

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
22 November 2007 (22.11.2007)

PCT

(10) International Publication Number  
**WO 2007/133881 A2**

(51) International Patent Classification:

A44C 25/00 (2006.01)

(21) International Application Number:

PCT/US2007/066756

(22) International Filing Date: 17 April 2007 (17.04.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

60/747,148 12 May 2006 (12.05.2006) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM,

AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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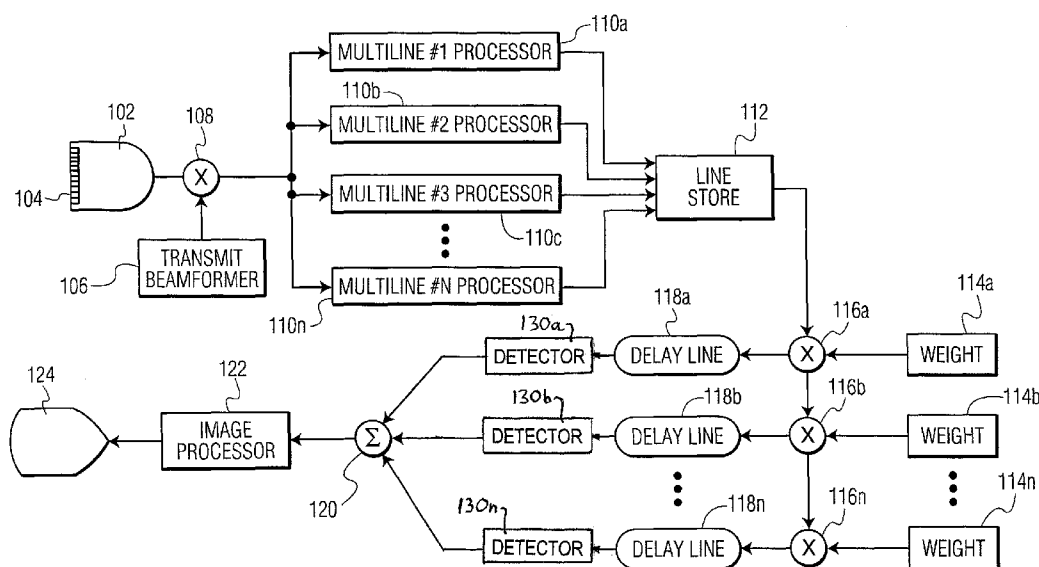
— as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))

Published:

— without international search report and to be republished upon receipt of that report

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(54) Title: INCOHERENT RETROSPECTIVE DYNAMIC TRANSMIT FOCUSING



(57) Abstract: An ultrasonic diagnostic imaging system produces an image with an extended focal range and reduced speckle by transmitting a plurality of beams spaced along an array for multiline reception. The receive multilines of a plurality of transmit beams are spatially aligned with phase adjustment between the respective receive multilines to effect signal alignment, detected and combined. The combined multilines produce the effect of an extended transmit focus so that an image produced using the combined multilines exhibits an extended focal range. Speckle is reduced by nonlinearly combining received multilines produced by different transmit apertures.

## INCOHERENT RETROSPECTIVE DYNAMIC TRANSMIT FOCUSING

This invention relates to medical diagnostic ultrasound systems and, in particular, to ultrasound systems which extend the focal region using a multiline receive beamformer.

The principles of synthetic focusing, by which an ultrasound image is focused at every point in the image field, have been the subject of considerable investigation. For instance, US patent 4,604,697 (Luthra et al.) describes a synthetic focus technique in which an ultrasound pulse is sequentially transmitted from each element of an ultrasonic transducer array. The echo signals received from each transmission is received by all of the elements of the array and are stored. After all of the signals have been received a focused echo signal can be formed at each point in the image field from the knowledge of the location of each transducer element relative to each point in the image and the time of flight of an ultrasound signal to and from each point. The appropriate received signals are combined to form a coherent echo signal for each point in the image. The selection of the stored data values used to form each point provides the beamformation for each point in the image. While this method will produce a focused signal at every point in the image field, it has several drawbacks. One is that the r.f. signals from the entire image field must be stored for processing. This requires a significant amount of information storage. A second drawback is that a significant amount of processing is required to select and weight the data for each point in the image, then combine the appropriately weighted data to compute the image data points. A third drawback

is that this approach is effective for only a shallow penetration depth, since the energy transmitted by a single transducer element is limited.

5 A specific application which employs the basic principles of synthetic focusing is the traditional delay-and-sum receive beamformer, in which the delays applied to the signals from each receiving element are the equivalent of data selection in the synthetic focus technique. The traditional beamformer is a  
10 limited application of these principles as it transmits a transmit beam focused at a specific focal region and dynamically focuses echoes only along this single transmit beam. Multiple transmissions are thus required to scan the entire image field. A  
15 resulting efficiency is that data does not need to be stored for all transmissions to every point in the image; the data received from a transmission is immediately processed to form coherent echo signals along the beam direction. A limitation is that each  
20 received beam is focused on transmit to only the selected focal region. But the signal-to-noise ratio at greater depths is improved because multiple transducer elements are actuated to transmit a beam, enabling a reasonable penetration to be obtained.

25 US patent 6,231,511 (Bae et al.) and a subsequent paper entitled "A Study of Synthetic-Aperture Imaging with Virtual Source Elements in B-Mode Ultrasound Imaging Systems" by Bae et al., IEEE Trans. UFFC, vol. 47, no. 6 (2000) at 1510 et seq.  
30 propose to combine aspects of the standard focused beamformer and synthetic focusing to improve lateral resolution outside of the conventional focal region and thus achieve the effect of transmit focusing at all points in the image field. This approach is  
35 premised upon the assumption of a "virtual source

element" at the focal point of a standard transmitted beam which radiates energy both outward and inward from this "virtual source." Following transmission of a standard transmit focused beam, energy is  
5 received by the transducer elements of the receive aperture and stored. After the entire image field has been scanned, an echo signal at each point is computed from the signals received by elements of each virtual source field which encompassed the point  
10 in the field. Image points at the focal point will be imaged from only one beam, as the virtual source model is an hourglass-shaped field about the transmit focal point, but points further removed in depth from the focal point are computed from the received  
15 signals of many scanlines. The result is said to be an image which shows improved lateral resolution at points outward and inward from the transmit focal point. But like the basic synthetic aperture approach described above, a significant amount of  
20 data must be stored for processing, the r.f. signals from every element in each receive aperture. In addition the resultant image is said to appear darker around the focal point, since only one transmission and reception contributes to this image point and its  
25 resolution, whereas multiple transmissions and receptions contribute to points removed from the transmit focal point. Accordingly it is desirable to effect transmit focusing over at least a significant portion of an image but without the need to store  
30 vast amounts of r.f. data.

A diagnostic ultrasound system and technique which overcome these shortcomings of prior art approaches is described in co-pending US patent application serial number 60/747148, filed May 12,  
35 2006, which describes a technique known as

retrospective dynamic transmit focusing (RDT). In this approach groups of multilