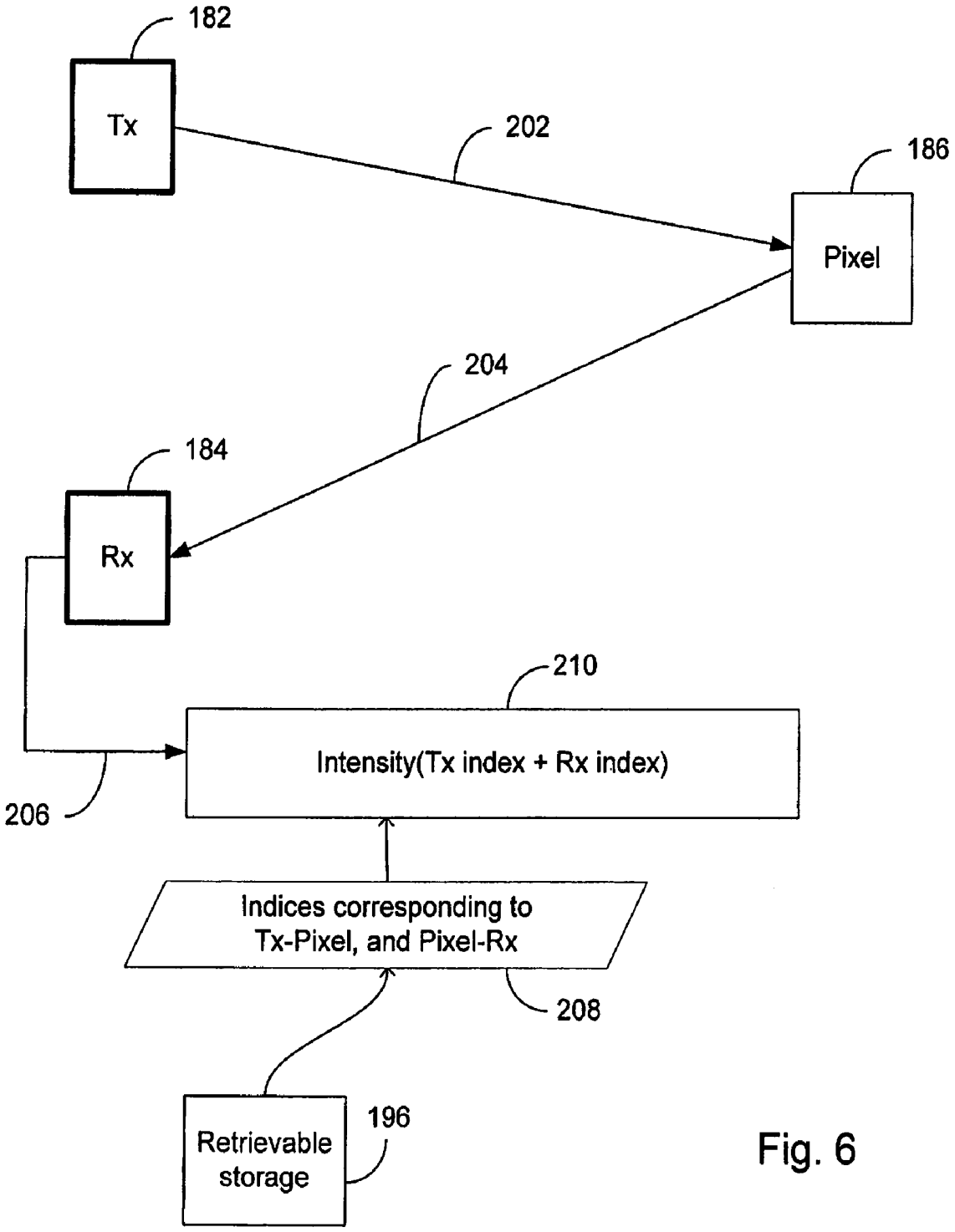

182
Tx
202
186
Pixel
204
184
Rx
210
Intensity(Tx index + Rx index)
206
Indices corresponding to
Tx-Pixel, and Pixel-Rx
208
196
Retrievable
storage

Fig. 6

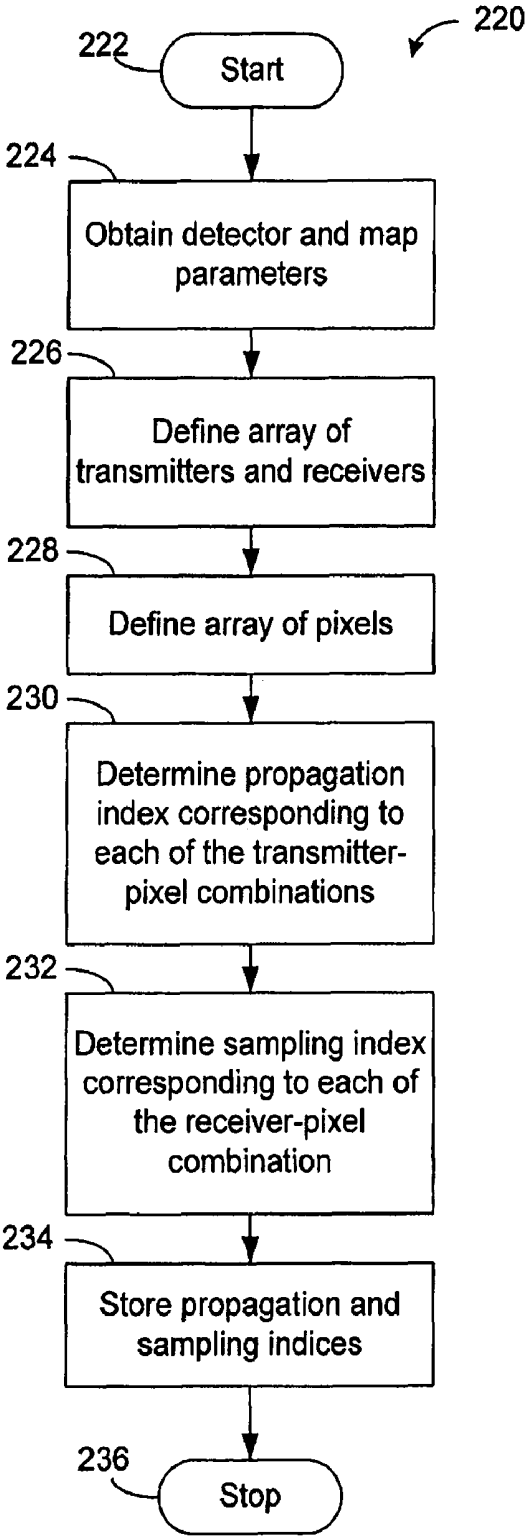

220
222
Start
224
Obtain detector and map parameters
226
Define array of transmitters and receivers
228
Define array of pixels
230
Determine propagation index corresponding to each of the transmitter-pixel combinations
232
Determine sampling index corresponding to each of the receiver-pixel combination
234
Store propagation and sampling indices
236
Stop

Fig. 7

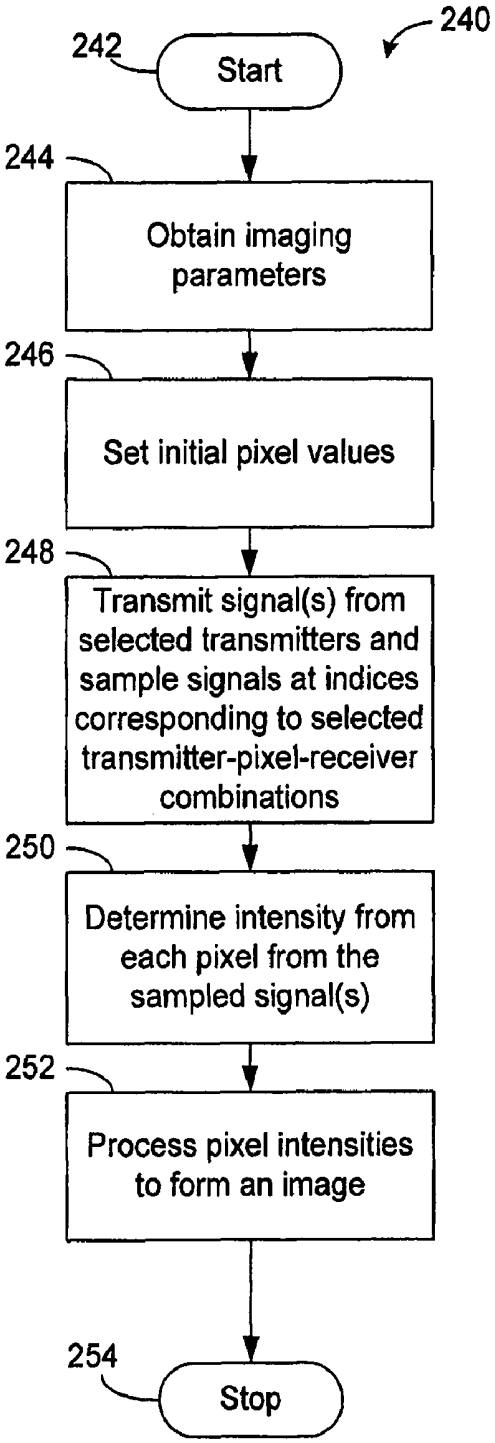

240
242
Start
244
Obtain imaging parameters
246
Set initial pixel values
248
Transmit signal(s) from selected transmitters and sample signals at indices corresponding to selected transmitter-pixel-receiver combinations
250
Determine intensity from each pixel from the sampled signal(s)
252
Process pixel intensities to form an image
254
Stop

Fig. 8

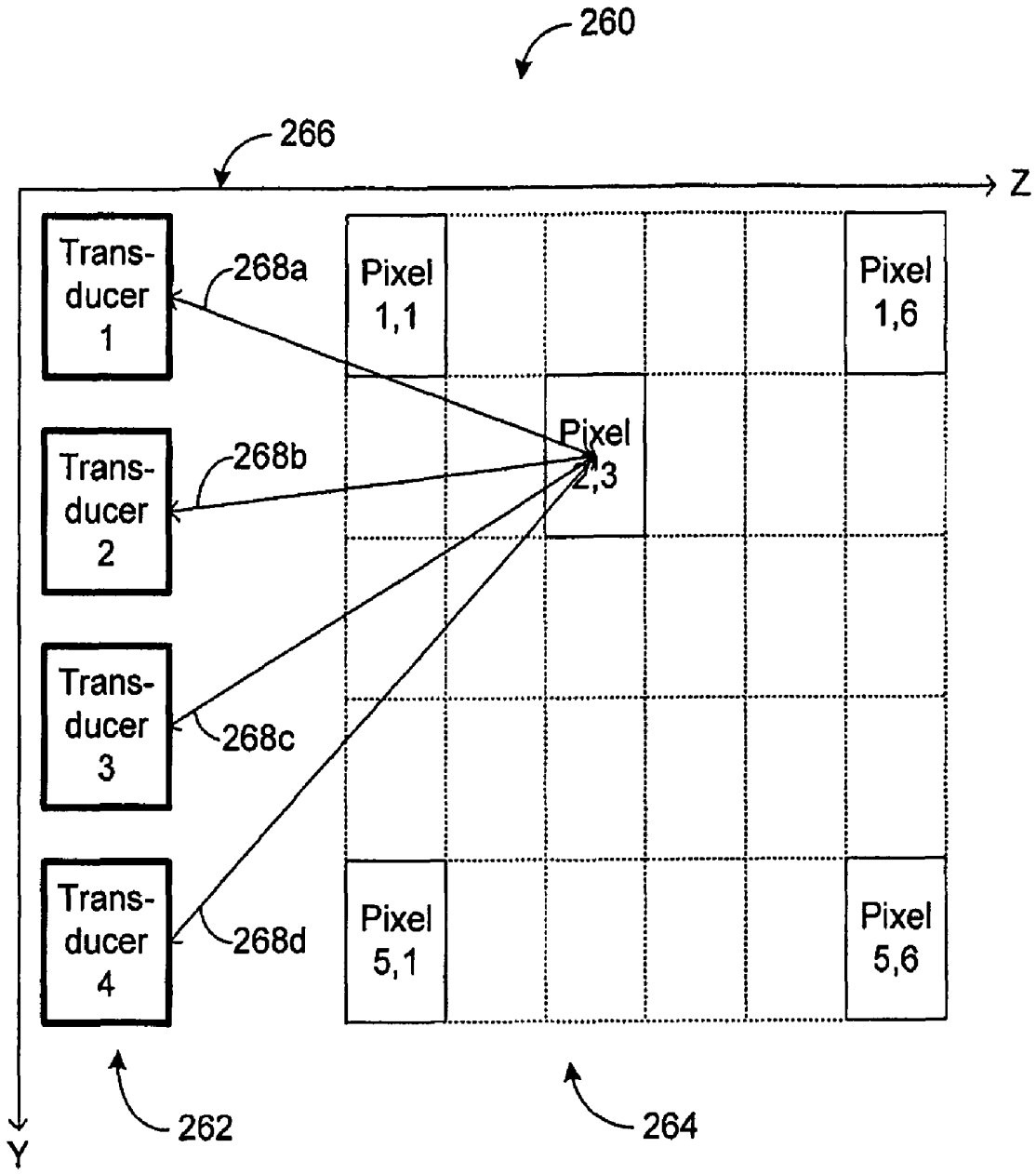

260
266
Z
Trans-
ducer
1
268a
Pixel
1,1
Pixel
1,6
Trans-
ducer
2
268b
Pixel
2,3
Trans-
ducer
3
268c
Trans-
ducer
4
268d
Pixel
5,1
Pixel
5,6
Y
262
264

Fig. 9

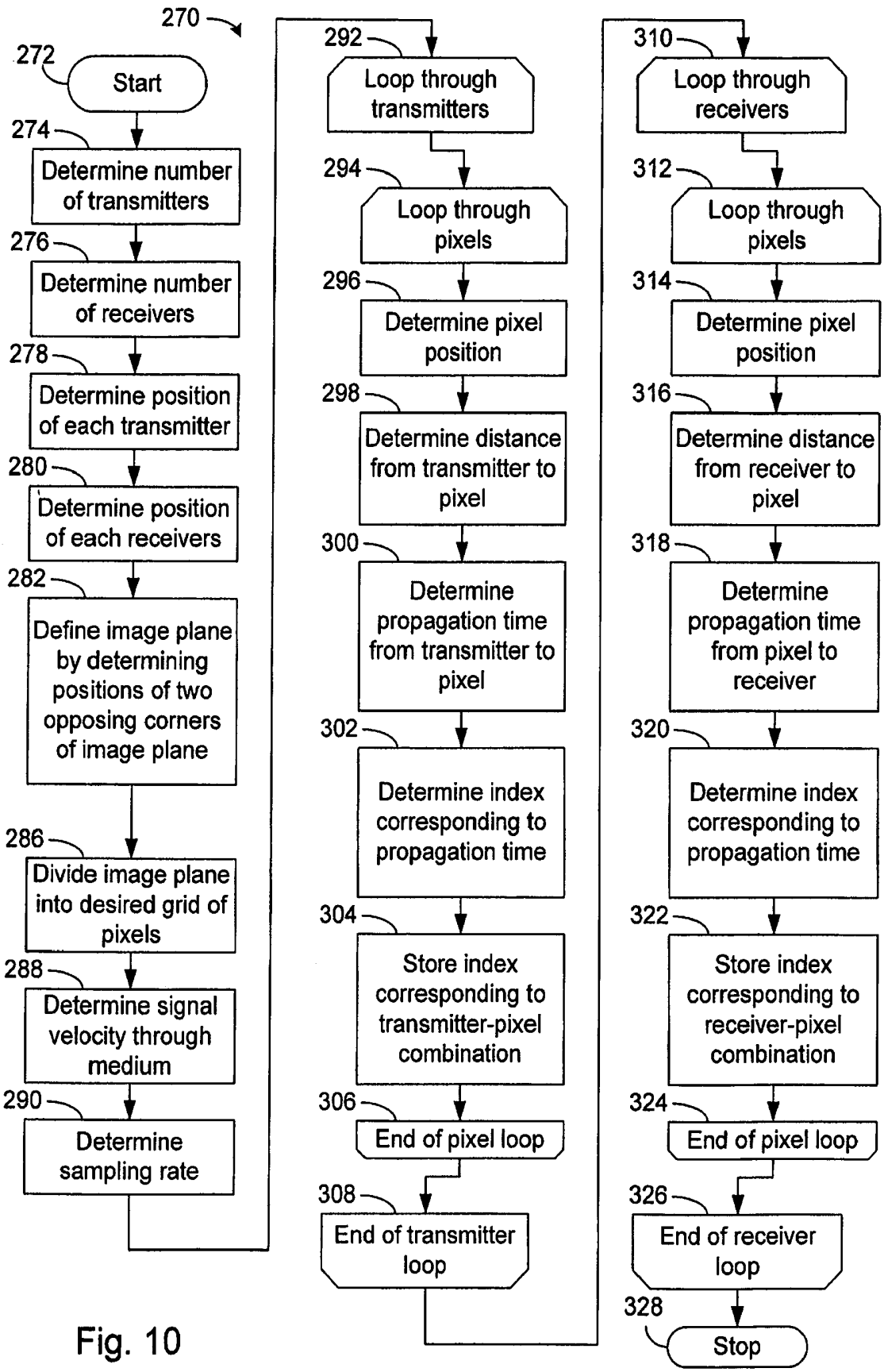

270
272
Start
274
Determine number of transmitters
276
Determine number of receivers
278
Determine position of each transmitter
280
Determine position of each receivers
282
Define image plane by determining positions of two opposing corners of image plane
286
Divide image plane into desired grid of pixels
288
Determine signal velocity through medium
290
Determine sampling rate
292
Loop through transmitters
294
Loop through pixels
296
Determine pixel position
298
Determine distance from transmitter to pixel
300
Determine propagation time from transmitter to pixel
302
Determine index corresponding to propagation time
304
Store index corresponding to transmitter-pixel combination
306
End of pixel loop
308
End of transmitter loop
310
Loop through receivers
312
Loop through pixels
314
Determine pixel position
316
Determine distance from receiver to pixel
318
Determine propagation time from pixel to receiver
320
Determine index corresponding to propagation time
322
Store index corresponding to receiver-pixel combination
324
End of pixel loop
326
End of receiver loop
328
Stop

Fig. 10

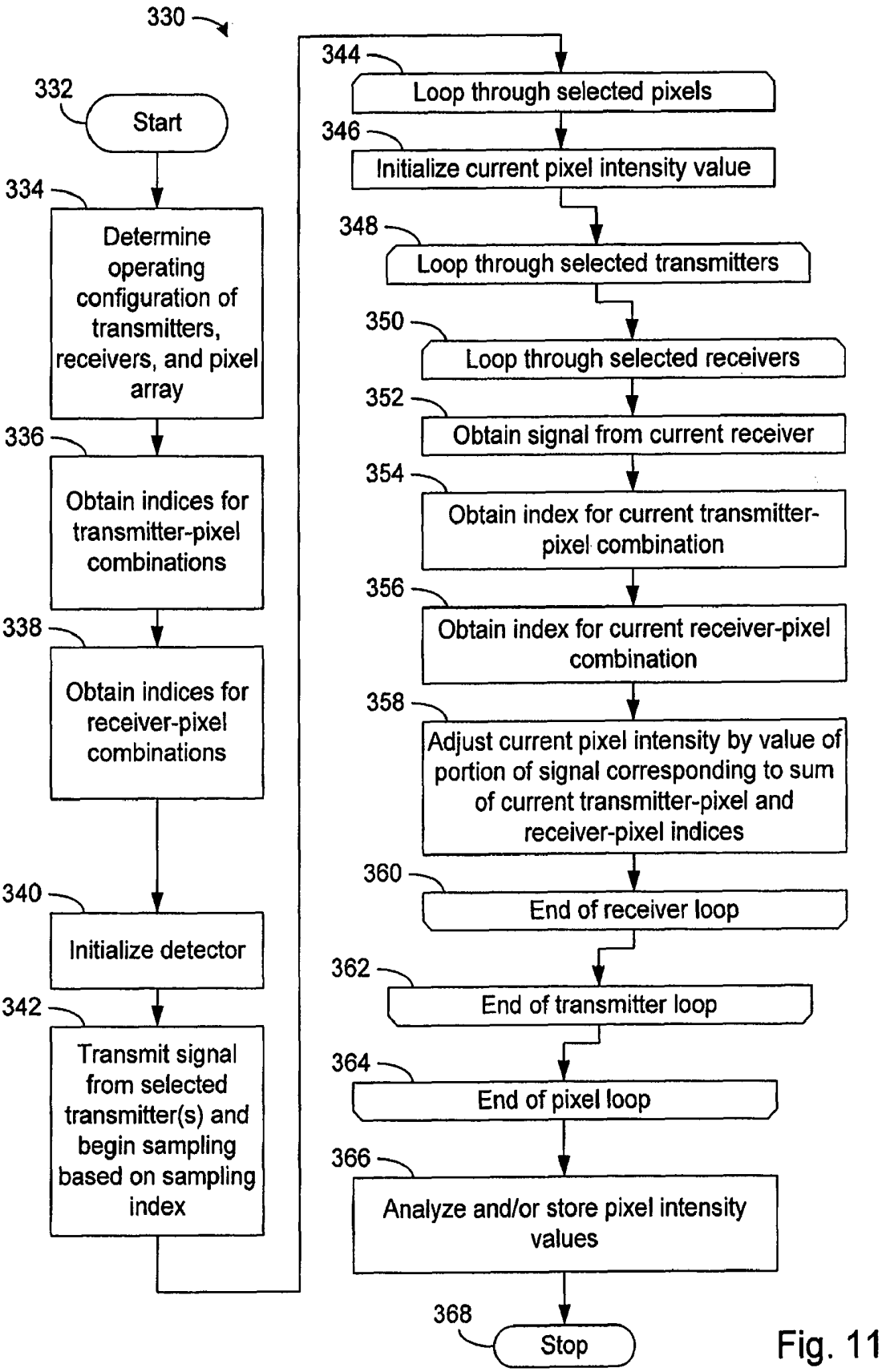

330
332
Start
334
Determine operating configuration of transmitters, receivers, and pixel array
336
Obtain indices for transmitter-pixel combinations
338
Obtain indices for receiver-pixel combinations
340
Initialize detector
342
Transmit signal from selected transmitter(s) and begin sampling based on sampling index
344
Loop through selected pixels
346
Initialize current pixel intensity value
348
Loop through selected transmitters
350
Loop through selected receivers
352
Obtain signal from current receiver
354
Obtain index for current transmitter-pixel combination
356
Obtain index for current receiver-pixel combination
358
Adjust current pixel intensity by value of portion of signal corresponding to sum of current transmitter-pixel and receiver-pixel indices
360
End of receiver loop
362
End of transmitter loop
364
End of pixel loop
366
Analyze and/or store pixel intensity values
368
Stop

Fig. 11

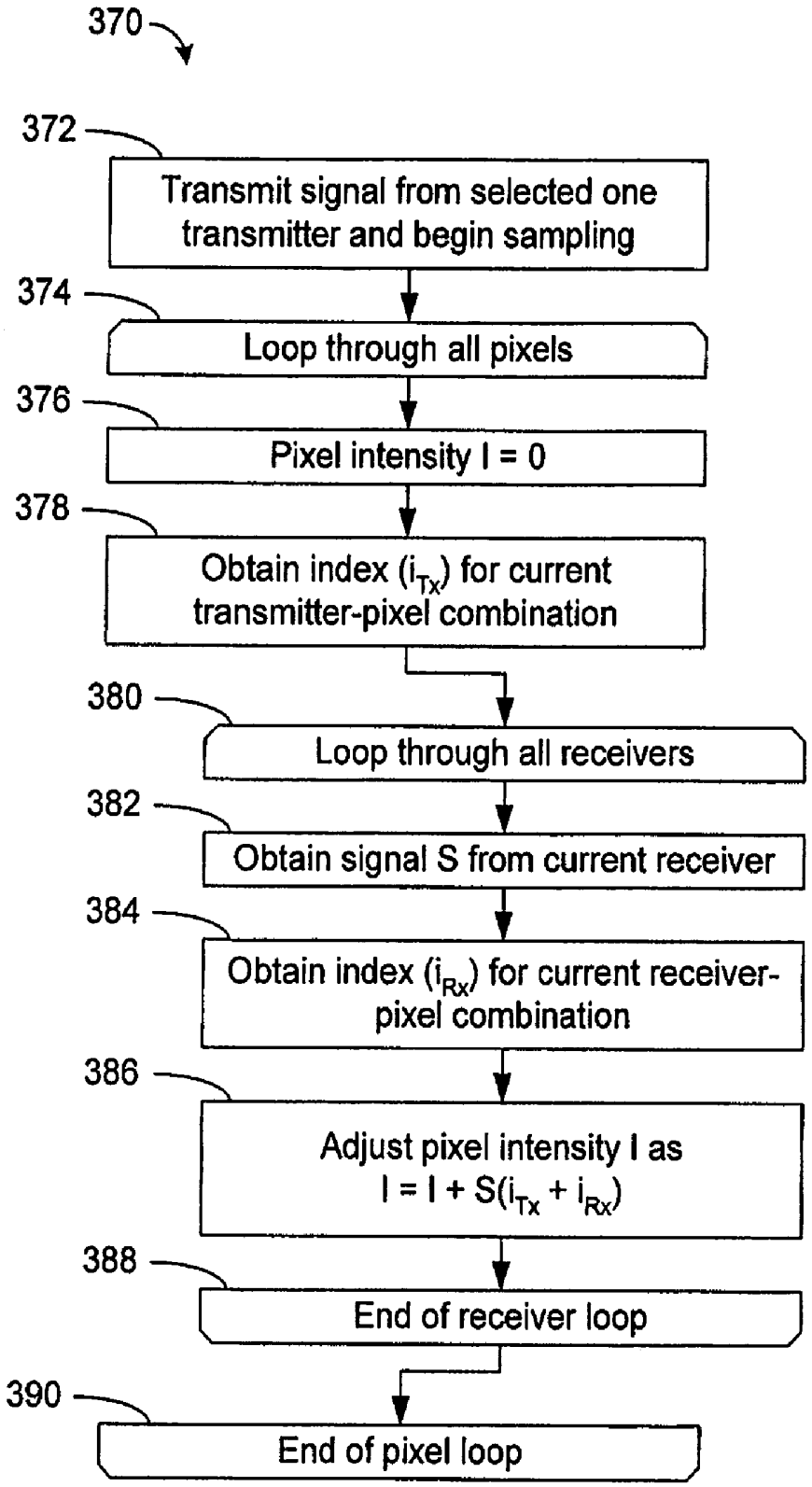

370
372
Transmit signal from selected one transmitter and begin sampling
374
Loop through all pixels
376
Pixel intensity I = 0
378
Obtain index (i_{Tx}) for current transmitter-pixel combination
380
Loop through all receivers
382
Obtain signal S from current receiver
384
Obtain index (i_{Rx}) for current receiver-pixel combination
386
Adjust pixel intensity I as $I = I + S(i_{Tx} + i_{Rx})$
388
End of receiver loop
390
End of pixel loop

Fig. 12

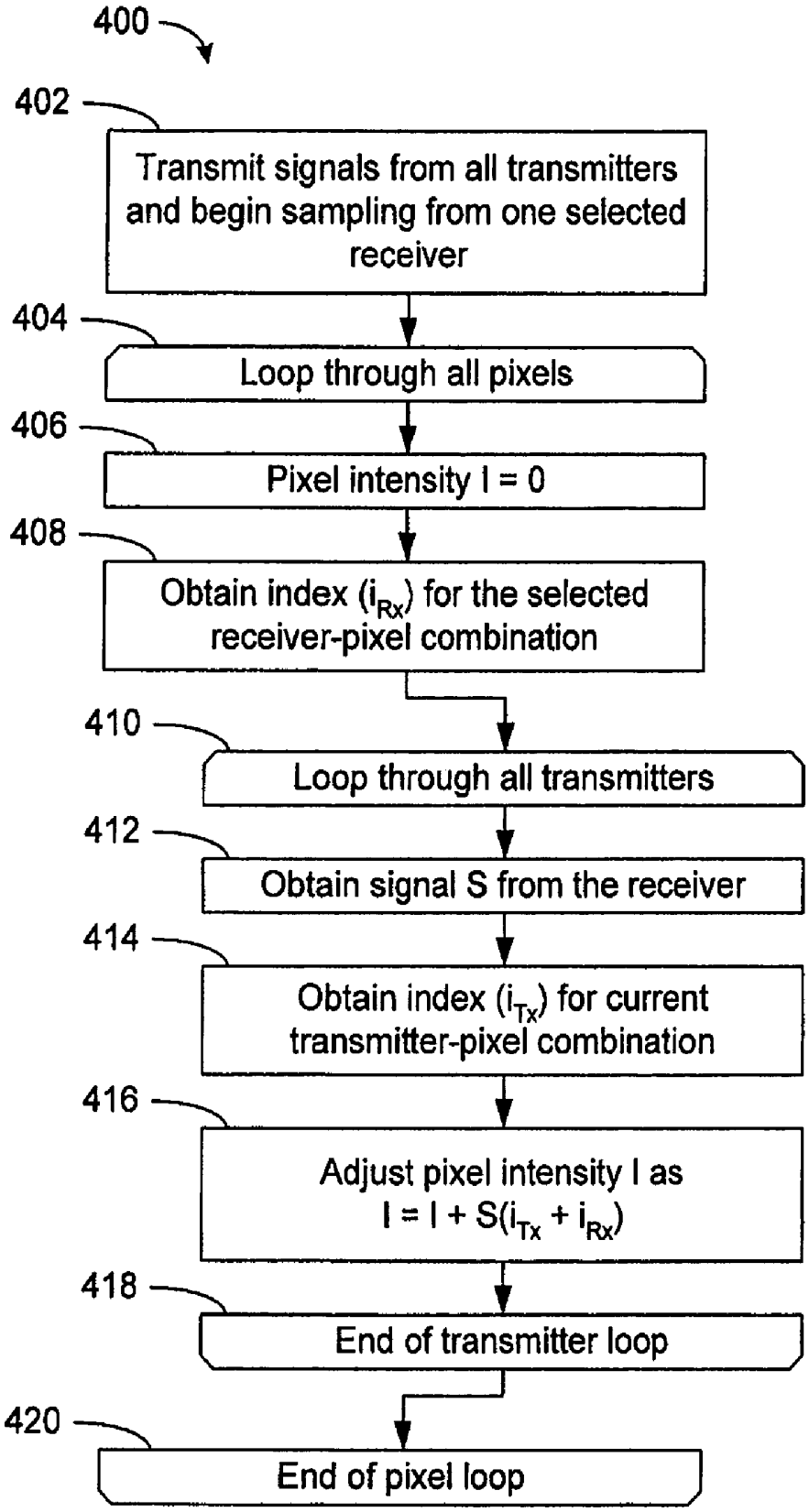

400
402
Transmit signals from all transmitters and begin sampling from one selected receiver
404
Loop through all pixels
406
Pixel intensity I = 0
408
Obtain index (i_{Rx}) for the selected receiver-pixel combination
410
Loop through all transmitters
412
Obtain signal S from the receiver
414
Obtain index (i_{Tx}) for current transmitter-pixel combination
416
Adjust pixel intensity I as $I = I + S(i_{Tx} + i_{Rx})$
418
End of transmitter loop
420
End of pixel loop

Fig. 13

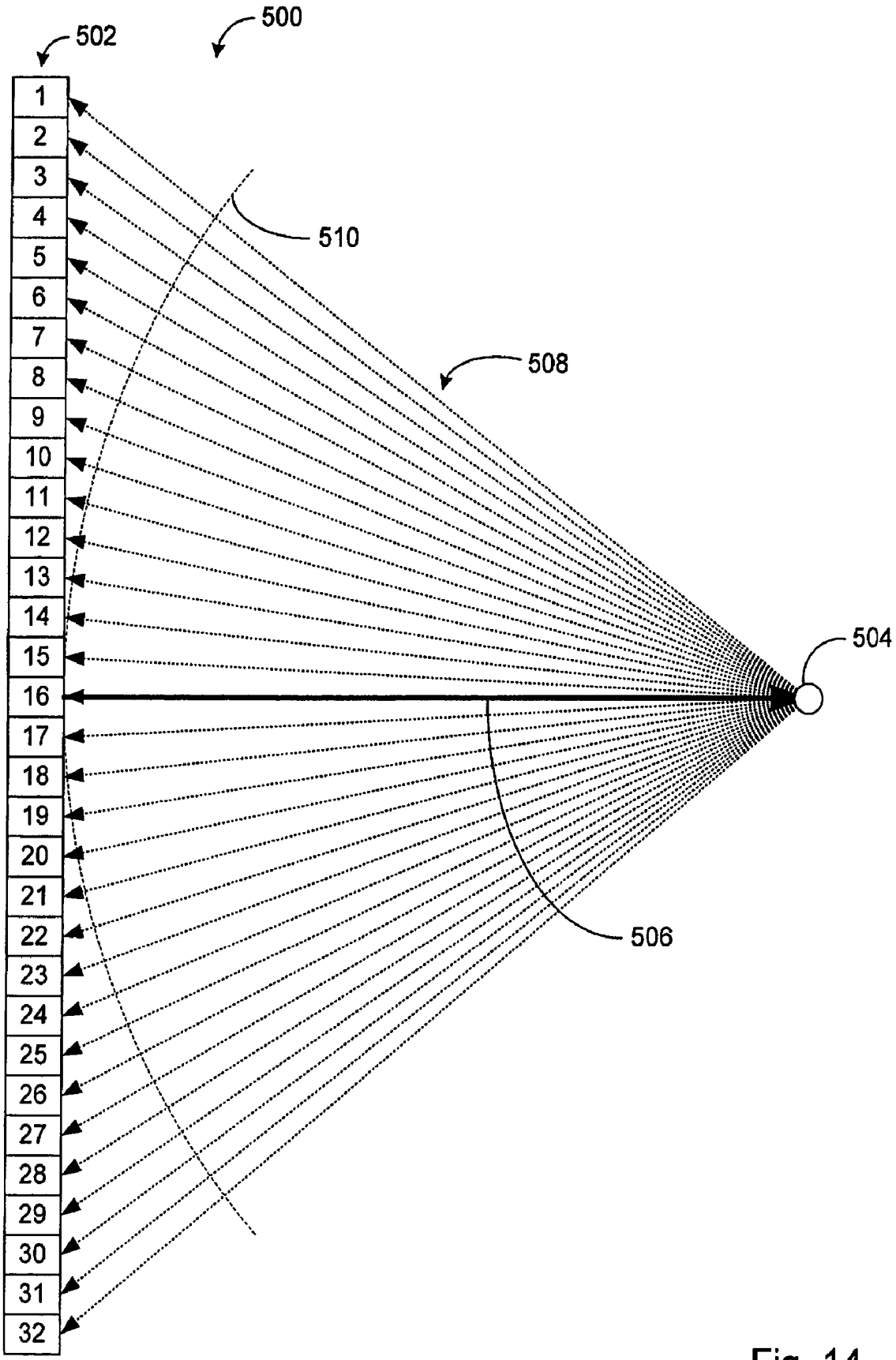

500
502
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
504
506
508
510

Fig. 14

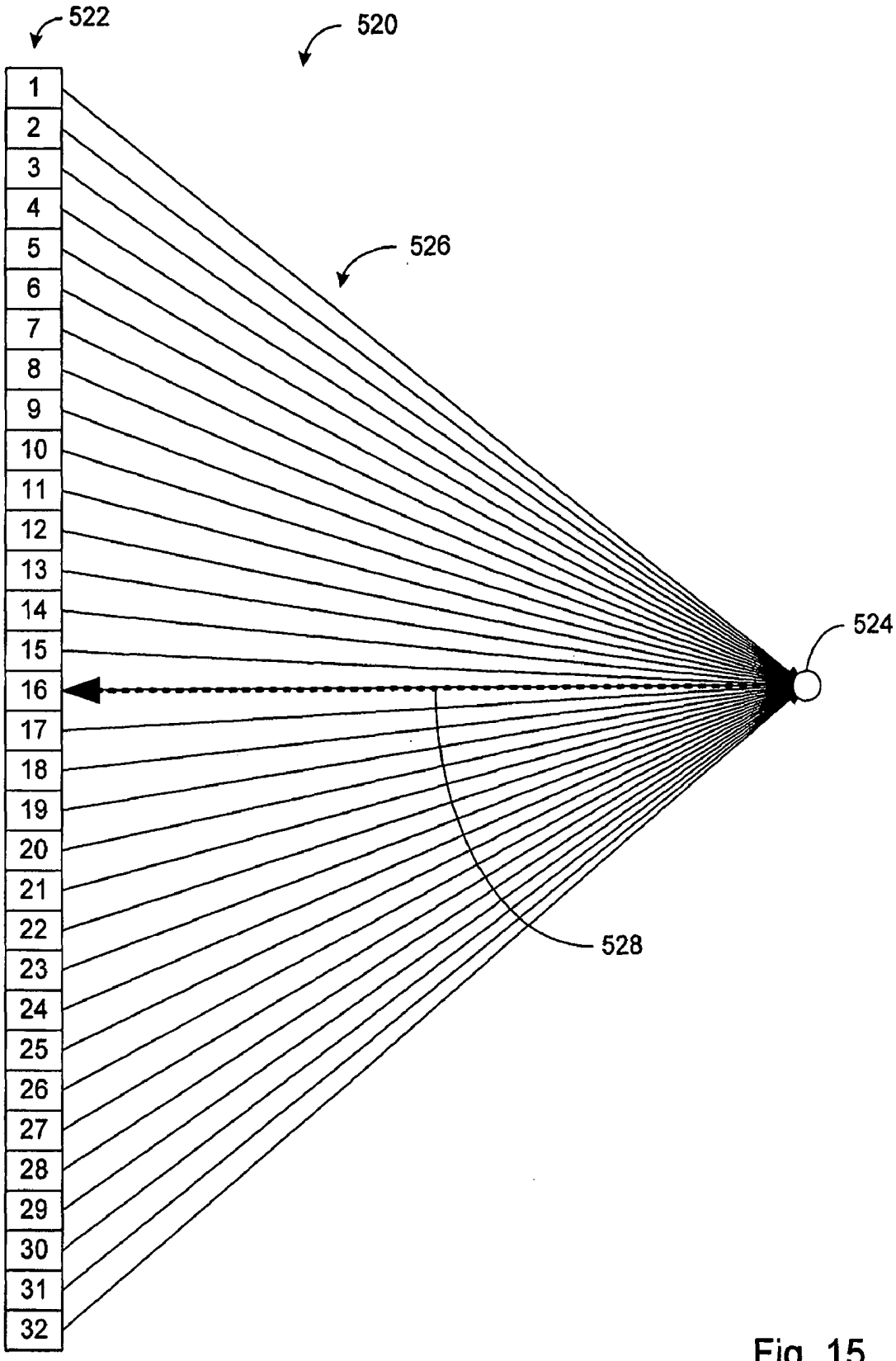

522
520
526
524
528
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

Fig. 15

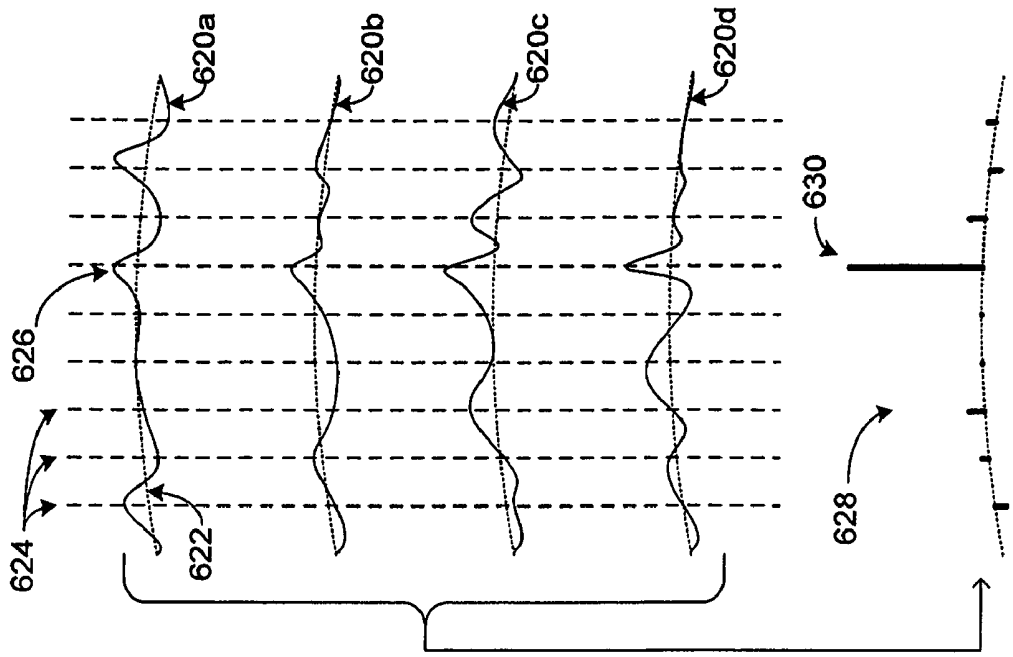

620a
620b
620c
620d
626
624
622
630
628

Fig. 17

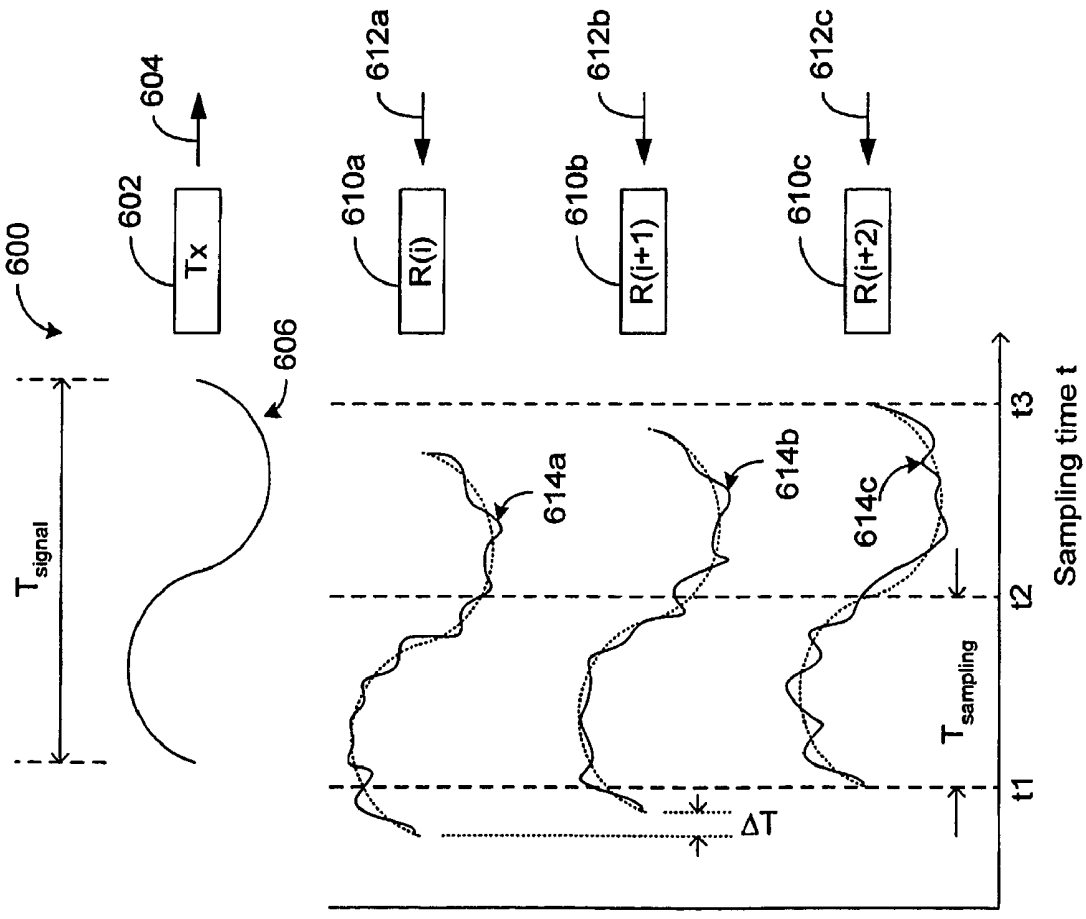

600
602
Tx
604
606
T_{signal}
610a
R(i)
612a
610b
R(i+1)
612b
610c
R(i+2)
612c
614a
614b
614c
ΔT
$T_{sampling}$
t1
t2
t3
Sampling time t

Fig. 16

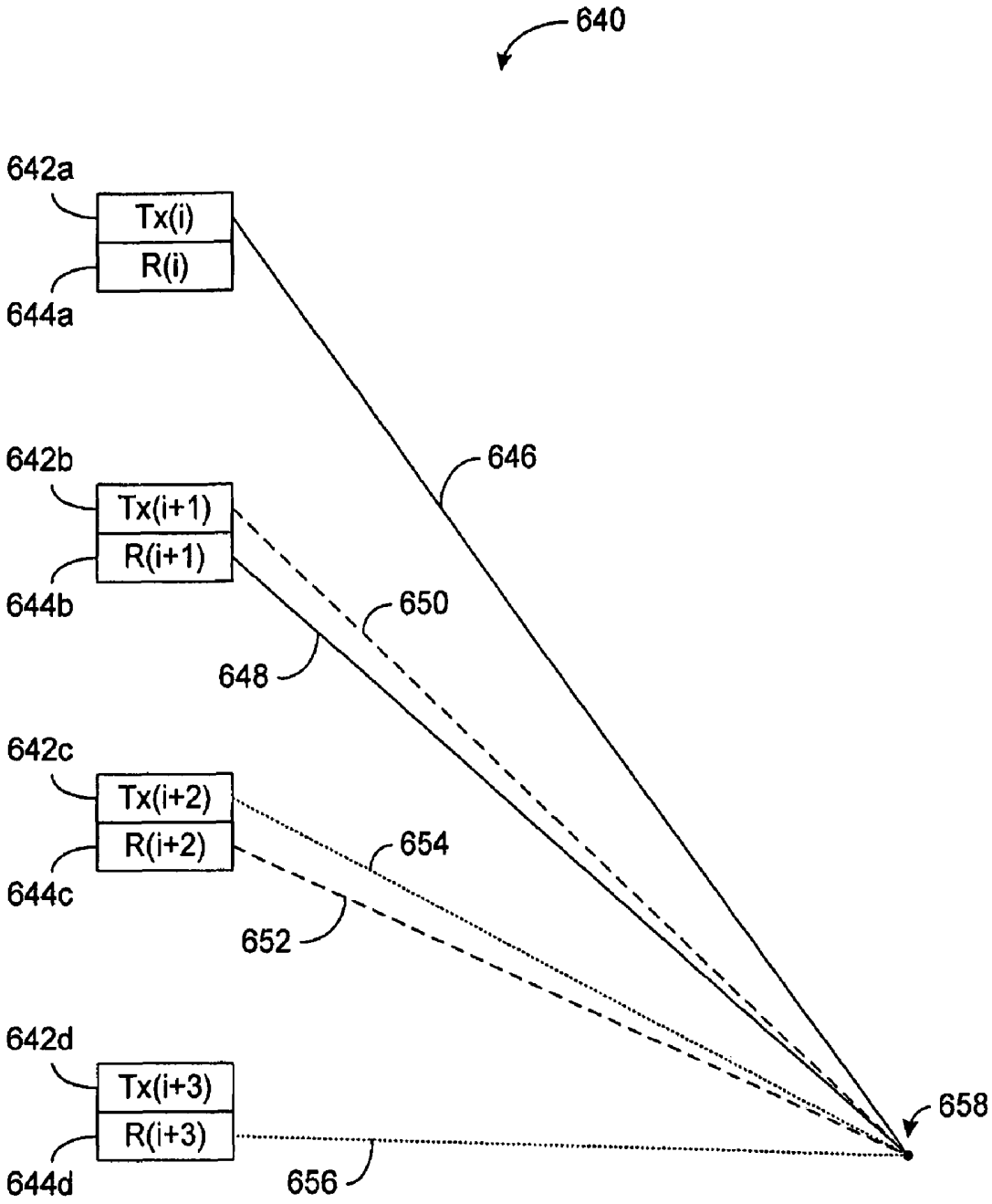

640
642a
Tx(i)
R(i)
644a
642b
Tx(i+1)
R(i+1)
644b
642c
Tx(i+2)
R(i+2)
644c
642d
Tx(i+3)
R(i+3)
644d
646
650
648
654
652
656
658

Fig. 18A

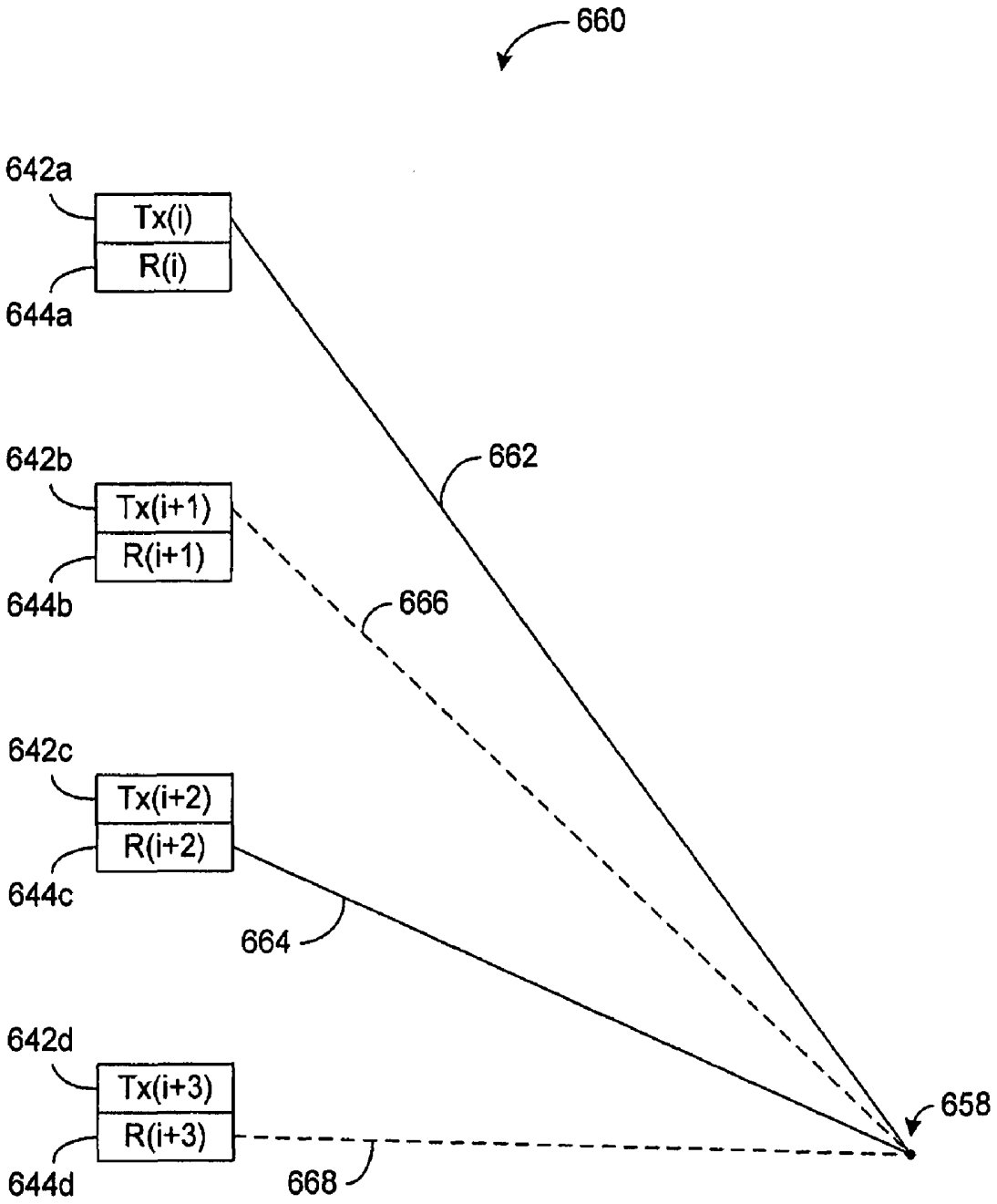

660
642a
Tx(i)
R(i)
644a
642b
Tx(i+1)
R(i+1)
644b
662
666
642c
Tx(i+2)
R(i+2)
644c
664
642d
Tx(i+3)
R(i+3)
644d
668
658

Fig. 18B

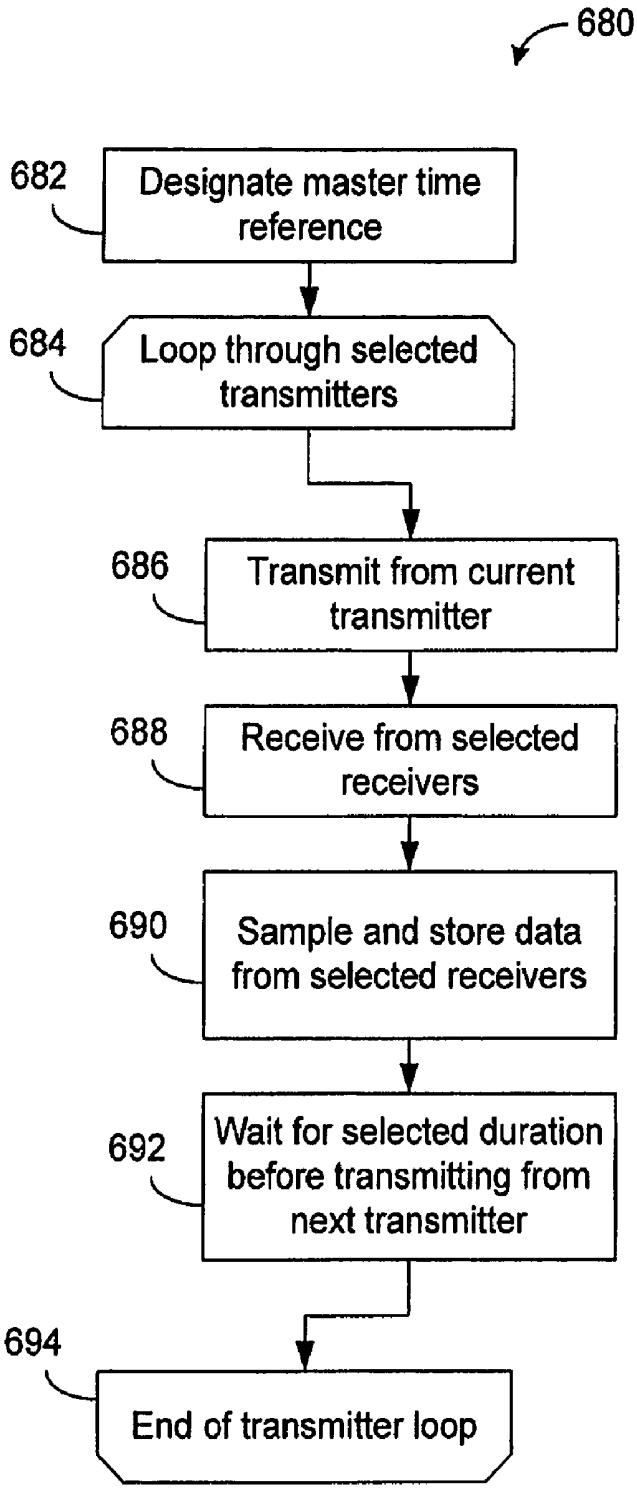

680
682
Designate master time reference
684
Loop through selected transmitters
686
Transmit from current transmitter
688
Receive from selected receivers
690
Sample and store data from selected receivers
692
Wait for selected duration before transmitting from next transmitter
694
End of transmitter loop

Fig. 19

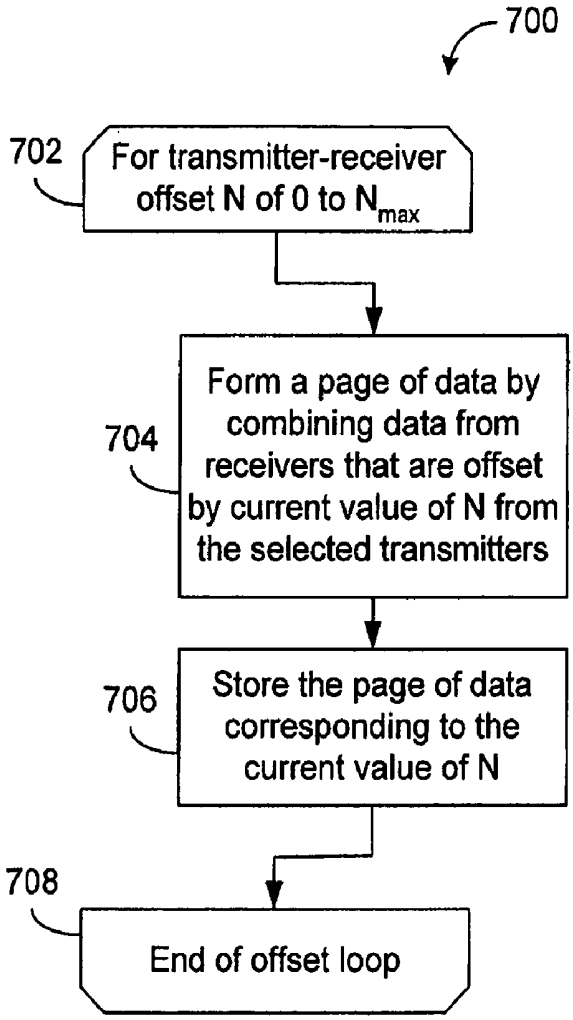

700
702
For transmitter-receiver offset N of 0 to N_{max}
704
Form a page of data by combining data from receivers that are offset by current value of N from the selected transmitters
706
Store the page of data corresponding to the current value of N
708
End of offset loop

Fig. 20

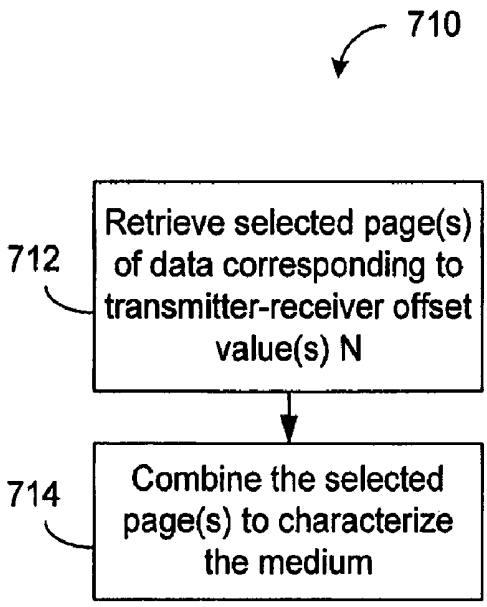

710
712
Retrieve selected page(s) of data corresponding to transmitter-receiver offset value(s) N
714
Combine the selected page(s) to characterize the medium

Fig. 21

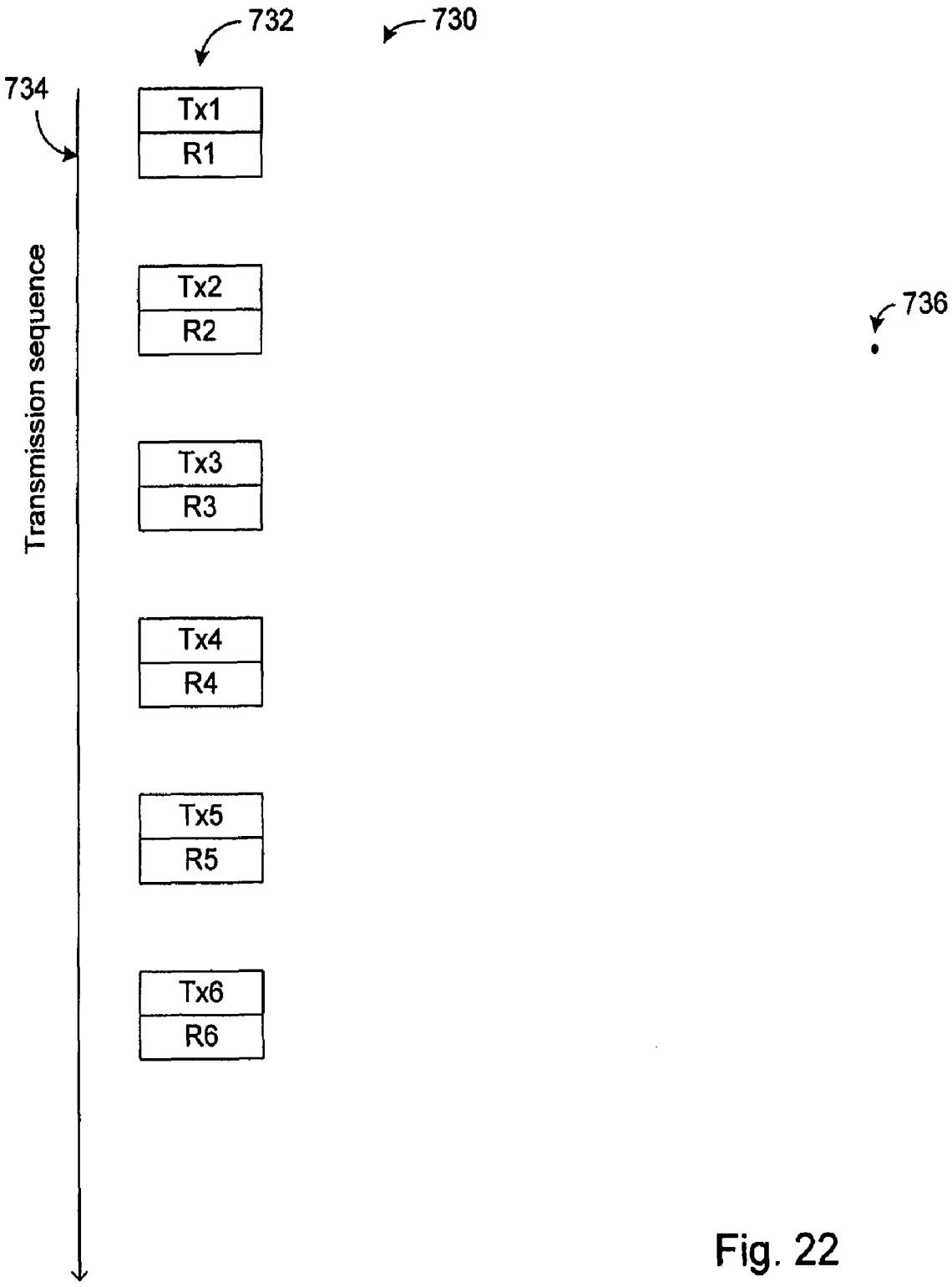

732
730
734
Tx1
R1
Transmission sequence
Tx2
R2
736
Tx3
R3
Tx4
R4
Tx5
R5
Tx6
R6

Fig. 22

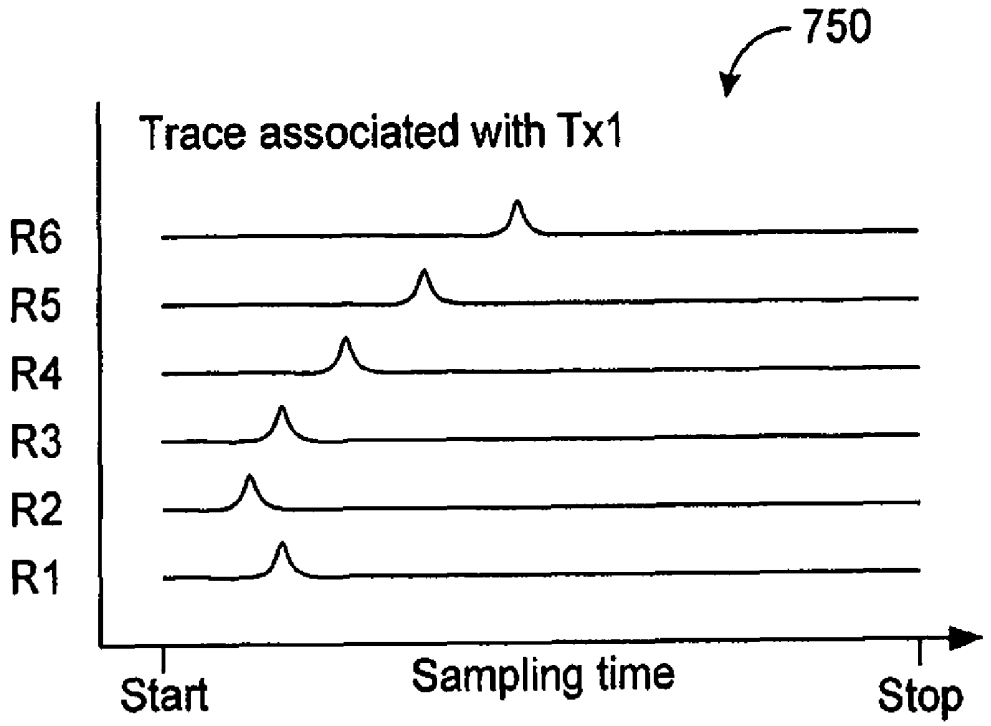


Fig. 23A

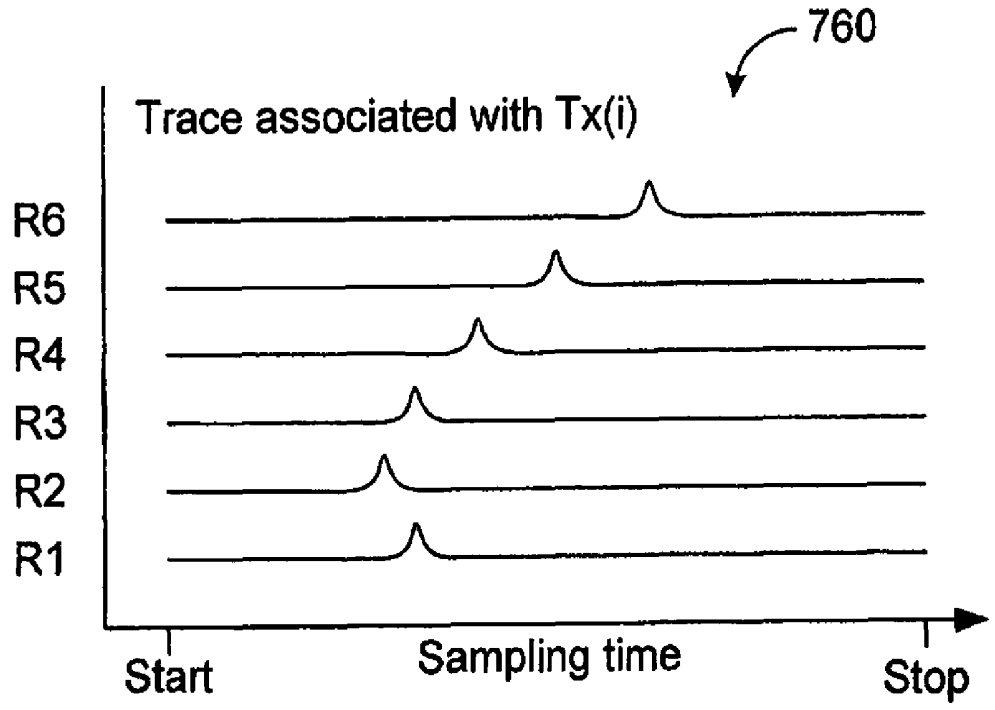


Fig. 23B

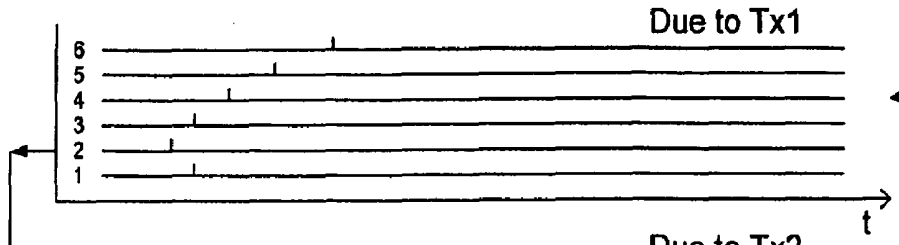


Fig. 24A

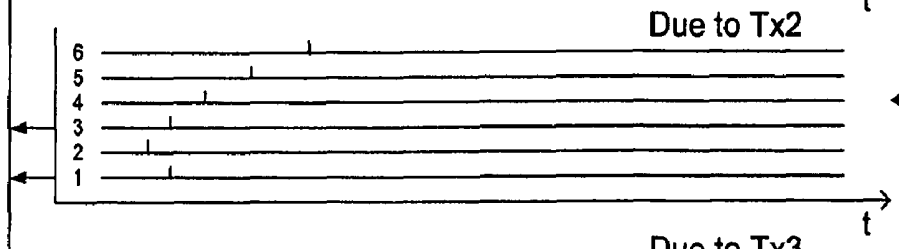


Fig. 24B

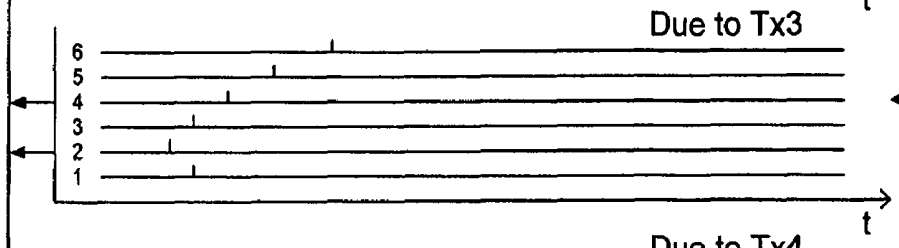


Fig. 24C

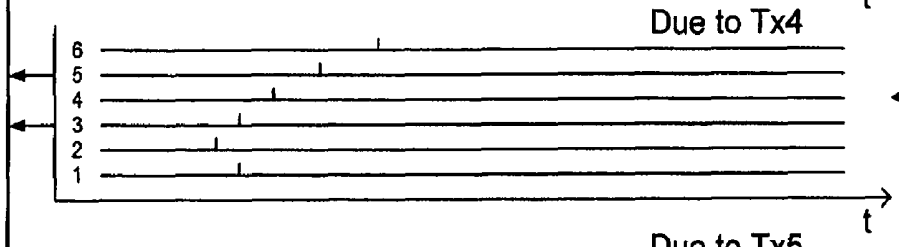


Fig. 24D

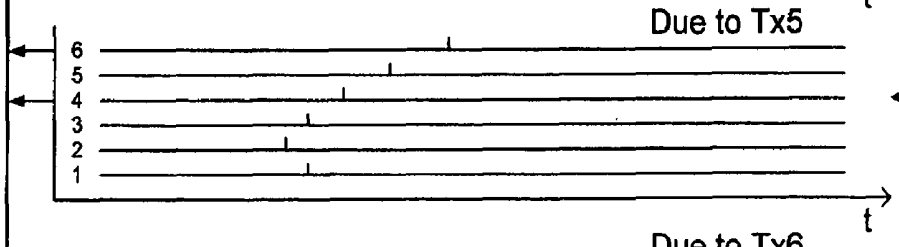


Fig. 24E

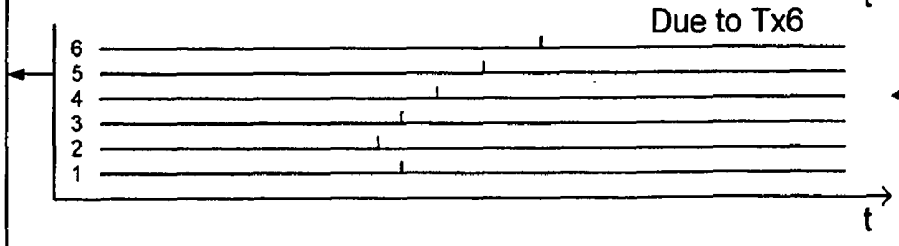


Fig. 24F

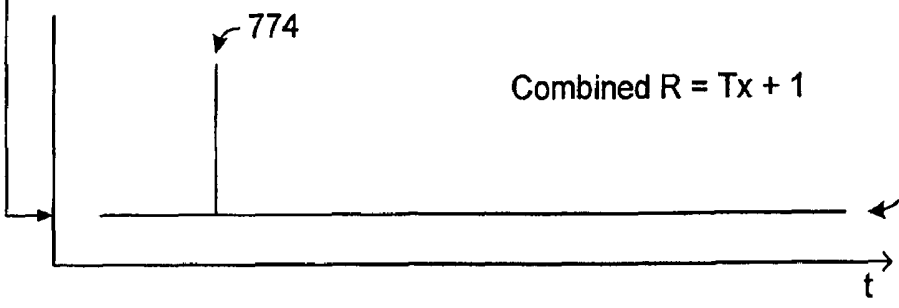


Fig. 24G

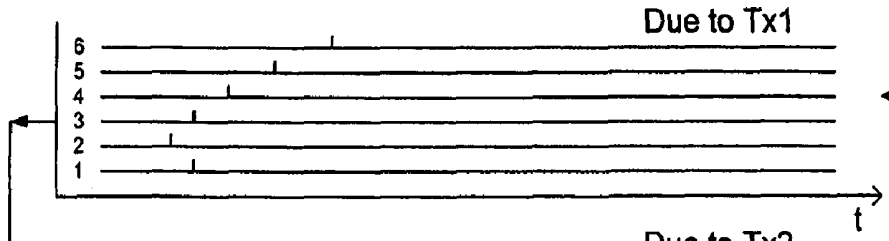


Fig. 25A

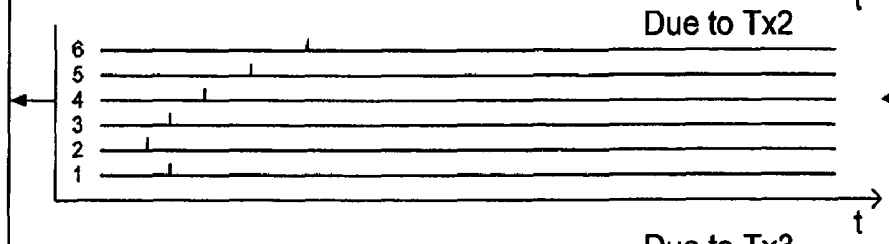


Fig. 25B

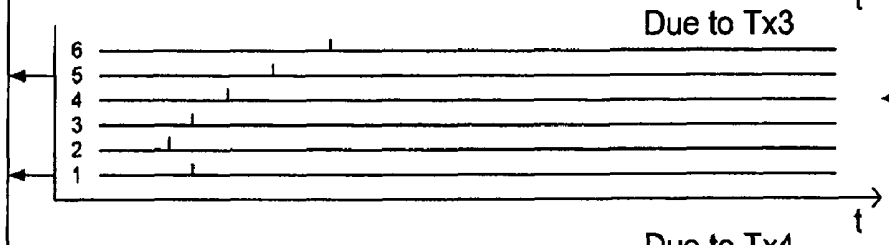


Fig. 25C

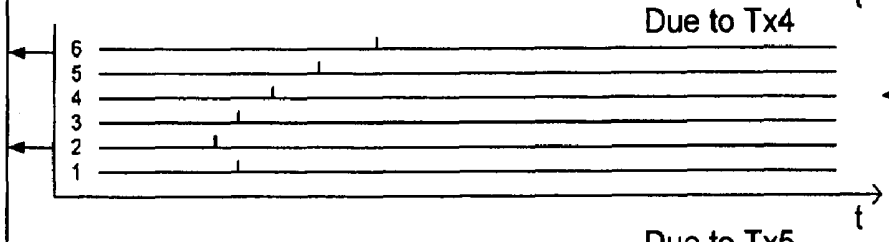


Fig. 25D

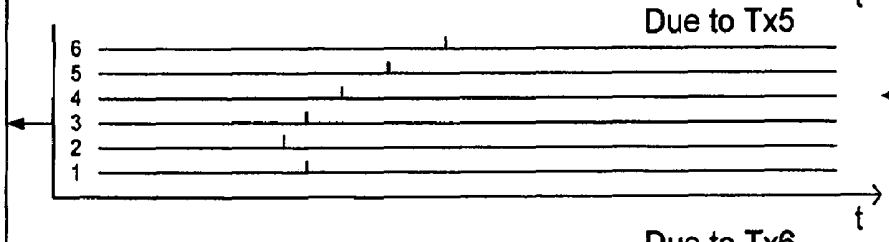


Fig. 25E

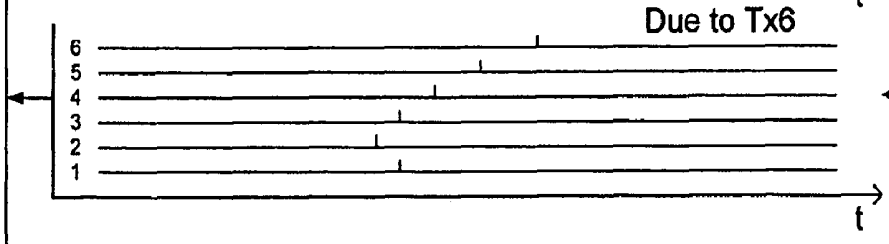


Fig. 25F

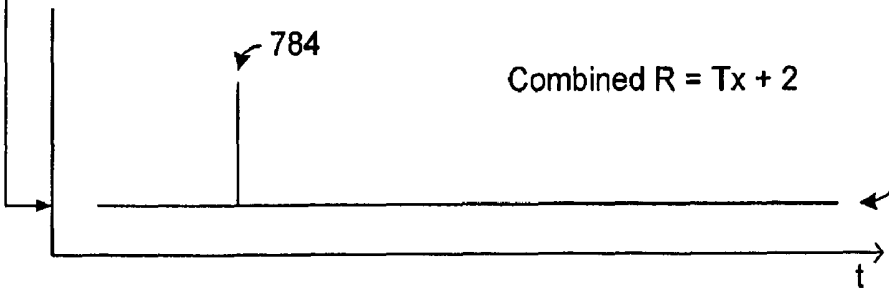


Fig. 25G

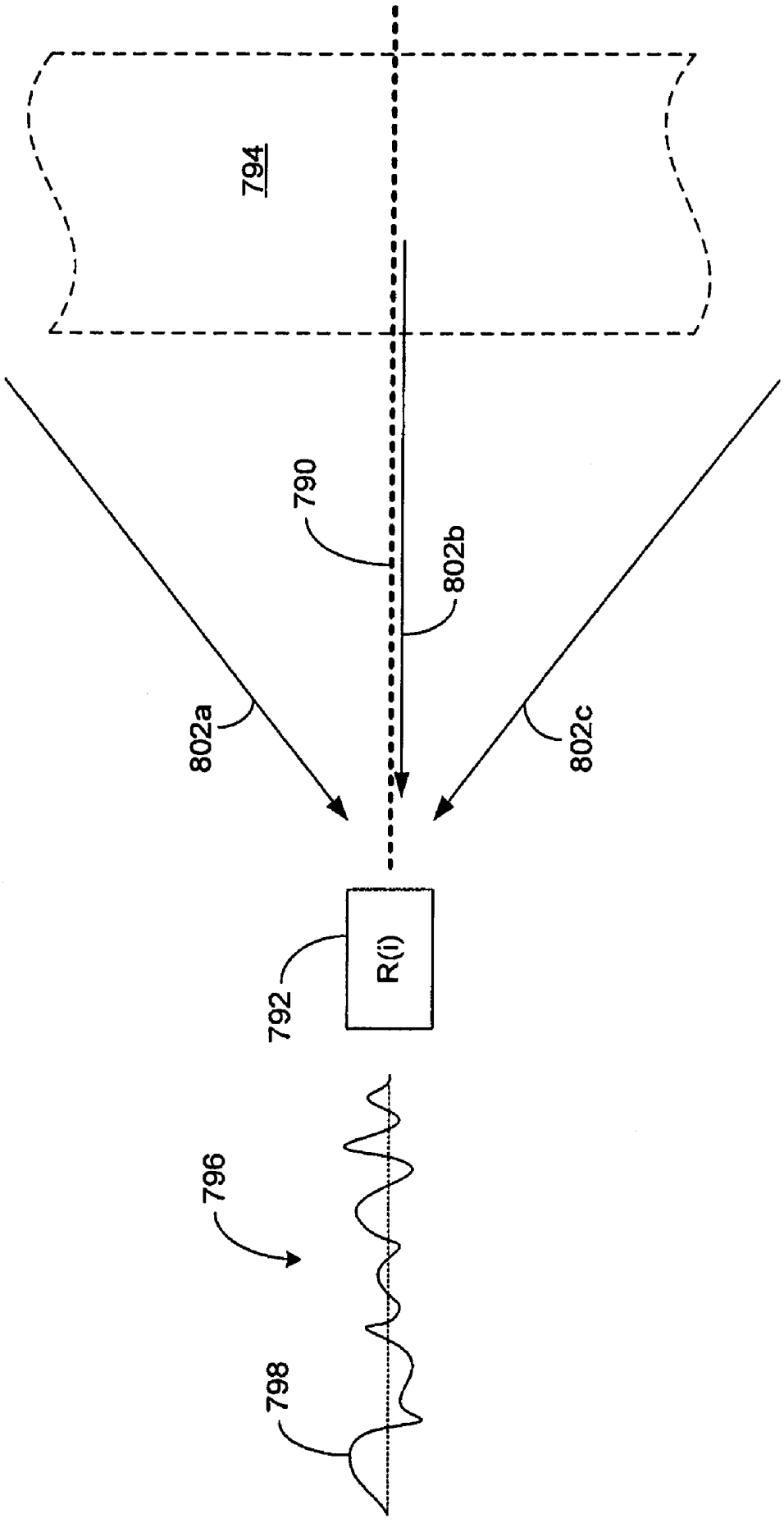


Fig. 26

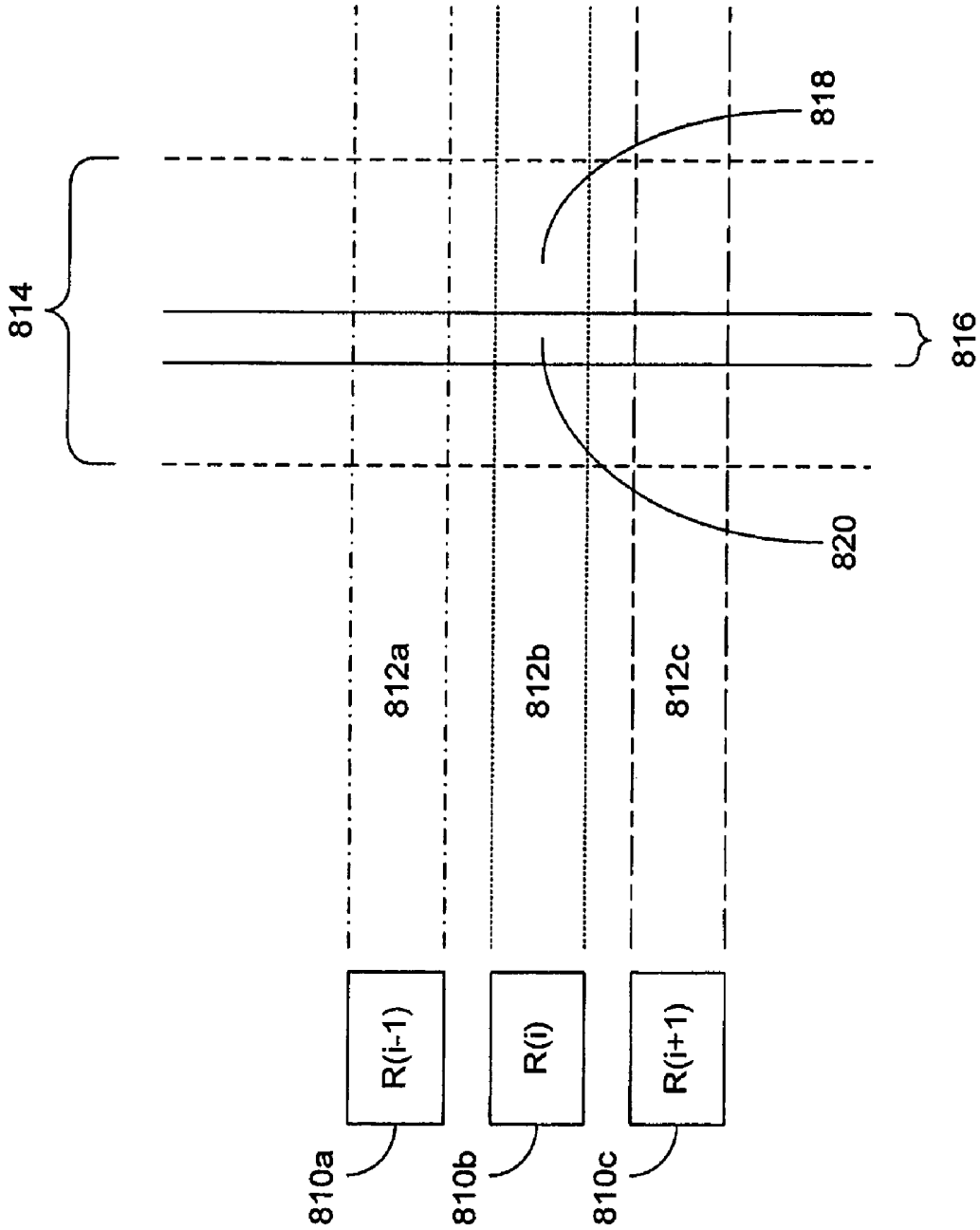


Fig. 27

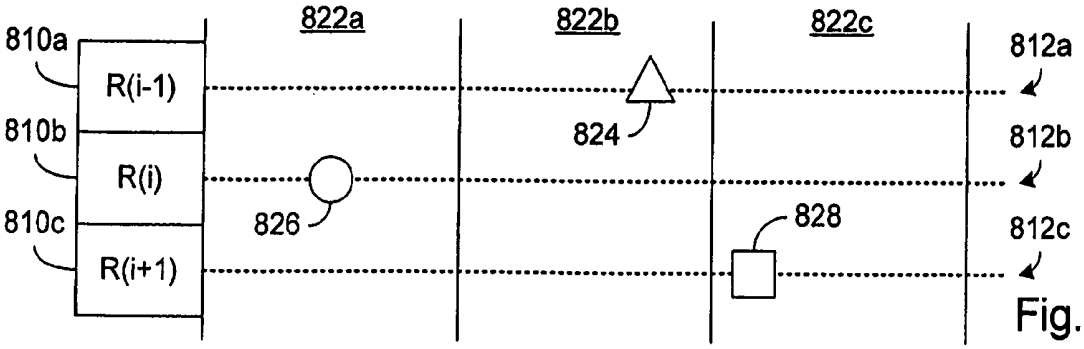


Fig. 28A

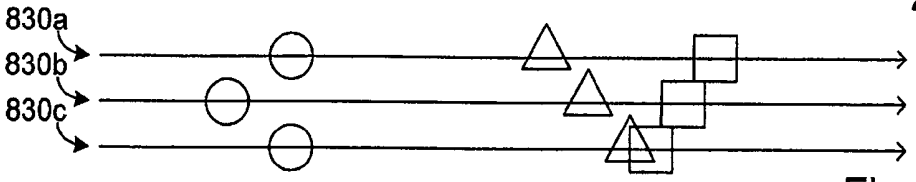


Fig. 28B

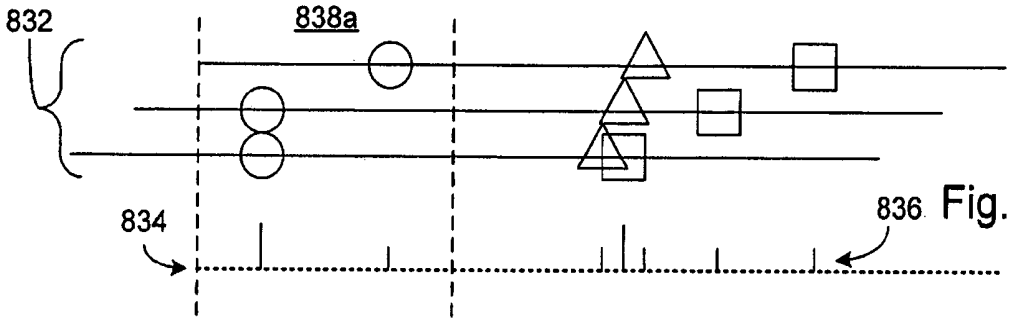


Fig. 28C

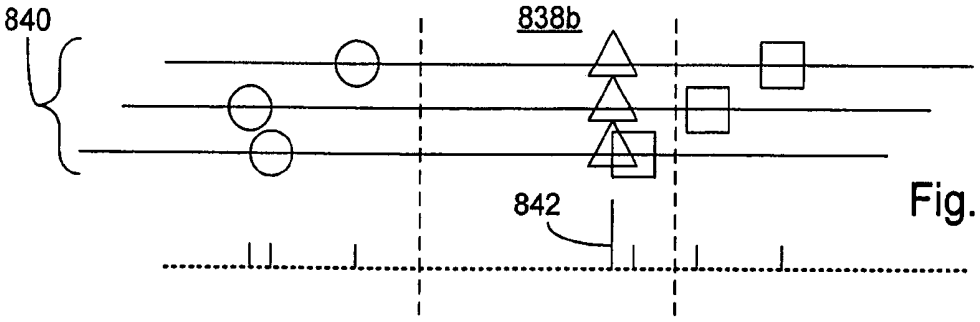
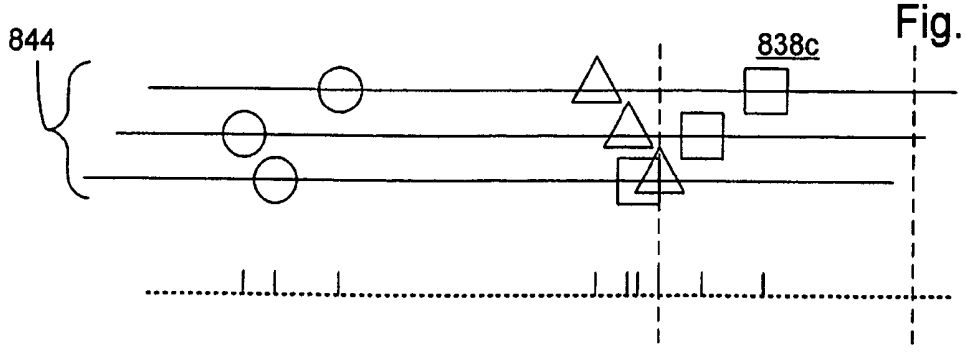


Fig. 28D

Fig. 28E



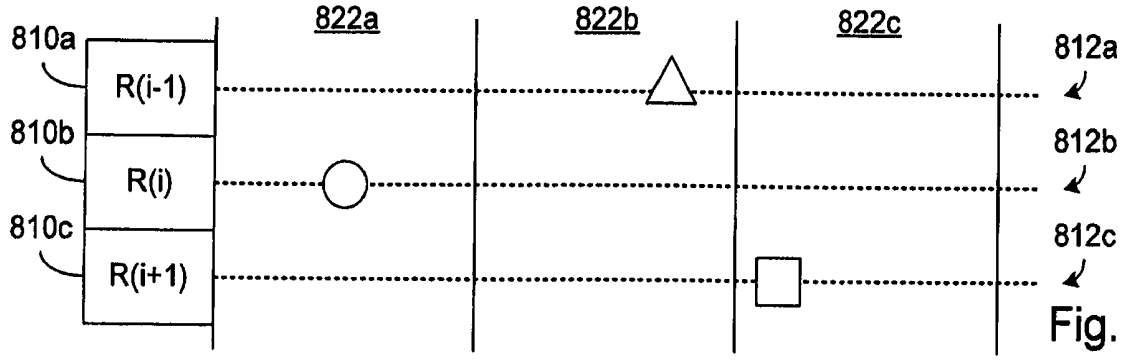


Fig. 29A

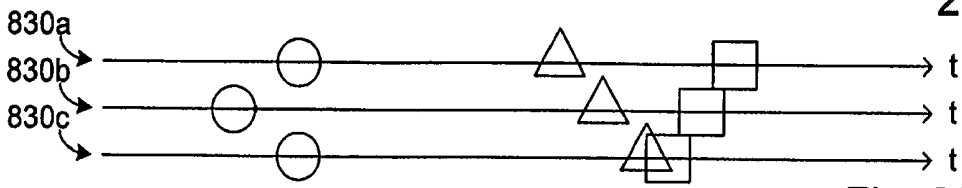


Fig. 29B

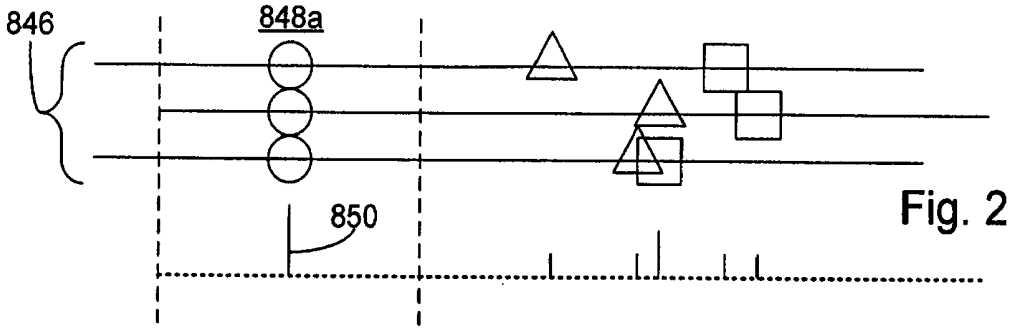


Fig. 29C

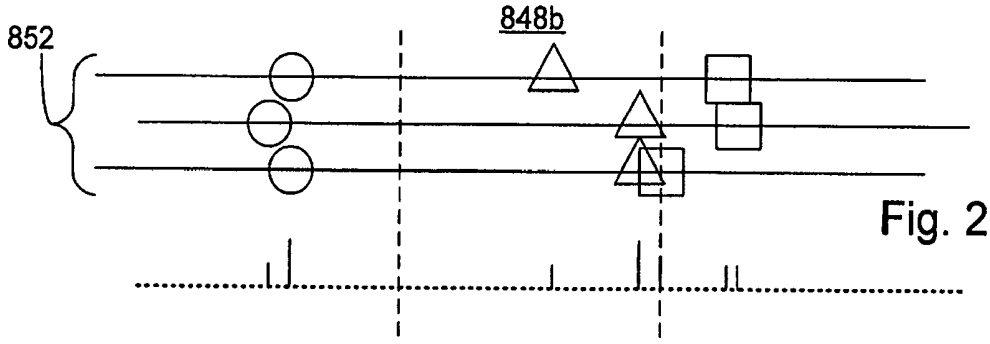
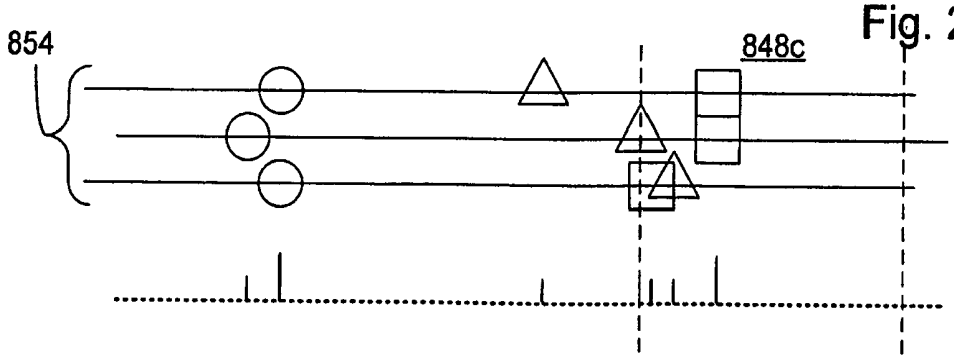


Fig. 29D

Fig. 29E



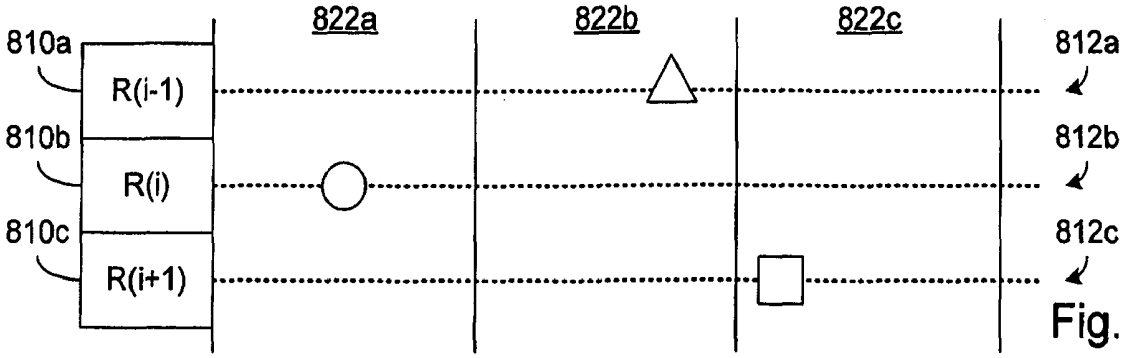


Fig. 30A

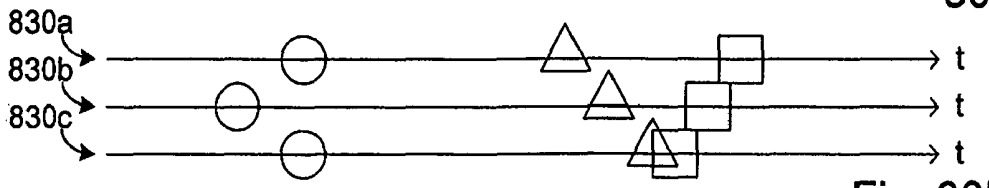


Fig. 30B

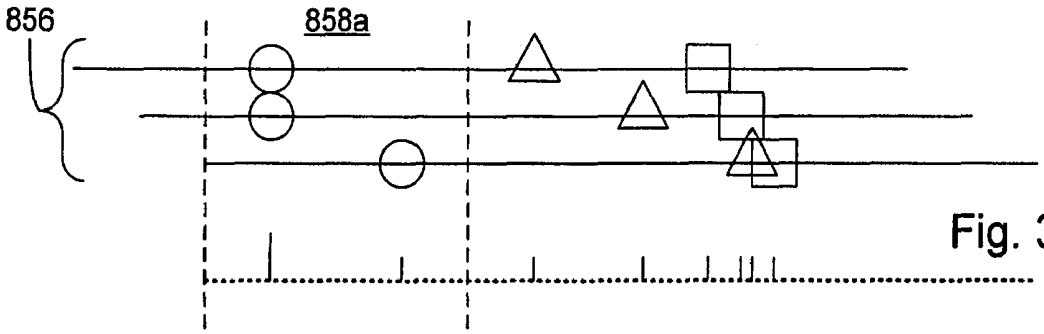


Fig. 30C

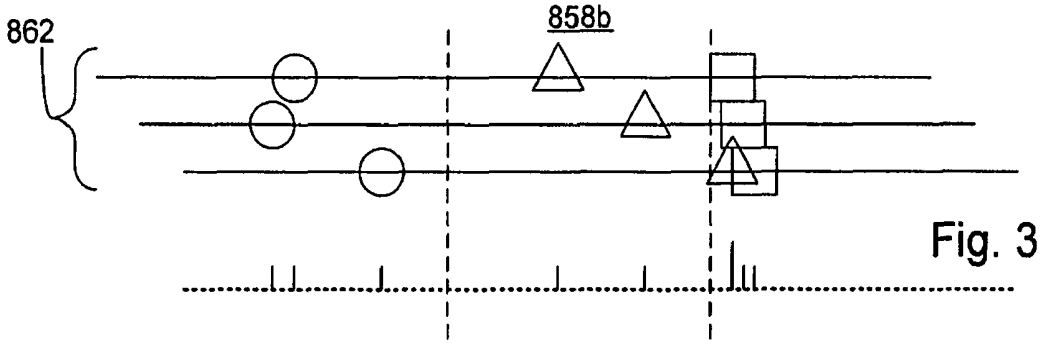
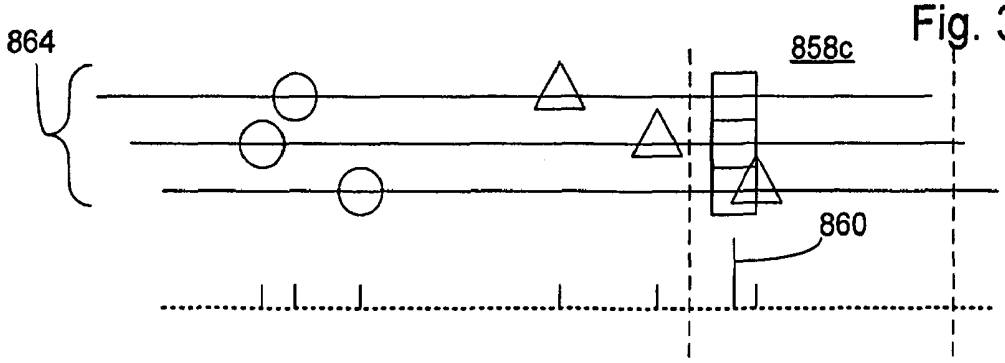


Fig. 30D

Fig. 30E



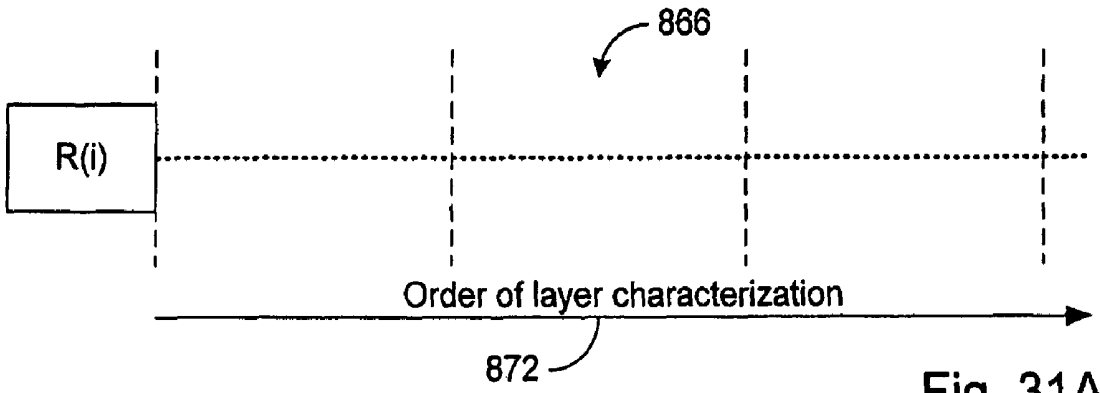


Fig. 31A

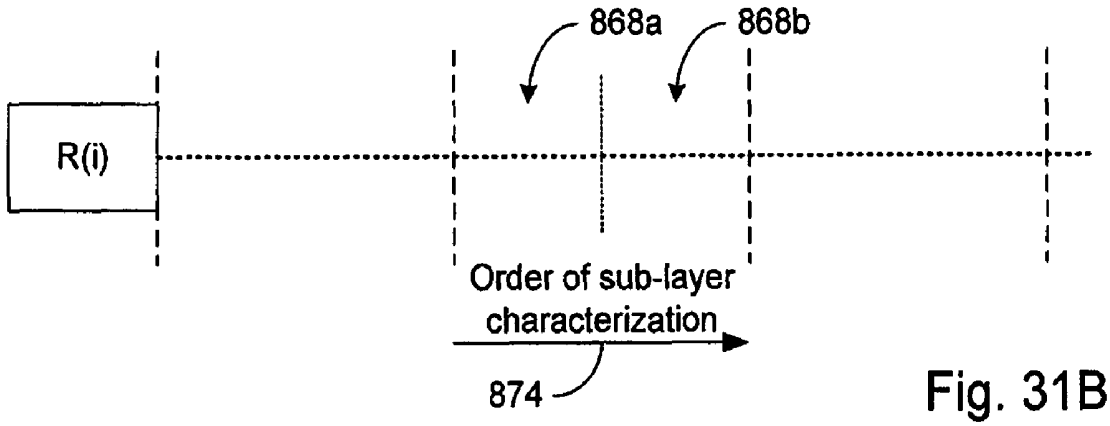


Fig. 31B

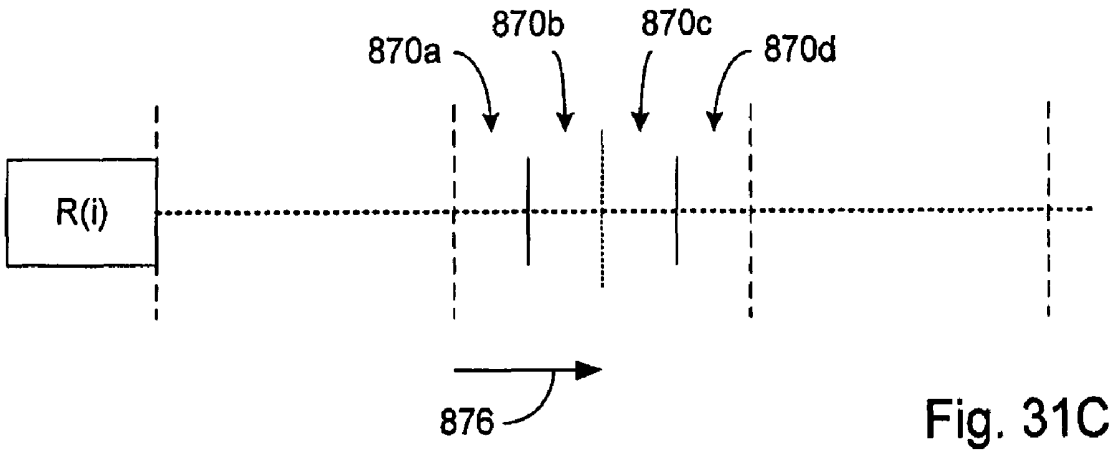


Fig. 31C

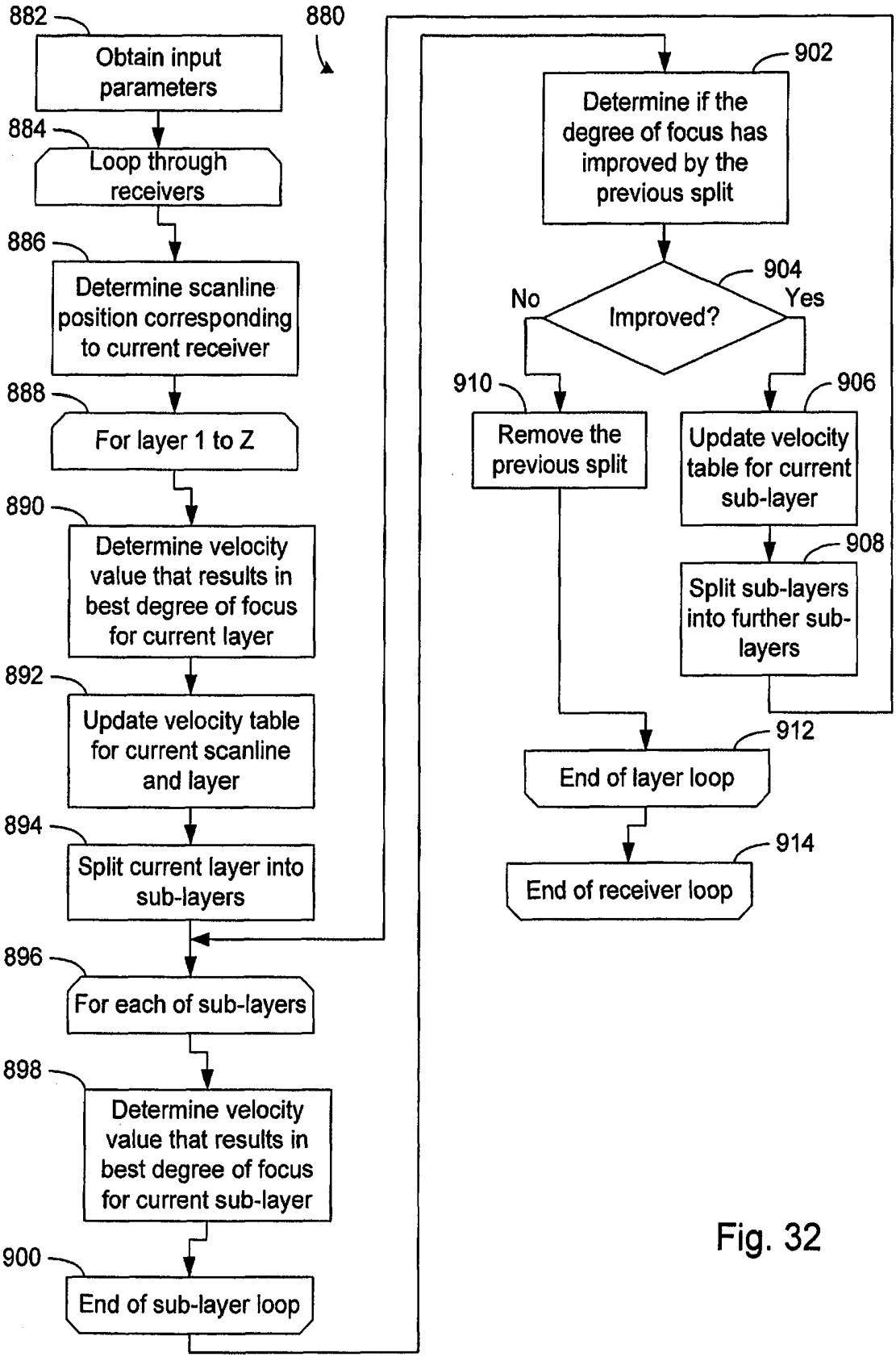

882
Obtain input parameters
880
884
Loop through receivers
886
Determine scanline position corresponding to current receiver
888
For layer 1 to Z
890
Determine velocity value that results in best degree of focus for current layer
892
Update velocity table for current scanline and layer
894
Split current layer into sub-layers
896
For each of sub-layers
898
Determine velocity value that results in best degree of focus for current sub-layer
900
End of sub-layer loop
902
Determine if the degree of focus has improved by the previous split
904
Improved?
No
Yes
910
Remove the previous split
906
Update velocity table for current sub-layer
908
Split sub-layers into further sub-layers
912
End of layer loop
914
End of receiver loop

Fig. 32

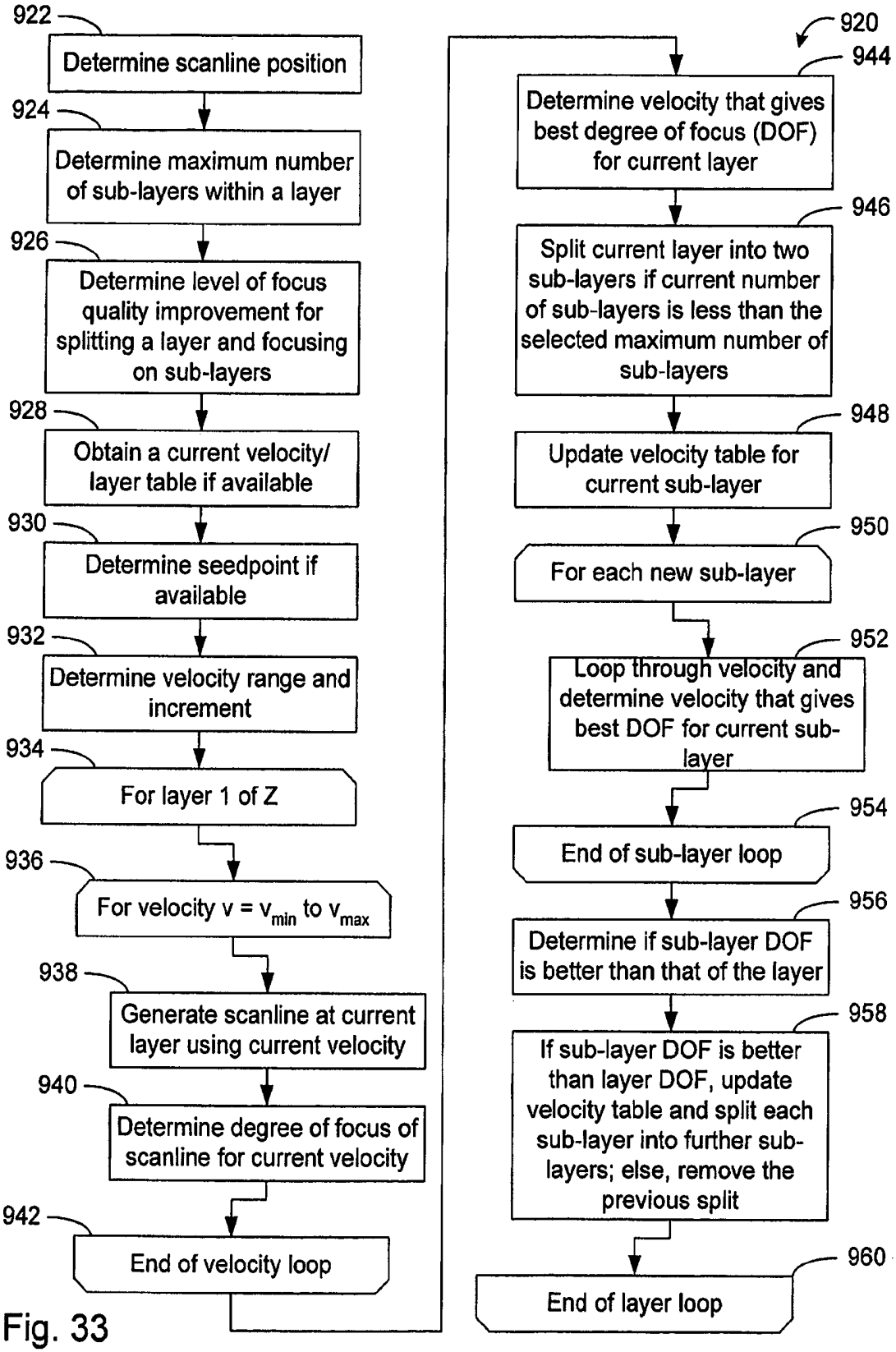

922
Determine scanline position
924
Determine maximum number of sub-layers within a layer
926
Determine level of focus quality improvement for splitting a layer and focusing on sub-layers
928
Obtain a current velocity/ layer table if available
930
Determine seedpoint if available
932
Determine velocity range and increment
934
For layer 1 of Z
936
For velocity v = v_{min} to v_{max}
938
Generate scanline at current layer using current velocity
940
Determine degree of focus of scanline for current velocity
942
End of velocity loop
920
944
Determine velocity that gives best degree of focus (DOF) for current layer
946
Split current layer into two sub-layers if current number of sub-layers is less than the selected maximum number of sub-layers
948
Update velocity table for current sub-layer
950
For each new sub-layer
952
Loop through velocity and determine velocity that gives best DOF for current sub-layer
954
End of sub-layer loop
956
Determine if sub-layer DOF is better than that of the layer
958
If sub-layer DOF is better than layer DOF, update velocity table and split each sub-layer into further sub-layers; else, remove the previous split
960
End of layer loop

Fig. 33

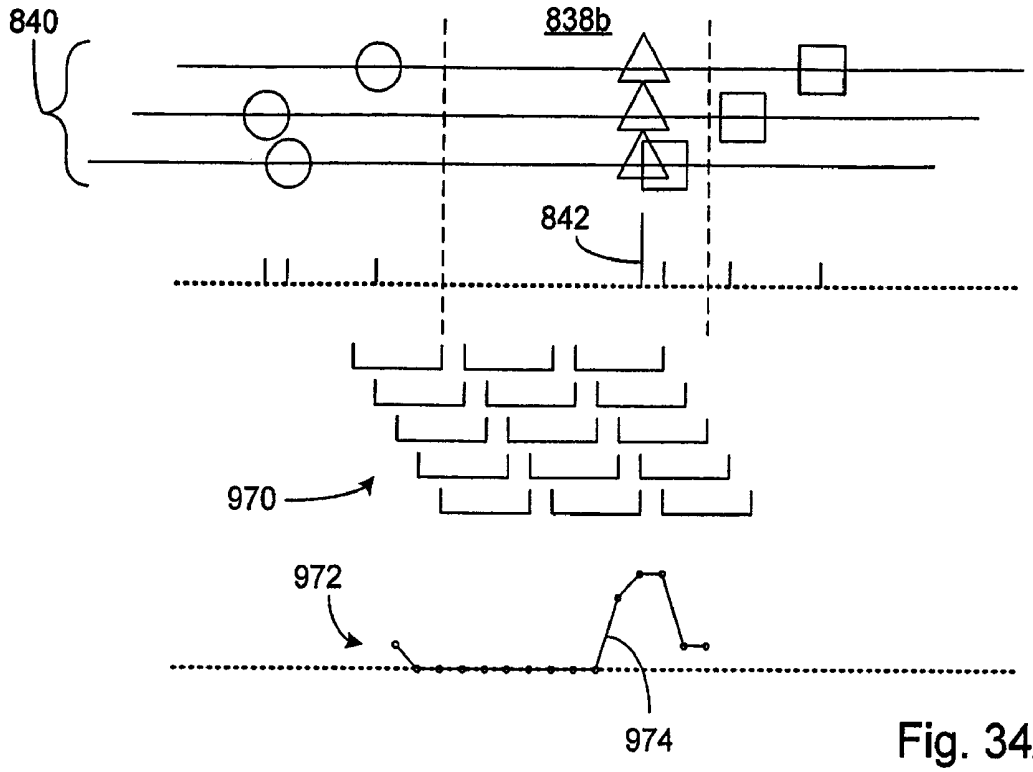


Fig. 34A

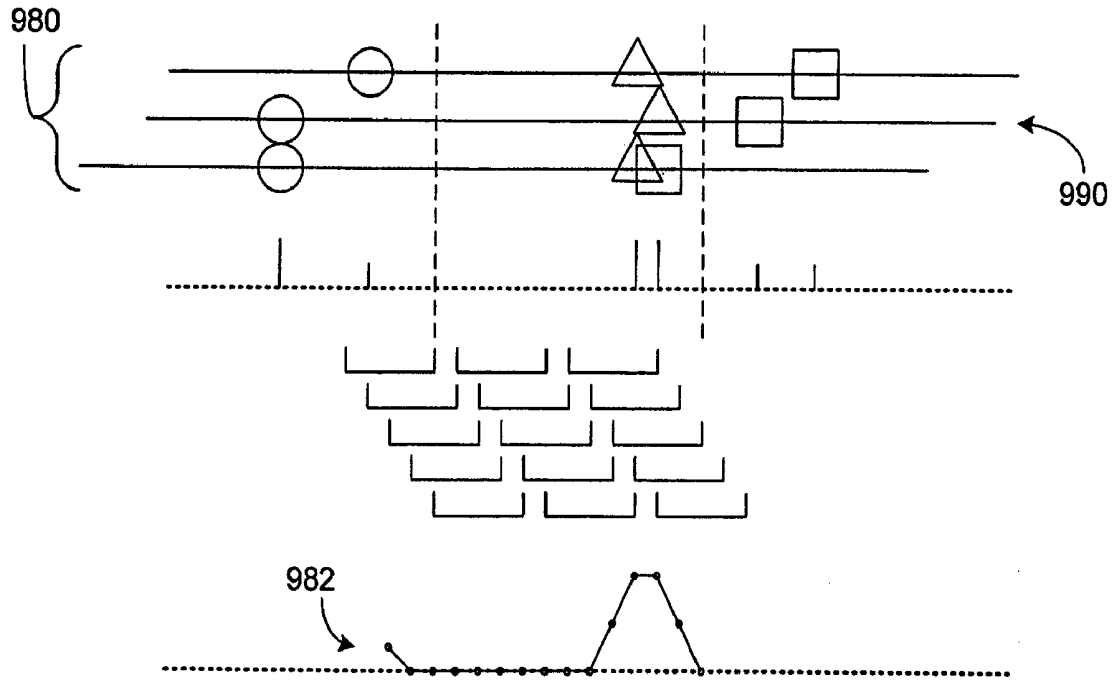


Fig. 34B

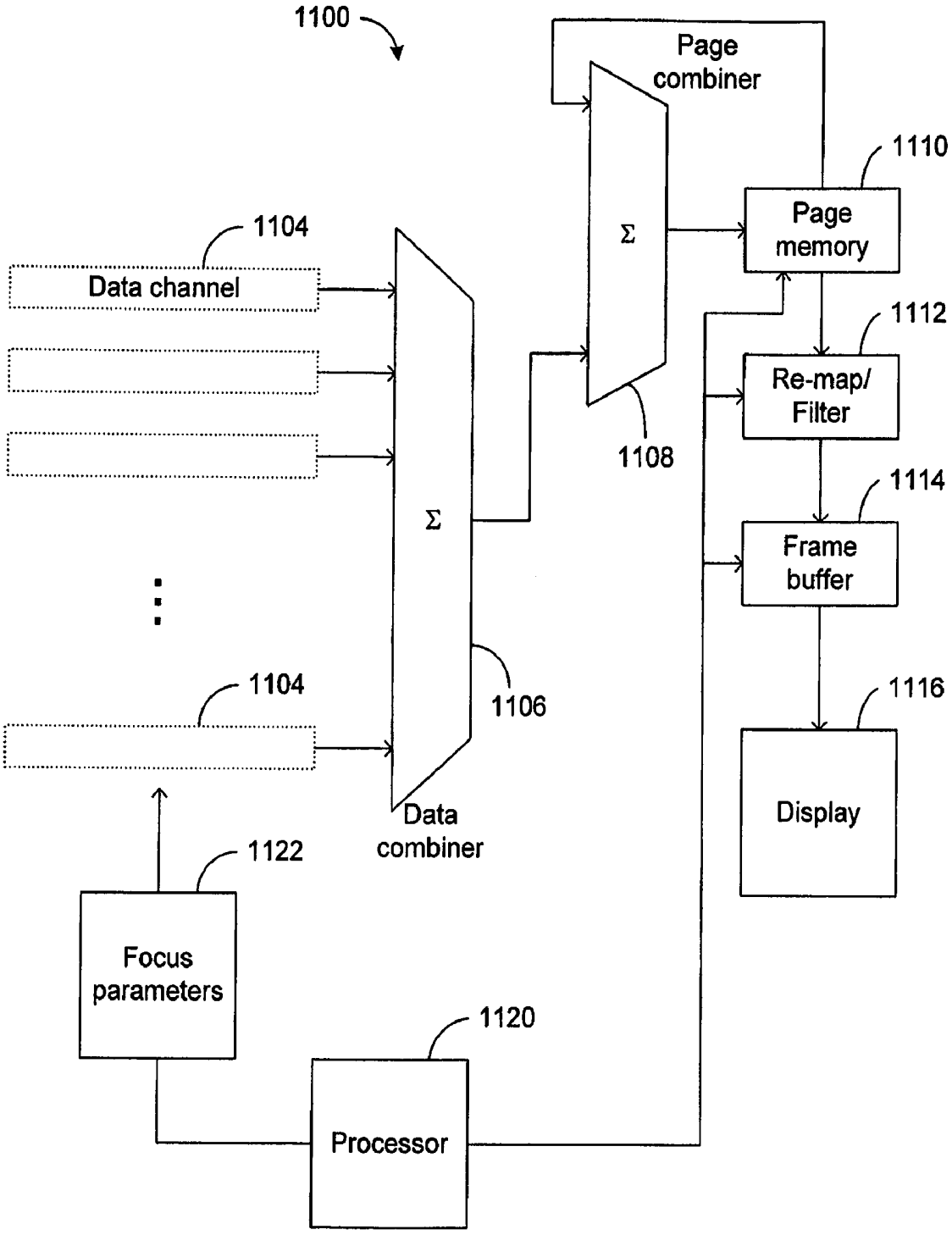

1100
Page combiner
1110
Page memory
1104
Data channel
Σ
1112
Re-map/ Filter
1108
Σ
1114
Frame buffer
1104
1106
1116
Display
Data combiner
1122
Focus parameters
1120
Processor

Fig. 35A

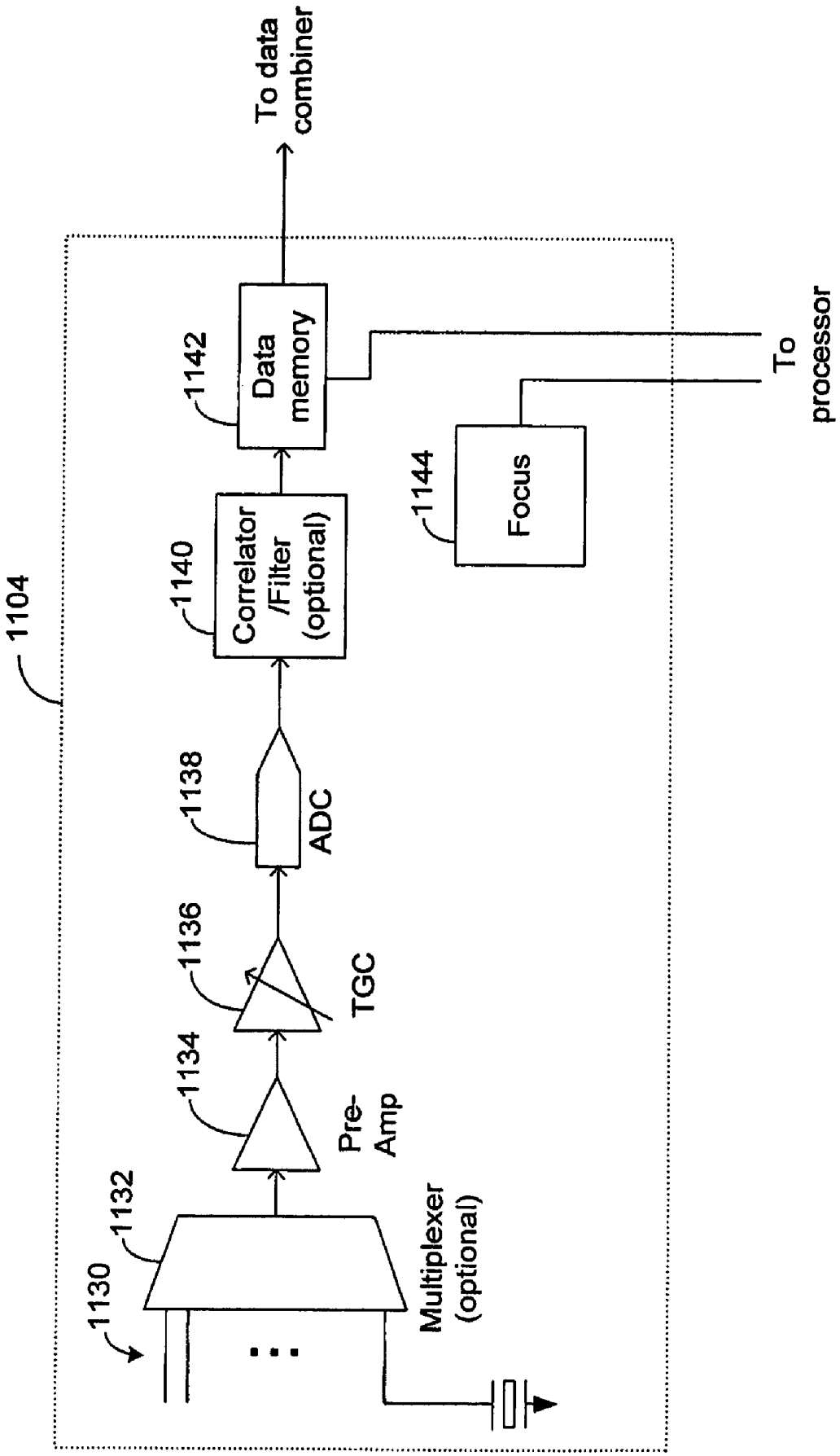

1104
1130
1132
Multiplexer (optional)
1134
Pre-Amp
1136
TGC
1138
ADC
1140
Correlator /Filter (optional)
1142
Data memory
1144
Focus
To data combiner
To processor

Fig. 35B

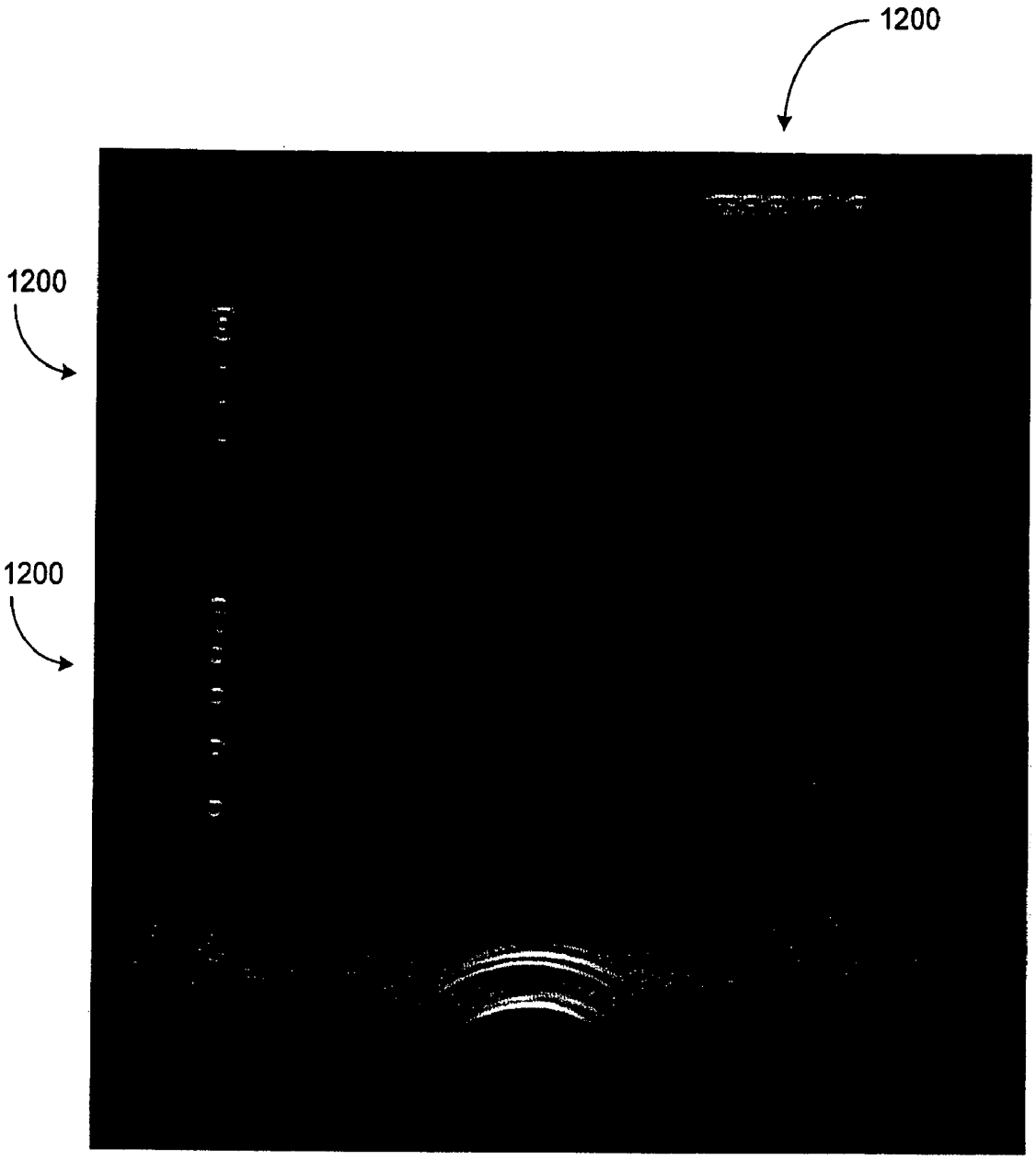


Fig. 36A

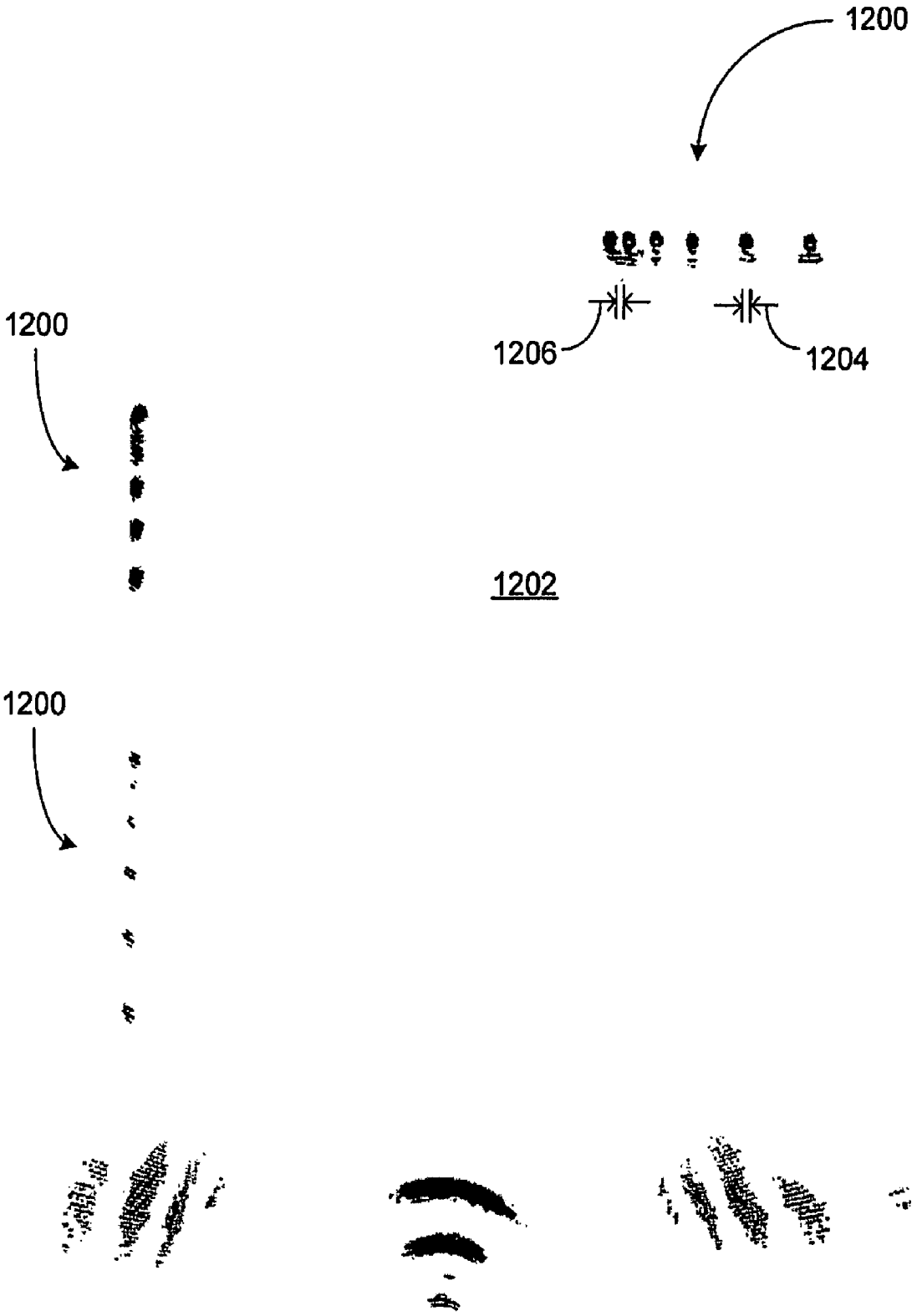


Fig. 36B

SYSTEM AND METHODS FOR IMPROVED ULTRASOUND IMAGING

BACKGROUND

1. Field

The present teachings generally relate to the field of imaging using waves and more particularly, to systems and methods for improving the resolution of images obtained by an array of transmitters and receivers.

2. Description of the Related Art

Imaging devices such as ultrasound devices transmit a signal into a medium, and measure reflections from various features in the medium. An image of a given feature can be reconstructed based on quantities such as intensity and frequency of the reflected signal from that feature. To form the image, one needs to somehow determine the relative location of the feature with respect to the imaging device, and in particular, to a location of a receiving element of the device.

Conventional ultrasound devices typically have an array of transmitter-receiver pairs. In operation, each pair only "sees" along a line, commonly referred to as a scanline, that extends from the pair into the medium. With such an assumption, a feature along that scanline can be brought into "focus" by determining the propagation times of the transmitted and reflected signals to and from the feature. A propagation time t can be calculated as t=d/v where v is the velocity of the signal in the medium, and d is the distance of interest (e.g., from the feature to the receiver). The distance d can be determined by dividing the scanline into discrete elements in a predetermined manner, such that the location of each element is known. The velocity v can either be assumed as a constant in the medium, or can be calculated in a manner generally known in the art.

Based on such an operation, one can see that the resolution and quality of the image formed can be limited by the size of the scanline element. Even if the scanline element can be made arbitrarily small, the effective operation of and obtaining an image from the device is subject to the intrinsic resolution of the transmitter-receiver pair, as well as the sampling criteria for yielding a meaningful result.

The intrinsic resolution of a detector can be expressed as depending on the ratio of the operating wavelength of the signal to the effective dimension of the detector (commonly referred to as a Rayleigh or Sparrow criteria). One can change such a resolution of the detector by either changing the wavelength and/or the effective dimension of the detector. For example, reducing the wavelength (increasing the frequency) and/or increasing the effective dimension of the detector can improve the resolution. However, such a change can be accompanied by undesired effects. For example, an increased frequency signal has a smaller penetration depth in ultrasound applications.

Furthermore, an increased operating frequency also forces the minimum sampling frequency. Commonly known as the Nyquist sampling criteria, a signal needs to be sampled at a frequency that is at least approximately twice the frequency of the operating signal to yield a meaningful result.

Because of the foregoing challenges and limitations, there is an ongoing need to improve the manner in which imaging devices are designed and operated.

SUMMARY

The foregoing needs can be addressed by systems and methods for improving the resolution and quality of an image formed by signals from an array of receivers. Multiple receivers introduce variations in arrival times that can be less than the period of an operating signal, and also less than the period associated with a sampling operation. Thus, multiple receivers allow sampling of fine features of reflected signals that would be considered beyond the resolution associated with the operating signal. Use of multiple receivers also provides an effective sampling rate that is greater than the sampling rate of an individual receiver. Similar advantages can be obtained using multiple transmitters. Such advantageous features can be used to obtain high resolution images of objects in a medium in applications such as ultrasound imaging.

In some embodiments, the present teachings relate to a method of imaging an object in a medium with ultrasound. The method includes transmitting acoustic energy from a transmitter to the object such that the acoustic energy becomes scattered. The method further includes receiving the scattered energy at a plurality of receivers so as to produce respective analog echo signals. The method further includes sampling the analog echo signals at a frequency of F, with each of the sampled analog echo signals includes substantial spectral frequency components above a frequency of F/2. Such sampling produces a respective plurality of digital echo signals. The method further includes combining the plurality of digital echo signals, with each of the digital echo signals being offset by time with respect to another of the digital echo signals, so as to produce a combined digital signal that is selected from a plurality of different combinations of the plurality of digital echo signals. The method further includes producing an image pixel of the object from the combined digital signal.

In one embodiment, the method further includes producing a plurality of image pixels from the plurality of different combinations of the plurality of digital echo signals. The plurality of pixels distinctly depicts two objects in the medium that are closer together than 4F divided into an average velocity of sound in the medium. In one embodiment, such a method can distinctly depict two objects in the medium that are closer together than approximately 100 micrometers when the acoustic energy has a central peak frequency of approximately 3.5 MHz.

In one embodiment of the method, the substantial spectral frequency components above a frequency of F/2 include a higher frequency having an intensity that is above a predetermined value. Such a predetermined value can have different values, such as 50 dB, 40 dB, 30 dB, 20 dB, 10 dB, or 10 dB less than a maximum intensity of the spectral frequency components of one of the sampled analog echo signals.

In one embodiment of the method, the step of combining the plurality of digital echo signals includes selecting a first digital echo signal associated with a first receiver. The step further includes performing a plurality of time-shift combinations of the first digital echo signal with one or more digital echo signals associated with one or more other receivers about a selected time window of the first signal. Each of the plurality of combinations has a quality value indicative of a quality of the combination.

In one embodiment of the method, the step of combining the plurality of digital echo signals further includes assigning one of the plurality of combinations having a particular quality value to a scanline for the first receiver. In one embodiment, the selected time window corresponds to a layer having a first thickness along the scanline. In one embodiment, the particular quality value includes a running average of an amplitude of the one of the plurality of combinations. In one embodiment, the particular quality value includes a slope of a running average of an amplitude with respect to time of the one of the plurality of combinations.

In one embodiment of the method, the step of combining the plurality of digital echo signals further includes splitting a parent layer into two or more sublayers and performing time-shift combinations on each of the sublayers. The step further includes determining a best quality value for each of the sublayers. The step further includes comparing a best quality value of the parent layer to the best quality value of each of the sublayers. If the best quality value of the parent layer is substantially less than the best quality value of each of the sublayers, then the step further includes continuing to divide each of the sublayers into final sublayers, where each of the best quality values of the final sublayers is less than the best quality value of a parent layer of the final sublayers. In one embodiment, the step further includes assigning a combined digital signal of the parent layer of the final sublayers to the scanline.

In one embodiment of the method, the scanline is divided into a plurality of layers, and determinations of the particular qualities of the combinations are performed successively starting from a layer closest to the receiver.

In some embodiments, the present teachings relate to a method of imaging an object with ultrasound. The method includes providing an array of transmitters Tx(i), where i represents a relative positional index that ranges from 1 to N, and where N is greater than or equal to 2. The method further includes providing an array of receivers Rx(i), where each of the receivers Rx(i) associated with a respective transmitter Tx(i). The method further includes transmitting ultrasound energy from the transmitters to the object such that the ultrasound energy is scattered. The method further includes receiving scattered energy at every receiver Rx(i+j) that was transmitted from transmitter Tx(i), where j represents a relative positional offset from i, and where j is greater than zero. The method further includes generating a first plurality of signals in response to the scattered energies received at every receiver Rx(i+j). The method further includes combining the plurality of signals so as to produce an image of the object.

In one embodiment the method, the value of j is one. In one embodiment, the method further includes receiving scattered energy at every receiver Rx(i+k) that was transmitted from transmitter Tx(i), where k represents a relative positional offset from i, and where k is greater than zero and is not equal to j. The method further includes generating a second plurality of signals in response to the scattered energies received at every receiver Rx(i+j) and Rx(i+k). The method further includes combining the first and second pluralities of signals so as to produce an image of the object.

In some embodiments, the present teachings relate to an ultrasound imaging apparatus that includes a plurality of transmitters configured to transmit acoustic energy to one or more objects in a medium such that the acoustic energy becomes scattered. The apparatus further includes a plurality of receivers configured to receive the scattered energy and in response produce respective analog echo signals. The apparatus further includes a processor that causes sampling of the analog echo signals at a frequency of F, where each of the sampled analog echo signals include substantial spectral frequency components above a frequency of F/2. The sampling produces a respective plurality of digital echo signals. The processor further causes combining of the plurality of digital echo signals, with each of the digital echo signals being offset by time with respect to another of the digital echo signals, so as to produce a combined digital signal that is selected from a plurality of different combinations of the plurality of digital echo signals. The processor further causes production of an image pixel of the object from the combined digital signal.

In one embodiment of the apparatus, the processor further causes production of a plurality of image pixels from the plurality of different combinations of the plurality of digital echo signals. The plurality of pixels distinctly depict two objects in the medium that are closer together than 4F divided into an average velocity of sound in the medium. In one embodiment, such an apparatus can distinctly depict two objects in the medium that are closer together than approximately 100 micrometers when the acoustic energy has a central peak frequency of approximately 3.5 MHz.

In one embodiment of the apparatus, the substantial spectral frequency components above a frequency of F/2 include a higher frequency having an intensity that is above a predetermined value. Such a predetermined value can have different values, such as 50 dB, 40 dB, 30 dB, 20 dB, 10 dB, or 10 dB less than a maximum intensity of the spectral frequency components of one of the sampled analog echo signals.

In one embodiment of the apparatus, the processor causes combining of the plurality of digital echo signals by a process that selects a first digital echo signal associated with a first receiver. The process further performs a plurality of time-shift combinations of the first digital echo signal with one or more digital echo signals associated with one or more other receivers about a selected time window of the first signal. Each of the plurality of combinations has a quality value indicative of a quality of the combination.

In one embodiment of the apparatus, the process further includes assigning one of the plurality of combinations having a particular quality value to a scanline for the first receiver. In one embodiment, the selected time window corresponds to a layer having a first thickness along the scanline. In one embodiment, the particular quality value includes a running average of an amplitude of the one of the plurality of combinations. In one embodiment, the particular quality value includes a slope of a running average of an amplitude with respect to time of one of the plurality of combinations.

In one embodiment of the apparatus, the process further includes splitting a parent layer into two or more sublayers, and performing time-shift combinations on each of the sublayers. The process further includes determining a best quality value for each of the sublayers. The process further includes comparing a best quality value of the parent layer to the best quality value of each of the sublayers. If the best quality value of the parent layer is substantially less than the best quality value of each of the sublayers, then the process continues to divide each of the sublayers into final sublayers. Each of the best quality values of the final sublayers is less than the best quality value of a parent layer of the final sublayers.

In one embodiment of the apparatus, the process further includes a combined digital signal of the parent layer of the final sublayers to the scanline. In one embodiment, the scanline is divided into a plurality of layers, and the determinations of the particular qualities of the combinations are performed successively starting from a layer closest to the receiver.

In some embodiments, the present teachings relate to an ultrasound imaging apparatus that includes a transducer assembly having a plurality of transmitting elements and a plurality of receiving elements. The plurality of transmitting elements are configured to transmit ultrasound energy, having a wavelength λ corresponding to a central peak frequency of the ultrasound energy, toward a region in a medium. The plurality of receiver elements generate a plurality of signals in response to scattered energy from the region. An aperture size D of the transducer assembly is the maximum distance between any two receiving elements in the transducer assem-

bly. The apparatus further includes a processor configured to sample the plurality of signals to produce a plurality of corresponding digital echo signals. The processor is further configured to combine the plurality of digital echo signals to generate an image having a spatial resolution limit that is equal to or better than $\theta=(0.25)\lambda/D$, where θ is the minimum resolvable angular separation of two objects in the medium.

In one embodiment of the apparatus, the spatial resolution limit allows resolving of two objects in the medium that are closer together than approximately 100 micrometers when the ultrasound energy has a central peak frequency of approximately 3.5 MHz. In one embodiment, the processor combines the plurality of digital echo signals by a process that includes selecting a first digital echo signal associated with a first receiver, and performing a plurality of time-shift combinations of the first digital echo signal with one or more digital echo signals associated with one or more other receivers about a selected time window of the first signal. Each of the plurality of combinations has a quality value indicative of a quality of the combination.

In one embodiment of the apparatus, the process further includes assigning one of the plurality of combinations having a particular quality value to a scanline for the first receiver. In one embodiment, the selected time window corresponds to a layer having a first thickness along the scanline. In one embodiment, the particular quality value includes a running average of an amplitude of the one of the plurality of combinations. In one embodiment, the particular quality value includes a slope of a running average of an amplitude with respect to time of the one of the plurality of combinations.

In one embodiment of the apparatus, the process further includes splitting a parent layer into two or more sublayers, and performing time-shift combinations on each of the sublayers. The process further includes determining a best quality value for each of the sublayers. The process further includes comparing a best quality value of the parent layer to the best quality value of each of the sublayers. If the best quality value of the parent layer is substantially less than the best quality value of each of the sublayers, then the process further includes continuing to divide each of the sublayers into final sublayers, where each of the best quality values of the final sublayers is less than the best quality value of a parent layer of the final sublayers.

In one embodiment of the apparatus, the process further includes assigning a combined digital signal of the parent layer of the final sublayers to the scanline. In one embodiment, the scanline is divided into a plurality of layers, and determinations of the particular qualities of the combinations are performed successively starting from a layer closest to the receiver.

In some embodiments, the present teachings relate to a method of imaging with ultrasound. The method includes transmitting ultrasound energy, having a wavelength X corresponding to a central peak frequency of the ultrasound energy, from a plurality of transmitters in a transducer assembly into a medium such that the transmission energy is scattered. An aperture size D of the transducer assembly is the maximum distance between any two transmitters in the transducer assembly. The method further includes receiving scattered energies from the medium at a plurality of receivers. The method further includes digitally combining signals generated from the scattered energies so as to produce an image having a spatial resolution limit that is equal to or better than $\theta=(0.25)\lambda/D$, where θ is the minimum resolvable angular separation of two objects in the medium.

In one embodiment of the method, the spatial resolution limit allows resolving of the two objects in the medium that are closer together than approximately 100 micrometers when the ultrasound energy has a central peak frequency of approximately 3.5 MHz. In one embodiment, the step of digitally combining the signals includes digitally sampling the signals so as to produce a plurality of digital echo signals. The step further includes selecting a first digital echo signal associated with a first receiver. The step further includes performing a plurality of time-shift combinations of the first digital echo signal with one or more digital echo signals associated with one or more other receivers about a selected time window of the first signal. Each of the plurality of combinations has a quality value indicative of a quality of the combination.

In one embodiment of the method, the step of digitally combining the signals further includes assigning one of the plurality of combinations having a particular quality value to a scanline for the first receiver. In one embodiment, the selected time window corresponds to a layer having a first thickness along the scanline. In one embodiment, the particular quality value includes a running average of an amplitude of the one of the plurality of combinations. In one embodiment, the particular quality value includes a slope of a running average of an amplitude with respect to time of the one of the plurality of combinations.

In one embodiment, the method further includes splitting a parent layer into two or more sublayers, and performing time-shift combinations on each of the sublayers. The method further includes determining a best quality value for each of the sublayers. The method further includes comparing a best quality value of the parent layer to the best quality value of each of the sublayers. If the best quality value of the parent layer is substantially less than the best quality value of each of the sublayers, then the method further includes continuing to divide each of the sublayers into final sublayers. Each of the best quality values of the final sublayers is less than the best quality value of a parent layer of the final sublayers. In one embodiment, the method further includes assigning a combined digital signal of the parent layer of the final sublayers to the scanline.

In one embodiment of the method, the scanline is divided into a plurality of layers, and determinations of the particular qualities of the combinations are performed successively starting from a layer closest to the receiver.

In some embodiments, the present teachings relate to a method of replicating information from a waveform energy emanating from an object over time, where the information includes a spectral frequency distribution having frequency components above a frequency F/2. The method includes digitally sampling the waveform energy at a temporal frequency of less than F to obtain sampled data. The method further includes producing a replica of the information from the sampled data, where the replica includes a spectral frequency distribution that substantially matches the spectral frequency distribution in a range below the frequency F/2. The energy is emitted from a plurality of emitters and is reflected from the object.

In one embodiment of the method, the energy is sampled with a plurality of detectors. In one embodiment, the energy is acoustic energy. In one embodiment, the energy is electromagnetic energy.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a block diagram of one embodiment of an imaging system that images a defined volume in a medium;

FIG. **2** shows an example transmitter and an example receiver of one embodiment of an array forming an image associated with an example pixel of an image volume;

FIG. **3** shows a wave representation of an example array of transducers, where a transmitted signal from one example transducer is shown to reflect from an example target object such that the reflected wave can be detected by a plurality of receivers;

FIG. **4** shows how an image volume can be mapped into a plurality of pixels with respect to a plurality of transducers;

FIG. **5** shows an example of how a position of a pixel relative to a transmitter and a receiver can be stored independently as time-dependent indices based on their respective distances and wave propagation speed;

FIG. **6** shows how the indices can be used to selectively sample a signal received by a receiver;

FIG. **7** shows a process for obtaining a set of indices separately for transmitters and receivers for a given an array of pixels;

FIG. **8** shows a process for using the indices to selectively sample signals obtained by one or more receivers;

FIG. **9** shows an example of how a pixel array can be defined with respect to a transducer array, thereby allowing determination of distances between transducers and pixels;

FIG. **10** shows a process that separately determines indices corresponding to various position-defined transmitter-pixel and receiver-pixel combinations;

FIG. **11** shows a process that uses the transmitter-pixel and receiver-pixel indices to image selected pixels using selected transmitters and selected receivers;

FIG. **12** shows an example process that images a pixel array by transmitting from one selected transmitter and sampling from substantially all receivers;

FIG. **13** shows an example process that images a pixel array by transmitting from substantially all transmitters and sampling from one receiver;

FIG. **14** shows a ray representation of an example 32-transducer device being operated in a single-transmitter/all-receiver mode;

FIG. **15** shows a ray representation of the 32-transducer device being operated in an all-transmitter/single-receiver mode;

FIG. **16** shows how use of multiple receivers can allow sampling of fine perturbation features that are significantly smaller than that of a carrier signal;

FIG. **17** shows how signals from the multiples receivers can be combined to enhance a fine perturbation feature of interest;

FIG. **18**A shows by example how a plurality of signals from receivers that are offset by one from their respective transmitters can be combined;

FIG. **18**B shows by example how a plurality of signals from receivers that are offset by two from their respective transmitters can be combined;

FIG. **19** shows a process for transmitting from one or more transmitters and receiving from a plurality of receivers to allow combination of resulting signals;

FIG. **20** shows how the received signals from the plurality of receivers can be grouped according to the receivers' respective offsets from transmitters;

FIG. **21** shows how selected groups of data based on the receiver offset can be combined;

FIG. **22** shows an example of one embodiment of an array of transmitter-receiver pairs where the transmitters are triggered in sequence;

FIGS. **23**A and B show a simplified depiction of example signal traces obtained from the example array of FIG. **22**;

FIGS. **24**A-F show a simplified depiction of example digitized data trace from the example signal traces of FIGS. **23**A and B;

FIG. **24**G shows an example of a combination of digitized data associated with receivers that are offset by one from their respective transmitters;

FIGS. **25**A-F show a simplified depiction of example digitized data trace from the example signal traces of FIGS. **23**A and B;

FIG. **25**G shows an example of a combination of digitized data associated with receivers that are offset by two from their respective transmitters;

FIG. **26** shows how a signal from a given receiver can be combined with signal(s) from other receiver(s) to form a scanline for the given receiver such that the scanline has an improved performance for imaging a given layer;

FIG. **27** shows a plurality of scanlines intersecting with a layer such that the plurality of scanlines can be focused to that layer, and wherein the layer can be split into one or more thinner layers so as to allow finer focusing of the plurality of scanlines;

FIG. **28**A shows an example of features located along different scanlines and in different layers;

FIG. **28**B shows an example of measured signal traces having components associated with the example features of FIG. **28**A;

FIGS. **28**C-E show by example "in-focus" combinations at various layers for the signals traces to form the scanline associated with the first example receiver;

FIG. **29**A shows an example of features located along different scanlines and in different layers;

FIG. **29**B shows an example of measured signal traces having components associated with the example features of FIG. **29**A;

FIGS. **29**C-E show by example "in-focus" combinations at various layers for the signals traces to form the scanline associated with the second example receiver;

FIG. **30**A shows an example of features located along different scanlines and in different layers;

FIG. **30**B shows an example of measured signal traces having components associated with the example features of FIG. **30**A;

FIGS. **30**C-E show by example "in-focus" combinations at various layers for the signals traces to form the scanline associated with the third example receiver;

FIGS. **31**A-C show that in one embodiment, a scanline can be focused from the layer closest to the receiver, and that a given layer can be split into finer layers for finer focusing;

FIG. **32** shows a process for focusing a plurality of scanlines in a plurality of layers, such that a given layer can be split for finer focusing if advantageous to do so;

FIG. **33** shows a more specific example of the process of FIG. **32**;

FIGS. **34**A-B show some of the many possible ways of combining various signal traces to obtain a best in-focus scanline at a given layer;

FIGS. **35**A and B show by way of example one embodiment of a signal processing system that combines signals from the plurality of receivers;

FIG. **36**A shows a photograph of an example of an actual image obtained using multiple receivers and combining signals therefrom in a manner described herein; and

FIG. **36**B shows a negative image of the photograph of FIG. **36**A.

These and other aspects, advantages, and novel features of the present teachings will become apparent upon reading the following detailed description and upon reference to the

accompanying drawings. In the drawings, similar elements have similar reference numerals.

DETAILED DESCRIPTION OF SOME EMBODIMENTS

The present teachings generally relate to systems and methods for forming an image of a portion of a medium. FIG. **1** shows a block diagram of one embodiment of an imaging device **100** that includes an array **110** of transducers. A transducer can represent a transmitter or a receiver. As is known, some transducers can operate as transmitters and as receivers. Thus for the purpose of description, a transducer can represent a transmitter, a receiver, or a combination thereof.

As shown in FIG. **1**, the imaging device **100** further includes an array interface **112** that facilitates operation of the array **110** of transducers. The array interface **112** may, for example, multiplex and/or demultiplex a plurality of signals to and/or from transmitters and/or receivers. The transducer array **110** via the interface **112** may be supplied with a signal from a signal generator **114**. The operation of the interface **112** in providing the signal to the array **110** and/or readout of the received signals from the receivers can be performed by a processor **116**. As described below in greater detail, the processor **116** can operate the imaging device **100** in a manner that improves the resolution of the obtained image.

As shown in FIG. **1**, the imaging device **100** further includes a storage device **118** that allows retrievable storage of various operating parameters in a manner described below. The imaging device **100** may further includes a user interface **120** that provides an output for a user and/or allow a user to control some of the manner in which the imaging device **100** is operated.

As shown in FIG. **1**, the imaging device **100** projects one or more signals into a medium **104** and detects responses of such transmitted signals therefrom. A region **102** that provides measurements in such a manner can be defined as an image volume **102**. In the description herein, image volumes are sometimes represented as a two-dimensional plane. In many applications, image "planes" accurately describe the image volume. It will be understood, however, that such representation is in no way intended to limit the scope of the present teachings. It will also be understood that the shape and size of the image volume **102** may vary depending on factors such as the medium, the type of signal being used, and the properties of the imaging device.

It will also be understood that the imaging device, such as the device **100** of FIG. **1**, may include both longitudinal-wave and transverse-wave devices. The longitudinal-wave device may include, but is not limited to, ultrasound-based devices, sonar-based devices, or devices that probe underground geological features. The transverse-wave device may include, but is not limited to, devices that operate based on electromagnetic waves such as optical devices or radar-type devices.

FIG. **2** now shows one embodiment of an example array **130** of transducers that images a volume **132**. The example volume **132** can be defined by a plurality of corner locations **134***a-h*. Within the volume **132** is shown an example elemental volume **136** (also referred to as a pixel and/or voxel herein). A plurality of such pixels **136** make up the volume **132**. It will be understood that the terms pixel (picture element) and voxel (volume element) are used interchangeably throughout the description.

In one embodiment, one or more transducers of the array **130** transmits one or more signals into the volume **132** so as to cover each of the pixels therein. A wave impinging on a pixel can be transmitted through the pixel, reflected from the pixel, or any combination thereof. For example, if an object occupies the pixel, that object can cause a partial reflection and a partial transmission. Measurement of the reflected wave or lack of the reflected wave can yield an image of the pixel.

Thus as shown in FIG. **2**, the example pixel **136** is depicted as being probed by a transmitted signal **138** from an example transmitter **142**. The pixel's response to that signal **138** as measured by an example receiver **144** is indicated by a dashed arrow **140**.

One can see that the resolution of an image of the volume depends on the size of the pixels, and the imaging device's ability to resolve such pixels. As described herein, one aspect of the present teachings relates to systems and methods of probing and measuring the pixels in a manner that improves the resolution of images formed therefrom.

FIG. **3** shows an example wavefront representation **150** of one embodiment of an array of transducers **154***a-e* probing a target object **160**. In the example, the transducers **154** are shown to function as transmitters and receivers, and one receiver **152** is shown to transmit a signal **156**. A wavefront **158** impinges on the target **160** and reflects therefrom into a reflected wave **166**. A propagated wave **164** is shown to be received first by the transducer **154***c*. The same wavefront **164** would then be received by other transducers **154***a, b, d, e* at later times. Rays representing the reflected wave propagation towards the transducers **154***a-e* are indicated by dashed arrows **162***a-e*.

By synchronizing and combining the measurements of the reflected wave (example wave **164**) by the various transducers, an improved image of the target can be formed. Although FIG. **3** shows a single-transmitter and multiple-receiver operation, it will be understood that any other combinations of transmitters and receivers can be used. As an example, the imaging device can be operated where multiple transmitters transmit multiple signals that are measured by a single receiver. In another example, a plurality of transmitters and a plurality of receivers can be used in various combinations. One aspect of the present teachings relates to performing synchronization and combination of transmitters and/or receivers to improve the performance of the imaging device.

The imaging device can form an image of a portion of a medium containing one or more targets by defining that portion into a plurality of pixels. Thus, in the example target of FIG. **3** can occupy one or more pixels. Probing of those pixels, along with other pixels, can yield an image of the target in its medium.

FIG. **4** shows one embodiment of an array of such pixels defined for an image plane **170**. The image plane **170** is shown to be divided into an M×N array of pixels. Although FIG. **4** depicts the pixels as squares for the purpose of description; it will be understood that the pixels can be of any definable shape. Furthermore, the overall shape of the image plane **170** need not be rectangular shaped. Moreover, the image plane **170** is referred to as a "plane" for the purpose of description, and is not intended to limit the scope of the present teachings.

Some or all of the pixels of the image plane **170** can be probed by an array **172** of transducer elements. Such probing of the pixels is depicted by a plurality of arrows **174**.

FIG. **4** shows L elements arranged along a line to form the array **172**. It will be understood that the line arrangement of the transducer elements is for the purpose of description of the image plane **170**. The array **172** of transducer elements can be arranged in a two-dimensional array, either in a planar manner or along some curved surface.

FIG. **5** now shows how a pixel **186** can be associated with a transmitter **182** and with a receiver **184**. By performing such associations for all possible transmitter-pixel and receiver-

pixel combinations, a spatial and/or temporal alignment set (also referred to as an "alignment set" herein) of an array of pixels is obtained with respect to an array of transmitters and receivers. One aspect of the present teachings relates to mapping the pixels with respect to the transmitters separately from the receiver-pixel mapping. As described below, such a feature provides significant advantages during certain types of high-resolution imaging operations.

As shown in FIG. **5**, the pixel **186** is positioned relative to the transmitter **182** by a distance d_{Tx} (as indicated by arrow **188**). Similarly, the pixel **186** is positioned relative to the receiver **184** by a distance d_{Rx} (as indicated by arrow **190**). The distance d_{Tx} can be used to determine when a signal from the transmitter **182** can be expected to reach the pixel **186**. Similarly, the distance d_{Rx} can be used to determine when a possibly-reflected signal from the pixel **186** can be expected to reach the receiver **184**. Such expectation information can be used to effectively combine signals associated with different transmitter-pixel and/or receiver-pixel combinations.

The expectation arrival information for the transmitter-pixel combination depends on the distance d_{Tx}, and can be represented as some form of an index. Such an index can also account for factors other than the distance that affect the arrival of the signal. As an example, electronic circuitry associated with the transmitter may cause the signal to be transmitted after a delay from some start time. Thus, an index data **194** corresponding to the distance d_{Tx} may also include such other factors.

Similarly, the expectation arrival information for the receiver-pixel combination depends on the distance d_{Rx}, and can be represented as some form of an index. Such an index can also account for factors other than the distance that affect the arrival of the signal. As an example, a readout process associated with the receiver may cause the signal to be sampled after a delay from the time when the signal impinges on the receiver. Thus, an index data **192** corresponding to the distance d_{Rx} may also include such other factors.

As shown in FIG. **5**, the indices **194** and **192** can be stored independently in a retrievable storage **196**. A collection of such indices for all possible transmitter-pixel and receiver-pixel combinations then defines the alignment set of the array of pixels.

FIG. **6** now shows how an alignment set for the pixel **186** can be used to obtain a selectively sampled signal **210** from an output **206** of the receiver **184**. A transmitted signal from the transmitter **182** propagating towards the pixel **186** is depicted as an arrow **202**. The signal **202** may or may not experience reflection from the pixel **186**. Thus, an arrow **204** represents how a reflected signal would propagate from the pixel **186** to the receiver **184**.

As further shown in FIG. **6**, data **208** having the transmitter-pixel and receiver-pixel indices can be retrieved from the storage **196**, and be used selectively sample the output **206** of the receiver **184**. In one embodiment, such selectively sampled signal **210** is obtained by sampling the output **206** at an index corresponding to the sum of the transmitter-pixel and receiver-pixel indices. Some possible forms of the indices are described below in greater detail.

FIGS. **7** and **8** now show processes that perform the index determination and subsequent use, respectively, for an array of transducers. A process **220** determines the indices for a given pixel array with respect to a given array of transducers. The process **220** begins at a start state **222**, and in a process block **224**, the process **220** obtains detector and map parameters. Detector parameters may include the number of transmitters and the number of receivers. Map parameters may include the number of pixels, the desired size of the pixels, and the arrangement of the pixels.

The process **220** in a process block **226** defines the array of transmitters and receivers. In one embodiment, each transmitter and each receiver are defined in terms of their positions relative to a chosen coordinate system. In an embodiment where transmitter and receiver function are performed by a common transducer, the array definition only needs to be performed for the transducer array. An example array definition is described below in greater detail.

The process **220** in a process block **228** defines the array of pixels as determined by the map parameters. In one embodiment, each pixel is defined in terms of its position relative to the transmitter/receiver array. An example array definition is described below in greater detail.

The process **220** in a process block **230** determines a propagation index corresponding to each transmitter-pixel combination. An example propagation index determination is described below in greater detail.

The process **220** in a process block **232** determines a sampling index corresponding to each receiver-pixel combination. An example sampling index determination is described below in greater detail.

The process **220** in a process block **234** stores the propagation indices and the sampling indices. An example storage of the indices is described below in greater detail. The process **220** ends at a stop state **236**. In one embodiment, the alignment set generation process **220** is performed once for a given transducer array and a given pixel array, and does not need to be re-done during the imaging operation.

As shown in FIG. **8**, an image generation process **240** determines the measured signals associated with some or all of the pixels using the previously determined alignment set for the transducer-pixel configuration. The process **240** begins at a start state **242**, and in a process block **244**, the process **240** obtains imaging parameters. In one embodiment, the imaging parameters include the number of transmitters and receivers, and alignment sets for transmitter-pixel and receiver-pixel combinations.

The process **240** in a process block **246** sets initial values for each of the pixels being evaluated. An example of such initialization is described below in greater detail

The process **240** in a process block **248** transmits signal(s) into the pixel array, and samples signal(s) at indices corresponding to selected transmitter-pixel-receiver combinations. An example of selected transmitting and sampling is described below in greater detail.

The process **240** in a process block **250** determines the intensity of each of the selected pixels from the sampled signal(s). An example of such intensity determination is described below in greater detail.

The process **240** in a process block **252** processes the pixel intensities to form an image associated with the pixel array. The process **240** ends at a stop state **254**.

FIGS. **9-11** now show more specific manner in which the transducer and pixel arrays can be configured, and how mapping and imaging operations can be performed on such a configuration. FIG. **9** shows an example configuration **260** of array of pixels **264** relative to an array of transducers **262**. It will be understood that use of four example transducers **262** is for descriptive purpose only, and in no way intended to limit the scope of the present teachings. Similarly, the use of 5×6 array of pixels **264** is for descriptive purpose only, and in no way intended to limit the scope of the present teachings.

In one embodiment, the positions of the transducers **262** are defined with respect to a coordinate system **266**. Although

a Cartesian coordinate system is used, it will be understood that any coordinate system can be used for such definition.

In one embodiment, the array of pixels **264** are formed by dividing up an image plane into a grid (5×6 in the example) of pixel regions. One way to define such a grid is to define the positions of set of opposing corner pixels—for example, (1,1) and (5,6), or (1,6) and (5,1), with respect to the coordinate system **266**. Then, one can specify number of rows (5 in this example) and columns (6 in this example). Such a definition of the grid provides sufficient information to define the size and position of each of the pixels. One can see that the pixel grid can be defined in any number of ways. Thus, the example method disclosed herein is not intended to limit the scope of the present teachings.

Once the pixel grid **264** is established with respect to the chosen coordinate system **266**, each pixel's position can be referenced to each transducer. As an example, the pixel (2,3) is shown to be referenced to transducers **1** to **4** as denoted by arrows **268***a-d*. Such relative positions of the pixel to the transducers can be used to obtain the transmission indices and sampling indices.

One way of obtaining an index associated with a given transducer-pixel combination is to first determine the distance between the transducer and the pixel. Such determination can be achieved by simple geometry calculation based on the chosen coordinate system. As an example, if the coordinates of the pixel and the transducer can be represented by (x_p,y_p,z_p) and (x_t,y_t,z_t) respectively, the distance d between the two points can be calculated as square root of the quantity $(x_t-x_p)^2+(y_t-y_p)^2+(z_t-z_p)^2$.

The distance d obtained in the foregoing manner can then be used to determine the propagation time t between the transducer and the pixel as t=d/v where v is the magnitude of the propagation velocity of the signal of interest in the medium. For sampling purposes, the propagation time t can further be expressed as a sample number i_{sample} for situations where the received signal is sampled at a sampling rate. In one embodiment, the sample number can be represented as i_{sample}=(t)(sample rate). As previously described, the actual time between some "start" time and sampling time may include time(s) in addition to the propagation times. Such additional time, if any, can also be represented as a sample-rate-based quantity, and-added to that associated with the propagation times.

From the foregoing description of the sample number determination, one can see that similar information can be obtained in any number of ways. Thus, it will be understood that any number of other methods, or variations of the disclosed method, can be used to obtain and store the indices associated with the transmitter-pixel and receiver-pixel combinations.

FIG. **10** now shows one implementation of a detailed process **270** for determining an alignment set for a given pixel array with respect to given transmitter and receiver arrays. The process **270** begins at a start state **272**, and in a process block **274**, the number of transmitters is determined. In a process block **276**, the number of receivers is determined. In a process block **278**, the position of each transmitter is determined. In a process block **280**, the position of each receiver is determined.

In a process block **282**, the process **270** defines an image plane by determining positions of two opposing corners of the image plane. In a process block **286**, the image plane is divided into a grid defined by desired numbers of rows and columns of pixels.

In a process block **288**, the process **270** determines the signal's velocity through the medium being imaged. In a process block **290**, the sampling rate is determined.

As shown by a loop **292** (with end-loop **308**), the process **270** loops through the transmitters. For each transmitter, the process **270** loops through the pixels (loop **294**, with end-loop **306**). Thus for each combination of the transmitter and pixel, the process **270** determines the pixel position in a process block **296**. In a process block **298**, the distance between the transmitter and the pixel is determined. In a process block **300**, propagation time between the transmitter and the pixel is determined based on the distance and signal velocity (t=d/v). In a process block **302**, an index corresponding to the propagation time is determined. In one embodiment, the index can be represented as a product of the propagation time and the sampling rate of the imaging device. In a process block **304**, the index corresponding to the transmitter-pixel combination is saved for later retrieval and use. The loops **294** and **292** end at loop-ends **306** and **308** respectively.

As shown by a loop **310** (with end-loop **326**), the process **270** loops through the receivers. For each receiver, the process **270** loops through the pixels (loop **312**, with end-loop **324**). Thus for each combination of the receiver and pixel, the process **270** determines the pixel position in a process block **314**. In a process block **316**, the distance between the receiver and the pixel is determined. In a process block **318**, propagation time between the pixel and the receiver is determined based on the distance and signal velocity (t=d/v). In a process block **320**, an index corresponding to the propagation time is determined. In one embodiment, the index can be represented as a product of the propagation time and the sampling rate of the imaging device. In a process block **322**, the index corresponding to the receiver-pixel combination is saved for later retrieval and use. The loops **312** and **310** end at loop ends **324** and **326** respectively. The process **270** ends at a stop state **328**.

As previously described, the alignment set generation, such as that of the process **270**, is generally performed once and does not need to be repeated during subsequent imaging operations. The stored indices corresponding to the transmitter-pixel and receiver-pixel combinations allow such subsequent improved-resolution imaging operations to be performed in an efficient manner.

FIG. **11** now shows one implementation of a detailed process **330** for performing an imaging operation utilizing the alignment set obtained previously. The process **330** begins at a start state **332**, and in a process block **334** an operating configuration of transmitters, receivers, and pixels is determined. In one embodiment, such an operating configuration defines the numbers and positions of the transmitters, receivers, and pixels in a manner similar to that used for the alignment set determination process. As such, one or more operating configurations can be stored, and one configuration can be either selected by a user or be used as a default.

In a process block **336**, the process **330** obtains a set of indices corresponding to the transmitter-pixel combinations of the operating configuration. In a process block **338**, a set of indices corresponding to the receiver-pixel combinations of the operating configuration is obtained.

In a process block **340**, the process **330** initializes the imaging detector. In one embodiment, such initialization includes initializing the values of the pixel intensities.

In a process block **342**, the process **330** transmits a signal from selected transmitter(s) and begins sampling for return signals from the pixel array using selected receiver(s). In one embodiment, a sampling "start" is issued at some predetermined time about the time when the signal leaves the transmitter. Referencing the samplings from such a common start

time allows correlated sampling of all the transmitter-pixel-receiver combinations. By having separate sets of transmitter-pixel and receiver-pixel indices, such correlated sampling, as well as other variations of operation of the imager, can be performed more efficiently.

In one embodiment, the process **330** measures the pixel array by sampling signals associated with each of the transmitter-pixel-receiver combinations. One way to cover all the combinations is to perform nested loops for the transmitters, pixels, and receivers. Thus, the process **330** is shown to loop through the selected pixels (loop **344**, end-loop **364**). For each pixel in the pixel loop **344**, its intensity value is initialized in a process block **346**. For each initialized pixel, the process **330** loops through the selected transmitters (loop **348**, end-loop **362**). For each pixel-transmitter combination, the process **330** loops through the selected receivers (loop **350**, end-loop **360**). Thus for each pixel-transmitter-receiver combination of the nested loops **344**, **348**, **350**, the process **330** in a process block **352** obtains a signal from the current receiver. In a process block **354**, the index for the current transmitter-pixel combination is obtained. In a process block **356**, the index for the current receiver-pixel combination is obtained. In a process block **358**, the pixel intensity is adjusted by a value of the receiver signal corresponding to the sum of current transmitter-pixel and receiver-pixel indices.

As shown in FIG. **11**, pixel, intensity values obtained in the foregoing manner can be further analyzed or stored (for later analysis) in a process block **366**. The process **330** ends in a stop state **368**.

FIGS. **12** and **13** now show two specific examples of using selected transmitter(s) and selected receiver(s) to obtain an improved image quality. In FIG. **12** an example process **370** is shown where a single selected transmitter and a plurality of selected receivers are used. In FIG. **13**, an example process **400** is shown where a plurality of selected transmitters and a single selected receiver are used.

As shown in FIG. **12**, the example process **370** in a process block **372** transmits a signal from a selected transmitter and begins sampling. Such a beginning of sampling can be at a predetermined time relative to the time when the transmitted signal begin propagating from the transmitter. The process **370** then loops through all of the pixels in a loop **374** (with an end-loop **390**). For each pixel, the process **370** sets that pixel's initial value to zero in a process block **376**. Also for that pixel, the process **370** obtains the index i_{Tx} for the current transmitter-pixel combination in a process block **378**.

For the current pixel, the process **370** then loops over all of the selected receivers in a loop **380** (with an end-loop **388**). The process **370** in a process block **382** obtains a signal S from the current receiver. In a process block **384**, the index for the current pixel-receiver combination i_{Rx} is obtained. In a process block **386**, the current pixel's intensity value is adjusted as $I=I+S(i_{Tx}+i_{Rx})$.

As shown in FIG. **13**, the example process **400** in a process block **402** transmits signals from all of the selected transmitters, and begins sampling from one selected receiver. Transmitting of the signals from the selected transmitters can be either simultaneous or in a predetermined sequence. In embodiments where the number of selected transmitters is relatively small, the signals may be transmitted substantially simultaneously, and the sampling may be able to temporally distinguish the transmitter-pixel-receiver combinations. In embodiments where the number of selected transmitters is relatively large, the signals being transmitted simultaneously may not allow effective selective sampling of the transmitter-pixel-receiver combinations.

In embodiments where the signals are transmitted simultaneously, beginning of sampling can be at a predetermined time relative to the time when the transmitted signals begin propagating from the transmitters. In embodiments where the signals are transmitted in some sequence, beginning of sampling can be defined in a variety of ways. One way is to have a common start time, and account for the different transmit times for different transmitters as adjustments to the transmitter-pixel combination indices.

The process **400** then loops through all of the pixels in a loop **404** (with an end-loop **420**). For each pixel, the process **400** sets that pixel's initial value to zero in a process block **406**. Also for that pixel, the process **400** obtains the index i_{Rx} for the current receiver-pixel combination in a process block **408**.

For the current pixel, the process **400** then loops over all of the selected transmitters in a loop **410** (with an end-loop **418**). The process **400** in a process block **412** obtains a signal S from the receiver. In a process block **414**, the index for the current transmitter-receiver combination i_{Tx} is obtained. In a process block **416**, the current pixel's intensity value is adjusted as $I=I+S(i_{Tx}+i_{Rx})$.

In one embodiment as shown in FIG. **14**, an imaging device includes 32 elements. In particular, FIG. **14** shows a ray representation **500** of the embodiment where one transmitter (transmitter **16**) transmits a signal **506** to an object **504**, resulting in a reflected wave **510** that is detected by 32 receivers (1 to 32). The reflected wave **510** propagating to the receivers **502** is represented by reflected rays **508**, and the intersection of the wavefront **510** with the rays **508** represent the in-phase portions of the rays **508**.

For the example embodiment **500**, the index i_{Tx} representative of the transmitted signal **506** is common to all of the sampling indices used by the 32 receivers. For the particular example where the object is located at the mid-level of the array **502**, the reflected wave **510** reaches receiver **16** first. Thus, the sampling index associated with the pixel where the object **504** is located would have a value that causes the signal from receiver **16** to be sampled first. Thereafter, signals from receivers **15** and **17** would be sampled, followed by **14** and **18**, etc. Signal from receiver **32** would be the last to be sampled at a time corresponding to the extra propagation distance of the wavefront **510**.

In one embodiment as shown in FIG. **15**, an imaging device includes 32 elements. In particular, FIG. **15** shows a ray representation **520** of the embodiment where all **32** transmitters transmit signals **526** to an object **524**, resulting in a reflected signal **528** that is detected by receiver **16**. For the example embodiment **520**, the index i_{Rx} representative of the reflected signal **528** is common to all of the sampling indices associated with the 32 receivers.

For the particular example where the object is located at the mid-level of the array **502**, the transmitted signal from transmitter **16** reaches the object **524** first (assuming that all signals are transmitted simultaneously). Thus, the sampling index associated with the pixel where the object **524** is located would have a value that causes the first sampled signal to be associated with transmitter **16**. The next set of sampled signals would be associated with transmitters **15** and **17**, and so on. The last set of sampled signals would be associated with transmitter **32**.

As previously described in reference to FIG. **13**, the plurality of signals can be transmitted from the transmitters in different ways. Sequenced transmission of signals from the plurality of transmitters can temporally separate the arrivals of the signals at the object **524**, as well as reflected signals at the receiver thereafter. One way to sequence the signal trans-

mission is to begin transmission at the transmitter **16**, followed at a predetermined time by transmission at transmitters **15** and **17**, etc. Such a sequence of transmission can increase the temporal separation of the samplings associated with the array of receivers **522**.

FIG. **16** now shows how sampling by a plurality of transducers can yield an effective sampling rate that is greater than a sampling rate associated with each of the transducers. In an example operating configuration **600**, a transmitter **602** is depicted as transmitting a transmission energy **604** into a medium (not shown) in response to a transmission signal **606**. The transmission signal **606** is depicted as a periodic signal; but such a characteristic is not a requirement. The transmission signal **606** can be of any waveform having some time-characterizable feature. For example, if the transmission signal **606** is a single pulse, it may be characterized by it temporal width.

The example operating configuration **600** further includes a plurality of receivers **610** that receive respective reflection energies **612**. In response to the reflection energies **612**, the receivers **610** output respective signals **614** that are sampled. In this example, the plurality of receivers **610** are shown to be sampled simultaneously for the purpose of description. It will be understood that simultaneous sampling of the receiver signals is not a requirement.

Also for the purpose of description, the common sampling is shown to have a period $T_{sampling}$ that is approximately half of the transmission signal period T_{signal}. As such, the sampling frequency in such a situation is approximately twice the transmission signal frequency. In general, a sampling frequency should be at least twice the frequency of a signal being analyzed to be able to characterize that signal; and the "twice" lower limit is often referred to as the Nyquist limit.

As shown in FIG. **16**, the example signals **614** output by the receivers **610** are shown to have an underlying "carrier" signal structure (dotted curve superimposed for descriptive purpose) that can have a similar structure as the transmission signal **606**. The signals **614** can include a plurality of perturbations about the carrier signal structure. Such perturbations can be the result of the interaction of the transmission signal **606** with some feature of interest in the medium, or due to background noise. Whatever the cause may be, such perturbations may have (and are depicted as having) sub-wavelength feature sizes when compared to the carrier signal structure or the sampling period. As such, sampling of an individual receiver alone will not be able to resolve the fine-feature structures associated with noises or legitimate signals.

When a plurality of receivers are used, the receivers may be arranged so that reflected energies arrive at the receivers at different times. Such arrival time differences can be caused by differences in propagation times due to the pathlength differences and/or velocity differences caused by medium anisotropy. In FIG. **16**, such an arrival difference is depicted as ΔT for the receivers **610***a* and **610***b*. For a given pair of receivers, the arrival difference ΔT can be made substantially smaller than the sampling period $T_{sampling}$ or the transmission signal period T_{signal}.

With an array of receivers, successive arrival differences can be introduced to the receivers. Then, a common sampling of the receivers can have an effect of having the individual receivers sampling different temporal parts of the received signals. Thus in the example configuration **600**, the common sampling at time t**1** causes the example signal **614***c* (that arrives late) to be sampled at a given temporal part of the carrier structure (beginning of the cycle in the example). Sampling at time t**1** causes the example signal **614***b* to be sampled at a temporal part of the carrier structure at a time approximately equal to the arrival difference between the receivers **610***b* and **610***c*. Similarly, sampling at time t**1** causes the example signal **614***a* to be sampled at a temporal part of the carrier structure at a time that is approximately equal to the arrival difference between the receivers **610***a* and **610***b*. When the samplings from the receivers **610***a, b,* and *c* are combined, the resulting measurement can be equivalent to sampling at intervals of arrival difference ΔT that is substantially smaller than the common sampling interval of $T_{sampling}$.

One can see that the number of receivers and/or the arrival time difference can be selected so that the effective sampling intervals are distributed between two common sampling intervals (for example, between common sampling times t**1** and t**2** in FIG. **16**). Thus, with proper configuration, an array of receivers can be used to sample the received signals at a frequency that is greater than the common sampling frequency, thereby be able to resolve higher frequency (than the transmission signal frequency) perturbation signal components that are "riding" on the carrier signal structure.

To be able to extract the higher frequency perturbation features, it is preferable in one embodiment to not filter the received signals. In some conventional systems, filtering is used to remove these higher frequency perturbations. Such filtering, however, can filter out a perturbation that is caused by an interaction of interest along with the noise perturbations.

One can see that sampling the received signals at a effectively higher frequency as described above is one aspect of achieving an improved imaging. Such sampling samples both the perturbations of interest and noise. Thus, another aspect of improved imaging includes a method of combining the samplings from different receivers so that the signal to noise ratio of the sampled perturbations is increased.

FIG. **17** shows an example of how combination of the samplings from a plurality of receivers can enhance a relatively weak signal from a reflection of interest from the medium. A plurality of example segments of signals **620** are shown superimposed to a carrier signal (dotted curve **622**). Each of the example signal segments **620** is shown to include a relatively weak signal of interest **626** among its own set of noise structures. Each signal may have different noise structures since the signal is representative of a path that is different from other signals. If any perturbation within the signal is present in at least some significant portion of the plurality of signals **620**, such a perturbation is likely due to some interaction of interest in the medium, and are likely correlated among the signals.

As described above in reference to FIG. **16**, such relatively fine-featured perturbations, whether a legitimate signal or noise, are more likely to be sampled with the effective sampling rate that can be substantially greater than that of the common sampling frequency. Thus, an example of a plurality of such effective samplings are depicted as dashed lines **624**. It should be understood that the effective sampling lines **624** in FIG. **17** are shown only for the purpose of demonstrating that when properly correlated, the plurality of signals **620** can yield an enhancement of the perturbation of interest over the surrounding noise perturbations. A method of forming such a correlation of signal samplings is described below in greater detail.

It should also be understood that the perturbation of interest **626** in FIG. **17** is depicted as being sampled near the peak for the purpose of description. Because the arrival differences (ΔTs) among the receivers may not be uniform, spacing between the effectively increased samplings may not be uniform. Consequently, samplings of the perturbation **626** may be at different parts of the perturbation peak structure. In one

embodiment, such an effect limits the resolution achievable by the effectively increased sampling.

In one embodiment, properly correlated analog signals from the selected receivers can be made to interfere with each other. In such an embodiment, the various analog signals can be provided with delays according to the manner in which the signals are correlated.

In one embodiment, the raw signals from the selected receivers are digitized during the common samplings. The plurality of receivers and their associated sampling electronics are then effectively sampling and digitizing different temporal portions of their respective signals. As shown in FIG. **17**, the digitized results are shown to be correlated and combined so as to yield a combined data sequence **628**. When the digitized results of the signals are combined properly, individual digitized values of the perturbation of interest **626** combine to yield an enhanced digitized value **630**. In contrast, the sampled and digitized noises either combine to generally cancel each other on average, or combine in a manner that is less than that of the correlated perturbation value **630**.

In principle, the combining of the signals can be performed with any receivers in the array. However, Applicant's experiences have shown that correlating and combining signals from some combinations of transmitter and receivers yield better results in the quality of images.

FIGS. **18**A and **18**B show two examples of such transmitter-receiver combinations. In FIG. **18**A, an example operating configuration **640** has an i-th transmitter **642***a* transmitting an energy **646**, and a receiver (i+1) **644***b* that is offset by one element spacing receiving a reflected signal **648** (from an arbitrary point **658** in the medium) and generating a signal. Thus, an energy **650** from a transmitter (i+1) **642***b* is reflected as an energy **652** and received by a receiver (i+2) **644***c*. Similarly, an energy **654** from a transmitter (i+2) **642***c* is reflected as an energy **656** and received by a receiver (i+3) **644***d*. In one embodiment, such transmit-receive combination between transducers offset by one unit provides a substantially "head-on" type of probing of the arbitrary point **658** in the medium.

In FIG. **18**B, an example operating configuration **660** has the i-th transmitter **642***a* transmitting an energy **662**, and the receiver (i+3) **644***c* that is offset by two element spacing receiving a reflected signal **664** (from the arbitrary point **658** in the medium) and generating a signal. Thus, an energy **666** from the transmitter (i+1) **642***b* is reflected as an energy **668** and received by the receiver (i+3) **644***d*. Such an offset can provide a more angled probing of the point **658** in the medium.

One can see that such offset pairing of the transmitter and receiver can extend to three, four, or greater offset units. In principle, any offset in the array can be used. In some applications, such a capability can be used to investigate reflections and/or emissions from a given object that are directed towards sidelobe angles.

FIGS. **19-21** now show various processes that perform the sampling and combining of signals from different transmitter-receiver offsets. FIG. **19** shows one embodiment of a process **680** that transmits from selected transmitters in a sequential manner. In one embodiment, a master time reference is designated in a process block **682**. Such a master time can be used for referencing subsequent time-related operations. The process **680** then loops through the selected transmitters (begin loop **684**, and end loop **694**). In a process block **686**, the process **680** induces the current transmitter to transmit energy into the medium. In a process block **688**, the return signals are received from selected receivers. In one embodiment, all of the receivers receive return signals impinging on them. In a process block **690**, the process **680** samples and stores the resulting data from the selected receivers. In one embodiment, the process **680** may wait for a selected duration before transmitting from the next transmitter.

FIG. **20** now shows one embodiment of a process **700** that combines the sampled data according to different transmitter-receiver offset groups. The process **700** loops through different values of offset N between the transmitter and the receiver of interest (begin loop **702**, end loop **708**). In one embodiment, the value of offset N ranges from zero to N_{max}, with N=0 representing a case where the receiver is in the same assembly as the transmitter. In a process block **704**, the process **700** forms a "page" of data by combining data from receivers that are offset by the current value of N from the selected transmitters. In a process block **706**, the process stores the page of data corresponding to the current offset value of N.

FIG. **21** now shows one embodiment of a process **710** that uses the page(s) of data to characterize the medium. In a process block **712**, the process **710** retrieves selected page(s) of data corresponding to transmitter-receiver offset value(s) of N. In a process block **714**, the process **712** combines the selected page(s) to characterize the medium. In one embodiment, characterization of the medium includes formation of an image of the medium.

FIGS. **22** to **25** now show a specific example of the data page formation based on the offset of the transmitter and receiver pairs. For the purpose of describing by example, an example operating configuration **730** having six sets of transmitter-receiver assemblies **732** are shown in FIG. **22**. It will be understood that such a configuration is only for descriptive purpose, and is not in any way intended to limit the scope of the present teachings.

In one embodiment, each transmitter-receiver assembly includes a transmitter (Tx) and a receiver (R) positioned in a close proximity to the transmitter. As depicted by an arrow **734**, the six example transmitters (Tx**1** to Tx**6**) are "fired" in sequence, starting from the first transmitter Tx**1**.

Also shown in FIG. **22** is an arbitrary point **736** in the medium. In one embodiment, a given transmitter does not transmit until return signals from the medium, including the point **736**, would have had time to return to all of the receivers. It will be understood that the arbitrary point **736** is shown to aid in the purpose of description, and a-priori knowledge or assumption of it's location with respect to the array **732** is not required.

FIGS. **23**A and **23**B now show examples of simplified raw analog traces from the six example receivers of FIG. **22** in response to receiving of reflected signals due to a given transmitter. For the purpose of describing how a particular perturbation peak can be at different temporal portions of different traces, the traces are depicted to only show the peak. It should be understood that there will likely be other perturbation features in the traces, as described above in reference to FIGS. **16** and **17**.

FIG. **23**A shows example traces **750** associated with transmission from Tx**1**. In one embodiment, each of the traces **750** are sampled between a "Start" time and a "Stop" time while being referenced to a master time reference. Thus, if the perturbation peak is assumed to originate from the point **736** in FIG. **22**, it will likely arrive at the second receiver R**2** first due to that receiver being closer than others. Other receivers will likely receive the perturbation from the same point **736** successively later due to the geometry of the receivers with respect to the point **736**. The differences in the arrival times can also be affected by variations in the velocity of sound in the medium. Whatever the cause may be, the arrival times

need to compensated for each of the receivers of interest from which the signals (or digitized data therefrom) are combined. One technique of performing such compensation is described below in greater detail.

FIG. **23**B shows example traces **760** associated with transmission from an i-th transmitter Tx(i). Similarly, each of the sampled traces **760** can be sampled between a "Start" time and a "Stop" time while being referenced to a time reference. The time reference may or may not be the same as the master time reference described above in reference to FIG. **23**A. One can see that because of the proximity of the example point **736** to the second receiver R**2**, the perturbation signal will likely reach R**2** first, followed by successively later arrivals to other receivers spaced from R**2**. The arrival times within the traces **760** can also be compensated for by the method described below.

From FIGS. **23**A and **23**B, one can see that signal traces (raw or digitized) from different "sets" associated with different transmitters can be combined. So, if one wants to analyze the return signals from receivers that are offset by one unit from their respective transmitters, the R**2** trace from the traces **750** can be combined with the trace (i+1) from the traces **760** (e.g., if i=3, then get trace from R**2** and/or R**4**). Combining signals in such a manner allows enhancement of the perturbation signal while generally maintaining a similar "perspective" with respect to the transmitters.

FIGS. **24** and **25** now show examples of specific possible combinations of offset-one and offset-two data associated with the example operating configuration of FIG. **22**. For the purpose of describing the combinations of traces associated with different transmitters, the traces are depicted in a simplified manner as to have already been digitized. Thus, the spikes in the traces represent the digitized values of the sampled perturbation signals (of FIGS. **23**A and B).

FIGS. **24**A-F show sampled data traces from the receivers associated with each of the six example transmitters. FIGS. **25**A-F show the same sampled data traces.

FIGS. **24**A-F and G show possible combinations of offset-one data, and FIGS. **25**A-F and G show possible combinations of offset-two data. Thus, one can see that the same set of data traces from the receivers associated with each of the transmitters can be used for different offset combinations. Furthermore, offset-three, four, or any number can be achieved in a similar manner as that described in reference to FIGS. **24** and **25**.

As shown in FIG. **24**A where transmitter Tx**1** is used, R**2** is the offset-one receiver. As shown in FIG. **24**B where transmitter Tx**2** is used, R**1** and R**3** are offset-one receivers; thus, data from either or both receivers can be used. Similar offset-one receivers corresponding to other transmitters are shown in FIGS. **24**C to **24**F.

FIG. **24**G shows a combined data **772** that can result from combination of data **770***a-f* for offset-one receivers. If the data are combined properly, the combined data **772** can include an enhanced peak **774** that corresponds to a feature of interest. A method for performing such combination is described below in greater detail.

FIGS. **25**A-F and G show possible combinations of offset-two data. As shown in FIG. **25**A where transmitter Tx**1** is used, R**3** is the offset-two receiver. As shown in FIG. **25**B where transmitter Tx**2** is used, R**4** is the offset-two receiver. As shown in FIG. **25**C where transmitter Tx**3** is used, R**1** and R**5** are offset-two receivers; thus, data from either or both receivers can be used. Similar offset-two receivers corresponding to other transmitters are shown in FIGS. **25**D to **25**F.

FIG. **25**G shows a combined data **782** that can result from combination of data **780***a-f* for offset-two receivers. If the data are combined properly, the combined data **782** can include an enhanced peak **784** that corresponds to a feature of interest. A method for performing such combination is described below in greater detail.

One can see that other receiver offset (three, four, etc.) data can also be combined in a similar manner. Thus, it will be understood that the example description of the offset-one and offset-two configurations is in no way intended to limit the scope of the present teachings.

FIGS. **26-33** now show how signals from different receivers can be combined so as to yield an enhanced signal of interest. It will be understood that the different receivers can be offset receivers, or simply part of multiple receivers.

FIG. **26** shows that a given receiver **792** can output an example signal **796** having fine perturbations **798** as described above in reference to FIGS. **16** and **17**. Such a receiver signal **796** can result from return signals **802** impinging on the receiver **792** from a plurality of directions, including a direction substantially directly in front of it. An imaginary line **790** that extends substantially directly front of the receiver is shown in FIG. **26**. For the purpose of description, the line **790** is shown to intersect a layer **794**. Although the line **790** and the layer **794** are depicted as being perpendicular, it will be understood that such orientation is not a requirement. A line may be oriented at an angle with respect to the layer. Furthermore, a layer does not need to have a planar shape—it can be curved and form a portion of a shell-like structure about the receiver.

In one embodiment, receiver signals are combined so as to enhance or "focus" on perturbation features positioned generally along the line **790** and within the layer **794**. Such "focused" combination of signals from a plurality of receivers can be thought of as a scanline associated with the receiver **792**. A plurality of such scanlines associated with a plurality of receivers can then form an image along the scanlines.

FIG. **27** shows that a plurality of example scanlines **812***a-c* associated with a plurality of receivers **810***a-c* can intersect with an example layer **814**. It will be understood that areas defined by such intersections are not necessarily equivalent to a "pixel." In some applications, the size of a pixel essentially places a limit on the resolution of the image generated therefrom, whether or not the detector is capable of better resolution.

In FIG. **27**, an example area **818** is defined as an intersection area defined by the scanline **812***b* and the layer **814**. In one embodiment, such an area defines a window (or depth-of-field of the scanline) in which a focus is performed. In one embodiment, if the area is not divided up any more, then that area can be considered to be a pixel for the purpose of imaging.

In one embodiment, the size of the focus area defined in the foregoing manner does not need to be fixed. As described below in greater detail, the layer **814** can be initially selected to be relatively large. Once a "coarse focus" is achieved for such a layer, that layer can be split into thinner layers. Then, the scanline(s) can be "fine focused" if desired and/or able to. Thus, as shown in FIG. **27**, the layer **814** can be split into thinner layers such as an example layer **816**, and a focus area **820** would be associated with that relatively thinner layer.

FIGS. **28** to **30** now show by example how scanlines associated with three example receivers can be brought into focus at different layers. For the purpose of description, an example array of three receivers **810***a-c* are shown in FIGS. **28**A, **29**A, and **30**A. Associated with the receivers **810***a-c* are imaginary lines **812***a-c* that extend therefrom respectively. For the purpose of description, the lines **812***a-c* are divided into three example layers **822***a-c*. Also for the purpose of description, a

first feature of interest **824** is shown to be located generally in an area defined by the line **812***a* and the layer **822***b*. A second feature of interest **826** is shown to be located generally in an area defined by the line **812***b* and the layer **822***a*. A third feature of interest **828** is shown to be located generally in an area defined by the line **812***c* and the layer **822***c*. For the purpose of showing how different features of interest can be shifted in sampling time, the three features of interest are depicted as triangle **824**, circle **826**, and square **828**.

FIGS. **28**B, **29**B, and **30**B are also common, showing that data traces **830***a-c* associated with their respective receivers **810***a-c* "sees" the three example features of interest **824**, **826**, and **828** at relatively different times. For example, the triangle **824** is generally in front of and closest to the receiver **810***a*. Consequently, as the data trace **830***a* associated with the receiver **810***a* shows, the receiver **810***a* will likely receive a return signal from the triangle **824** first, followed by the receiver **810***b*, which in turn is followed by the receiver **810***c*. Similarly, the circle **826** is generally in front of and closest to the receiver **810***b*. Consequently, as the data trace **830***b* shows, the receiver **810***b* will likely receive a return signal from the circle **826** first, and the receivers **810***a* and **810***c* after that.

As shown in FIGS. **28**A, **29**A, and **30**A, the receivers **810***a-c* are depicted as being arranged in an ordered array. It will be understood that such a depiction is only for the purpose of describing the concept of relative arrival times of return signals to the different receivers, and how such signals can be combined to form a focused scanline. In particular, it will be understood that although the example receivers **810***a-c* are shown in sequence, they do not necessarily need to be as such physically. For example, different receiver-offset data can be combined as described above; and in such situations, the receivers whose signals are being combined may not be next to or even relatively close to each other. Thus, the arrangement of the receivers **810***a-c* should be considered to represent a logical arrangement for the purpose of description.

FIG. **28**C shows an example focused layer **838***a* for a scanline **834** associated with the receiver **810***a*. Depicted along with the scanline **834** are relative peak heights **836** associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **832** of shifted traces. It will be noted that one does not need to know how much to shift one trace relative to another trace beforehand to achieve a focus. A method for determining a focused state from different combinations of shifting is described below in greater detail. For the purpose of describing the result of such focusing for a given scanline in reference to FIGS. **28-30**, the scanlines are depicted as being brought into focus.

Similarly, FIG. **28**D shows an example focused layer **838***b* for the scanline **834** associated with the receiver **810***a*. Depicted along with the scanline **834** are relative peak heights **836** associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **840** of shifted traces.

Similarly, FIG. **28**E shows an example focused layer **838***c* for the scanline **834** associated with the receiver **810***a*. Depicted along with the scanline **834** are relative peak heights **836** associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **844** of shifted traces.

In FIG. **28**D, one can see that the focused layer **838***b* results in an enhance peak **842** corresponding to the aligning (by proper shifting of the data traces) of the triangle **824**. Such enhanced peaks can be utilized to determine whether a scanline is in focus in a given layer. Such determination is described below in greater detail.

Also note that for the line **812***a* associated with the receiver **810***a*, the first and third layers **822***a* and **822***c* do not have any features. Thus, an image resulting from a properly focused scanline should not show features in those two layers **822***a* and **822***c*. In one embodiment, such result can be achieved by making a threshold cut on the peak(s) in a given focused layer so that peaks below that threshold are not processed for image formation. For example, if one was to set the threshold so as to accept the enhanced peak **842** but reject lower peaks, the first and third focused layers **838***a* and **838***c* can form focus areas having substantially null images.

FIG. **29**C shows an example focused layer **848***a* for a scanline associated with the receiver **810***b*. Depicted along with the scanline are relative peak heights associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **846** of shifted traces.

Similarly, FIG. **29**D shows an example focused layer **848***b* for the scanline associated with the receiver **810***b*. Depicted along with the scanline are relative peak heights associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **852** of shifted traces.

Similarly, FIG. **29**E shows an example focused layer **848***c* for the scanline associated with the receiver **810***b*. Depicted along with the scanline are relative peak heights associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **854** of shifted traces.

In FIG. **29**C, one can see that the focused layer **848***a* results in an enhanced peak **850** corresponding to the aligning (by proper shifting of the data traces) of the triangle **826**. Such an enhanced peak can be used to form an image for the area associated with the line **812***b* and the layer **848***a*.

FIG. **30**C shows an example focused layer **858***a* for a scanline associated with the receiver **810***c*. Depicted along with the scanline are relative peak heights associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **856** of shifted traces.

Similarly, FIG. **30**D shows an example focused layer **858***b* for the scanline associated with the receiver **810***c*. Depicted along with the scanline are relative peak heights associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **862** of shifted traces.

Similarly, FIG. **30**E shows an example focused layer **858***c* for the scanline associated with the receiver **810***c*. Depicted along with the scanline are relative peak heights associated with the combined return signals from the three features **824**, **826**, and **828** when the scanline is in focus. Relative shifting of return signal traces to achieve the focus is shown as a set **864** of shifted traces.

In FIG. **30**E, one can see that the focused layer **858***c* results in an enhanced peak **860** corresponding to the aligning (by proper shifting of the data traces) of the square **826**. Such an

enhanced peak can be used to form an image for the area associated with the line **812***c* and the layer **858***c*.

In one embodiment, a layer closest to a given receiver is focused first, followed by successive layers therefrom. Focusing of a given layer allows determination of propagation time within that layer, since the amount of shifting of various data traces depends on how much differences there are in the propagation times. Thus, a given layer is brought into focus when the proper amount of shifting is applied (i.e., when the proper propagation time is determined for that layer).

In one embodiment, the foregoing focusing process and/or the focus results therefrom can be implemented with physical movements of one or more transducer elements. For example, arrays having movable elements similar to that of adaptive optics can be adjusted to either aid the focusing process, or to re-position the elements so that subsequent focusing process can be achieved more efficiently. In one specific example, suppose that a focused section of a scanline is achieved when data traces from one or more receivers are shifted so as to be near their limits. In such cases, the corresponding receivers may be moved so as to introduce changes in propagation times thereto, so that likely "focused" sections of the corresponding data traces are now located more centrally, thereby providing more "working" room in the shifting of data traces.

By focusing on the closest layer, the propagation time for that layer is determined. Focusing of the next layer can then be facilitated by the knowledge of the first layer. This building of propagation time information can build successively outward away from the receiver.

It will be understood that the shifting of data traces described for the purpose of combining those data traces refer to shifting in time. In one embodiment where each data trace includes a series of digital representation of samplings, each sampling has a time associated with it. Thus, time-shifting can be in the form of shifting data trace based on such "time stamp" of the samplings. Based on the foregoing, a "time-shift combination" operation includes shifting of time or phase associated with portions of a plurality of data traces with respect to each other. For example, if a scanline is being focused at a given layer, temporal ranges of data traces being combined can be identified (for example, by an initial estimation based on geometry). Then, digital data within those ranges can be shifted with respect to each other and combined to yield a quality value associated with that combination.

FIGS. **31**A-C show such a successive layer characterization method. In FIG. **31**A, an arrow **872** directed away from a receiver indicates the order of layer characterization. Also in FIG. **31**A, an example layer **866** is shown. If that layer is to be split for finer focusing, such as layers **868***a* and **868***b* in FIG. **31**B, characterization of those sub-layers can be characterized successively beginning from the sub-layer closest to the receiver (as indicated by an arrow **874**). Similarly, each of the sub-layers **868** can be split further into layers **870***a-b* and **870***c-d*. Again, such layers can be characterized successively beginning from the one closest to the receiver (as indicated by an arrow **876**).

It will be understood that the foregoing successive layer characterization (beginning with the closest layer to the receive) is just one example of focusing on the plurality of layers. As described herein, focusing on a given layer does not necessarily depend on the knowledge of another layer. Thus, focusing can begin at any layer in the medium without departing from the scope of the present teachings.

FIGS. **32-33** now show how a scanline can be focused at a given layer—that is, how signal traces from different receivers can be combined so as to optimally enhance perturbation features of interest. For the purpose of describing the focusing technique, "velocity" (generally inversely proportional to time) is used to characterize the propagation time within a given layer. It should be noted that in the focusing technique of FIG. **32-33**, a prior knowledge of velocity is not necessary.

FIG. **32** shows a process **880** for determining focused scanlines for one or more receivers at different layers. In one embodiment, the process **880** further includes finer-focusing capability that splits a given layer if that split provides an improved scanline focus quality. The process **880** in general includes a process block **882** where input parameters are obtained. Some of the input parameters are described in a more specific process in reference to FIG. **33**.

The process **880** then loops through the receivers (end loop **914**). In a process block **886**, the process **880** determines the position of a scanline corresponding to the current receiver. For the current receiver, the process **880** loops through each of the Z layers (end loop **912**). In one embodiment, the layers are successively looped through from layer one to layer Z, with layer one being the closest to the receiver.

For the current receiver and the current layer, the process **880** in a process block **890** determines a velocity value that results in the best degree of focus for the current scanline in the current layer. Various methods of determining the degree of focus selecting the "best" therefrom are described below in greater detail. As previously described, a prior knowledge of velocity value is not necessary. However, providing a likely range of velocity values may result in a more efficient combinatoric computation for combining and determining the degree of focus.

The process **880** in a process block **890** then updates the velocity data corresponding to the current scanline and the layer. Such data can be stored as a table, or any manner that allows retrieval for later use.

In one embodiment, the current layer is initially split into sub-layers in a process block **894**, and focusing is performed in each of the newly created sub-layers in a sub-layer loop **896** (end loop **900**). Each of these sub-layers may be further split, and each of those newly created layers may undergo similar loop. This successive splitting process may continue further. Thus, for the purpose of description, the sub-layer loop **896** is depicted as a module that can be accessed whenever a set of sub-layers are looped through.

Within the sub-layer loop **896**, the process **880** in a process block **898** determines a velocity value that results in the best degree of focus for the current sub-layer. Whether that velocity value will replace the existing velocity value for the area overlapping the current sub-layer depends on whether the current sub-layer focus is an improvement. In one embodiment, such determination can be made on a sub-layer by sub-layer basis, or collectively for the set of sub-layers. As an example, an average of the degrees of focus for the sub-layers can be compared to the degree of focus for the parent layer. For the purpose of description, the process **880** is shown to determine if the degree of focus has improved collectively by the split in a process block **902**.

Once such determination is made, the process **880** in a decision block **904** determines whether the focus has improved by the split. If the answer is "yes," then the process **880** in a process block **906** updates the velocity table for the sub-layers of the current layers. To see if the focus can be made even finer, thereby improving the resolution, each of the current sub-layers are further split in a process block **908**, and focusing is performed on each of the newly created sub-layers by invoking the sub-layer loop **896**. If the answer in the decision block **904** is "no," then the process **880** removes the previous split in a process block **910**, since the finer "focus" did not yield a better result.

FIG. **33** now shows a more specific example process **920** of how the process **880** of FIG. **32** can be implemented. For the purpose of simplicity, the process **920** is described for one given receiver. But as shown in FIG. **32**, such a process can be looped over a plurality of receivers.

The process **920** in a process block **922** determines the position of a scanline associated with the receiver being analyzed. In a process block **924**, a maximum number of sub-layers within a given layer is obtained. In one embodiment, that maximum number places a limit on the extent of splitting for finer focusing. In a process block **926**, the process **920** obtains a level of focus quality improvement to trigger additional splitting for finer focusing. In a process block **928**, the process **920** obtains a current velocity table for the layers if available and/or desired. In a process block **930**, a seedpoint (such as a value representative of a lowest expected velocity) is obtained if available and/or desired. In a process block **932**, the process **920** obtains the range and increment of velocity for determining the velocity associated with the best degree of focus.

The process **920** then loops through layers one to Z in a loop **936** (end loop **960**). For each current layer, the process **920** loops through the range of velocity values in a loop **936** (end loop **942**). For the current velocity value, the process **920** generates a scanline at the current layer in a process block **938**. The process **920** then determines a degree of focus of the scanline for the current velocity in the process block **940**.

Once the process loop **936** is completed, the process **920** in a process block **944** determines a velocity that results in the best degree of focus for the current layer. In a process block **946**, the process **920** splits the current layer into two sub-layers if the current number of sub-layers is less than the selected maximum number of sub-layers (obtained in the process block **924**). In a process block **948**, the velocity table is updated with the velocity value that gave the best degree of focus for the current layer.

The process **920** then loops through the newly created sub-layers (if any) in the process block **946** in a loop **950** (end loop **954**). For each sub-layer, the process **920** in a process block **952** loops through the velocity range and determines a velocity value that results in the best degree of focus for that sub-layer in a manner similar to that of the loop **936**. The process **920** then determines if degree of focus associated with the sub-layers is better than that of the parent layer in a process block **956**. In one embodiment, the new degree of focus is considered to be better than that of parent layer if it exceeds the level of focus quality improvement obtained in the process block **926**.

If the sub-layer degree of focus is better than the parent layer degree of focus, the process **920** in a process block **958** updates the velocity table and splits each of the current sub-layers into two sub-layers. Again, this splitting can be limited by the maximum number of sub-layer as determined in the process block **924**. If the sub-layer degree of focus is not better than the parent degree of focus, the process **920** removes the previous split and retains the parent layer level of focus.

In the description herein in respect to FIGS. **26-33**, various references are made about focusing, degree of focus, and the like. FIGS. **34**A and B now show by example how a focus can be achieved by determining a parameter representative of the best degree of focus. A "focus" associated with an array of signal values can be determined in a variety of ways. For example, some autofocus cameras compare relative contrasts of adjacent or nearby signal values—the reason being that a sharply focused image will have more of a sudden change in the contrast. A similar method can be applied for determining the degree of focus for a scanline of interest.

In one embodiment, the splitting of layers can provide a substantial advantage in how effectively a given volume can be imaged. As an example, suppose that a volume includes a relatively small group of features of interest localized in a relatively small region. The rest of the volume is substantially homogeneous for the purpose of propagating signals. Such homogeneous portions likely will not need to be split, since the velocity therein is substantially uniform. When the small inhomogeneous region is encountered, it can be split into smaller layers to allow characterization of sub- regions with different velocity values. Thus, one can see that the combining process does not need to waste time attempting to split the homogeneous portion. Moreover, the inhomogeneous region can be characterized better by the splitting method, thereby allowing improved characterization of the volume.

FIG. **34**A shows the shifted data trace set **840** corresponding to "in focus" configuration as described above in reference to FIG. **28**D. FIG. **34**A further shows one of a number of possible ways of determining the degree of focus for the trace combination set **840**. In one embodiment, a running average of the combined scanline is obtained for a selected window. In one embodiment, such a window may overlap the focus layer **838***b* and extend beyond. In one embodiment, the window may be defined as temporally substantially similar to the boundaries corresponding to the focus layer **838***b*.

In one embodiment, the running averages are formed by a plurality of partially overlapping averaging intervals **970**. Average values **972** associated with the intervals **970** are depicted at the approximate centers of the intervals **970**.

FIG. **34**B show a shifted data trace set **980** corresponding to "almost in focus" configuration. In particular, the combination **980** has the second trace (**990** in FIG. **34**B) not shifted as much as that of FIG. **34**A. Average values **982** associated with the running average intervals are also shown.

In one embodiment, a best degree of focus can be determined by looking for the greatest change in the running average value. Thus in the example scanlines shown in FIGS. **34**A and B, a change in average denoted as **974** is has the greatest slope (i.e., the greatest "contrast") within the window. The data trace combination **840** corresponds to the greatest slope **974**, and thus represents the "in focus" scanline having the best degree of focus value (in this example, the greatest slope).

In another embodiment, a best degree of focus can be determined by looking for the greatest sum of average values within the window. In FIGS. **34**A and B, one can see that the average values **972** add up to a greater value than that of the average values **982**. Thus, the data trace combination **840** can be said to be the "in focus" scanline having the best degree of focus value (in this example, the sum of average values).

One can see that there are many other ways of determining the best degree of focus. Thus, it will be understood that the two examples described above in reference to FIGS. **34**A and B are not to be construed as limiting the scope of the present teachings. Furthermore, "quality value" can represent the various degrees of focus described herein, and "best quality value" can represent the corresponding "best degree of focus." It will be understood that the term "best" does not necessarily mean a value having the largest value. It can mean a value having the smallest value, or any value that represents a particular combination having the desired property for the purpose of assigning to a scanline.

FIGS. **35**A and B now show block diagrams of one embodiment of a signal processing assembly **1100** that can perform various functions described herein (such as obtain-

ing data traces from receivers, digitally sampling, and combining the digitally sampled data). As shown in FIG. **35**A, one embodiment of the assembly **1100** includes a plurality of data channels **1104** that are input into a data combiner **1106**. Each data channel **1104** forms a stream of digital data corresponding to data traces from one or more receivers in a manner described below in greater detail. Thus in one embodiment, such digital data represents digital echo signals having amplitudes and time information of samplings of the data traces.

As shown in FIG. **35**A, such digital data from the data channels **1104** are combined by a data combiner **1106**. In one embodiment, the data combiner **1106** combines the digital data according to the relative orientation of the receivers with respect to transmitters. For example, data corresponding to offset-one receivers can be combined as one set of data. In one embodiment, such combining of data is performed by parallel processing (as depicted in FIG. **35**A) so as to allow timely processing of relatively large amount of data.

In one embodiment, each stream of data in the channel **1104** is associated with a receiver and a transmitter. Thus, focus information can be associated with such receiver and/or transmitter can be provided to the channel **1104** by a focus parameter database **1122**. For example, for pixel imaging, the focus information can include the transmitter and receiver alignment sets. For focusing on a layer along a scanline, the focus information can include default velocity information for the receivers.

Thus in one embodiment, an output from the data combiner **1106** represents group(s) of data corresponding to different receiver-transmitter combinations. As shown in FIG. **35**A, such combined data can form a "page" of data, and such pages of data can be further combined by a page combiner **1108**. For example, pixel intensity as determined by selected groups of transmitter-receiver combinations (pages) can be further combined to enhance the real signal from that pixel, by using the transmitter-pixel and pixel-receiver geometries. In another example, pages of data can be combined with respect to a scanline for a receiver at a given layer, such that each combination yields a degree of focus or a quality value. As described above, a "best" degree of focus or quality value can be determined in a number of ways to select a "best" scanline for the receiver.

As shown in FIG. **35**A, an output from the page combiner **1108** can be stored in a page memory **1110**. Such stored page combinations can be refined further as shown. For example, the finer focusing by layer-splitting described above can be facilitated by such a feature.

In one embodiment, the page memory **1110** can include a plurality of "final" pages of data that can be used for imaging. As shown in FIG. **35**A, such pages of data can be processed further to clean up the data and/or map to a display representation in a re-map/filter block **1112**. Output from the block **1112** can be built into a frame of image in a frame buffer **1114**, and be displayed via a display **1116**.

FIG. **35**B now shows one embodiment of each of the data channel **1104** described above in reference to FIG. **35**A. The data channel **1104** is shown to include an optional multiplexer **1132** that receives as inputs **1130** analog data traces from a plurality of receivers (not shown). In one embodiment, the multiplexer is not used, and data trace from one receiver is input into one data channel.

As shown in FIG. **35**B, the multiplexer output (or signal from the receiver) can be amplified by a pre-amp **1134** and have its temporal gain corrected by a TGC **1136**. The output from the TGC **1136** is shown to be digitally sampled by an ADC **1138** (analog-digital converter). In one embodiment, the ADC **1138** is a 12- or 16-bit amplitude ADC that samples the amplitude of the data trace at a sampling frequency.

As shown in FIG. **35**B, the output from the ADC **1140** can be cleaned up and/or formatted for subsequent processing by an optional correlator/filter **1140**. The output from the correlator/filter **1140** is input into a data memory **1142** for combining with the focus information from a focus database **1144** as described above in reference to FIG. **35**A. The output from the data memory **1142** is then sent to the data combiner (**1106** in FIG. **35**A).

One can see that foregoing example signal and data processing, such as combining of different pages of data to determine the best scanline for a given receiver, can involve a substantially large amount of computation. Timely computation of such a task can be achieved, in one embodiment, by parallel processing.

One can also reduce the amount of computation in combining of data by limiting the combinations to a selected window in time. For example, suppose each digital echo data has N samples so as to represent a sampling duration of T. As described above, one way to form an image of a scanline is to focus onto a layer that intersects with the scanline. Such a layer with a given thickness is positioned from the receiver in a known manner. Thus one can estimate the approximate time values associated with the layer based on its relative position and its thickness by knowing the average propagation velocity of the echo signal in the medium. So to image the scanline for that layer, one can limit the digital echo data to a range that corresponds to the layer thickness.

FIGS. **36**A and B now show an example image obtained using some of the imaging methods described herein. FIG. **36**A shows a black-and-white photograph of the image. FIG. **36**B shows a negative image of the photograph of FIG. **36**A. A sectional view of a plurality of wires **1200** is formed by imaging a slice through a medium **1202** where the wires are located. Each wire has a diameter (denoted as **1204**) of approximately 100 micrometers, and a spacing (denoted as **1206**) between (edge-to-edge) two closest adjacent wires is approximately 100 micrometers. The medium **1202** is water contained in a volume of approximately 350 cm^3, and the wires are located approximately 6.7 cm from an array of receivers (not shown).

To obtain such an image, **32** receivers were used to receive echo signals that resulted from sequenced transmission energy from **32** transmitters. The transmission energy was transmitted at approximately 3.5 MHz, and the echo signals detected by the receivers were sampled at a rate of approximately 20 MHz.

One can readily see from FIGS. **36**A and B that the resulting high quality and contrast image displays a spatial resolution that appears to be better than 100 micrometers. For the example transmitted 3.5 MHz signal, a corresponding wavelength in water is approximately 440 micrometers (for an average velocity of 1540 m/s). Thus, one can see that resolving of a 100 micrometers feature at the transmitted energy frequency of 3.5 MHz is equivalent to a resolution being better than quarter of the operating wavelength.

In terms of Nyquist sampling criteria, the example 3.5 MHz signal would require sampling at a rate of approximately 7 MHz (twice the signal frequency) or higher for conventional devices. In a similar token, measurement of an example feature size of 100 micrometers would require a sampling rate of approximately 30.8 MHz (twice the frequency that can be assigned to a 100-micrometer feature size—i.e., 1540 [m/s]/100 [micrometers]=15.4 MHz) for conventional devices. Thus, one can see that sampling at multiple receivers and combining data therefrom can yield a

high-quality result even if the sampling rate (example, 20 MHz) is less than the conventional Nyquist limit (example, 30.8 MHz).

From the description of the example image and the methods used herein, it is apparent that one can obtain a spatial resolution that is less than the wavelength associated with an operating transmission energy. Intrinsic resolution of a detector is often expressed in terms of λ/D, a ratio of the operating wavelength λ and the effective aperture size D of the detector. A constant factor associated with such a ratio can vary depending on the configuration of a particular detector. For the purpose of description herein, it will be assumed that the intrinsic angular resolution is represented as $\theta=\lambda/D$.

One can reduce the value of θ (i.e., increase of "better" the resolution) by either reducing the wavelength and/or increasing the detector size D. The effective size D of the detector can be increased either by increasing the individual detector size, or by forming an array whose overall size can be substantially larger than that of each detector. Such methods have been used in some fields. In the field of ultrasound imaging, Applicant believes that currently, the image quality and resolution as disclosed herein has not been achieved using conventional systems and methods. For example, one embodiment of the imaging system and method yields an angular resolution that is equivalent to using a wavelength that is less than a quarter of the operating wavelength for a given detector size D. That is, the resolution is better than $\theta=(0.25)\lambda/D$ in one embodiment.

From the description herein it is also apparent that the sampling frequency can be less than the frequencies associated with perturbation features that "ride" on the "carrier-wave" echo of the transmission energy. One way to characterize such performance is by way of Nyquist criteria that essentially states that a signal needs to be sampled at a frequency F that is at least twice the frequency of the signal to obtain any useful information. Thus for example, if a signal has a frequency of 1 MHz, it needs to be sampled at 2 MHz or higher.

If the sampling frequency is less than twice the signal frequency, an effect known as "aliasing" occurs, where frequencies above the Nyquist frequency (F/2) "fold over" to behave like lower frequencies. As is known, aliased frequency f in the range F/2 to F becomes f' that can be expressed as |f-F|.

From the description herein, it is apparent that in one embodiment (that produces the example image of FIGS. **36**A and B, for example), the sampling frequency can be less than twice the frequency associated with the size feature of interest. For example, the feature size of the wires in FIGS. **36**A and B is approximately 100 micrometers, and its corresponding "frequency" can be represented as approximately (1540 mls)/(100 micrometers)=15.4 MHz. From the results obtained by sampling at approximately 20 MHz (which is less than twice the frequency corresponding to the feature size), one can see that such relatively small perturbation features can be imaged with excellent quality and resolution.

It should be noted that for the purpose of description, the term "frequency" means the frequency associated with the central peak associated with the signal. Thus, if the signal is a sinusoidal wave, its frequency corresponds to the standard meaning. If the signal is a pulse (e.g., Gaussian shaped), then the frequency corresponds to the central peak of the pulse. If the signal is a perturbation feature having a peak structure, then the frequency corresponds to that peak.

With such example definition of frequency, one can characterize the performance of the present teachings as being able to image an echo signal in terms of spectral frequency components. If a given echo signal has a maximum intensity value, then the resolvable spectral frequency components above the Nyquist frequency of F/2 can include higher frequency components having intensities that are above a predetermined value. Such a predetermined value can be set at different values, such as 50 dB, 40 dB, 30 dB, 20 dB, 10 dB, or 10 dB less than the maximum intensity value the echo signals.

Although the above-disclosed embodiments have shown, described, and pointed out the fundamental novel features of the invention as applied to the above-disclosed embodiments, it should be understood that various omissions, substitutions, and changes in the form of the detail of the devices, systems, and/or methods shown may be made by those skilled in the art without departing from the scope of the invention. Consequently, the scope of the invention should not be limited to the foregoing description, but should be defined by the appended claims.

What is claimed is:

1. A method for ultrasonic imaging of an object, the method comprising:

in turn, for each transmitter in a plurality of transmitters, transmitting ultrasound energy from the transmitter into the object such that the ultrasound energy is scattered and detecting the scattered energy at each of a plurality of receivers to obtain signals corresponding to a plurality of transmitter-receiver pairs wherein each transmitter-receiver pair is characterized by a value, N, indicative of a spatial separation between the transmitter and the receiver of the transmitter-receiver pair;

processing the signals by:

preparing a first page by: for each pixel in a plurality of pixels within the object, sampling a plurality of those of the signals corresponding to transmitter-receiver pairs characterized by a first value of N at a first index representing a time delay corresponding to the pixel, transmitter and receiver to yield a first set of sample values corresponding to the pixel the first set of sample values including only sample values from transmitter-receiver pairs having the first value for N; and combining the values of the first set of sample values to provide first pixel values associated with the first page of data; and

preparing one or more additional pages, each corresponding to a different value for N by: for each pixel in the plurality of pixels, sampling a plurality of those of the signals corresponding to transmitter-receiver pairs characterized by the value of N corresponding to the page at a second index corresponding to the pixel, transmitter and receiver to yield another set of sample values corresponding to the pixel the another set of sample values including only sample values from transmitter-receiver pairs having the value of N corresponding to the additional page; and combining the values of the another sets of sample values to yield pixel values associated with the additional page; and,

displaying image data based on at least one of the pages.

2. A method according to claim **1** wherein:

the transmitters are provided in an array of transmitters Tx(i), where i represents a relative positional index that ranges from 1 to M, where M is greater than or equal to 2;

the receivers are provided in an array of receivers Rx(j), where j represents the relative positional index of each of said receivers, positional index j being offset from posi-

tional index i by the value N, where N ranges from zero to N_{max}, where N_{max} is a positive value greater than zero; and,

the method comprises:

storing the first page as a page of signal data generated from energy received at said receivers Rx(j) offset from said transmitters Tx(i) by the first value of N.

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

creating an image from a single one of said pages; and

displaying said image.

4. The method of claim **1** comprising:

creating an image from one of said pages;

displaying said image;

combining data from two or more of said pages to yield combined data and creating another image from said combined data;

repeating said creating another image from said combined data and displaying said another image at least once, each repetition comprising combining into said combined data at least one additional page not having been previously combined.

5. The method of claim **1**, wherein said pages are iteratively combined in a predetermined order.

6. The method of claim **5**, wherein said pages are iteratively combined in a sequential order.

7. A method according to claim **1** comprising combining at least two of the pages to provide the image data.

8. A method according to claim **1** comprising determining the first index corresponding to the pixel, transmitter and receiver by combining a first index value corresponding to the pixel and transmitter with a second index value corresponding to the pixel and receiver.

9. A method according to claim **1** wherein:

the ultrasound energy has a wavelength A corresponding to a central peak frequency of said ultrasound energy,

the transmitters are arranged in a transducer assembly such that an aperture size D is the maximum distance between any two transmitters in the transducer assembly; and

the image has a spatial resolution limit θ representing the minimum resolvable angular separation of two features within the object wherein θ is equal to or better than $\theta=(0.25)\lambda/D$.

10. An ultrasound imaging apparatus comprising:

a plurality of ultrasound transmitters and a plurality of ultrasound receivers wherein the transmitters are arranged to permit ultrasound energy to be transmitted from the transmitters into an object such that the ultrasound energy is scattered and the receivers are arranged to detect the scattered energy;

a processor configured to process signals from the receivers to yield image data; and,

a display for displaying the image data;

wherein the apparatus is configured to, in turn, for each one of a plurality of the transmitters, cause the transmitter to transmit ultrasound energy into the object and to obtain at the receivers signals corresponding to a plurality of transmitter-receiver pairs wherein each transmitter-receiver pair is characterized by a value, N, indicative of a spatial separation between the transmitter and the receiver of the transmitter-receiver pair; and

wherein the processor is configured to process the signals by:

preparing a first page by: for each pixel in a plurality of pixels within the object, sampling a plurality of those of the signals corresponding to transmitter-receiver pairs characterized by the first value of N at a first index representing a time delay corresponding to the pixel, transmitter and receiver to yield a first set of sample values corresponding to the pixel; and combining the values of the first set of sample values to provide first pixel values associated with the first page of data the first set of sample values including only sample values from transmitter-receiver pairs having the first value for N; and

preparing one or more additional pages, each corresponding to a different value for N by: for each pixel in the plurality of pixels, sampling a plurality of those of the signals corresponding to transmitter-receiver pairs characterized by a value of N corresponding to the page at a second index representing a time delay corresponding to the pixel, transmitter and receiver to yield another set of sample values corresponding to the pixel the another set of sample values including only sample values from transmitter-receiver pairs having the value of N corresponding to the additional page; and combining the values of the another sets of sample values to yield pixel values associated with the additional page.

11. Apparatus according to claim **10** wherein:

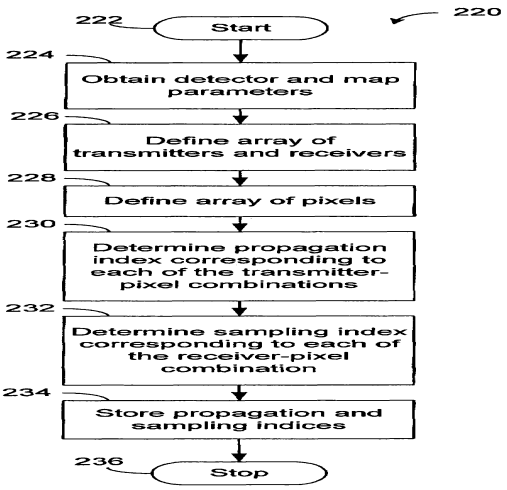
the ultrasound energy has a wavelength λ corresponding to a central peak frequency of said ultrasound energy,

the transmitters are arranged in a transducer assembly such that an aperture size D is the maximum distance between any two transmitters in the transducer assembly; and

the image has a spatial resolution limit θ representing the minimum resolvable angular separation of two features within the object, wherein θ is equal to or better than $\theta=(0.25)\lambda/D$.

* * * * *

专利名称(译)	用于改进的超声成像的系统和方法		
公开(公告)号	US7850611	公开(公告)日	2010-12-14
申请号	US10/945459	申请日	2004-09-20
[标]申请(专利权)人(译)	DAVIES TIMOTHYĴ EVANS RICHARD		
申请(专利权)人(译)	DAVIES TIMOTHYĴ EVANS RICHARD		
当前申请(专利权)人(译)	锐珂医疗，INC.		
[标]发明人	DAVIES TIMOTHY J EVANS RICHARD		
发明人	DAVIES, TIMOTHY J. EVANS, RICHARD		
IPC分类号	A61B8/00		
CPC分类号	G01S7/52028 G01S7/52046 G01S15/8918 G01S7/52003 G01S7/52036 G01S15/8927 A61B8/4483		
其他公开文献	US20060064015A1		
外部链接	Espacenet USPTO		

摘要(译)

公开了用于改善由来自接收器阵列的信号形成的图像的分辨率和质量的系统和方法。多个接收器引入到达时间的变化，其可以小于操作信号的周期，并且还小于与采样操作相关联的周期。因此，多个接收器允许对反射信号的精细特征进行采样，这些特征将被认为超出与操作信号相关联的分辨率。使用多个接收器还提供了有效的采样率，该采样率大于单个接收器的采样率。使用多个发射器可以获得类似的优点。这些有利特征可用于在诸如超声成像的应用中获得介质中的对象的高分辨率图像。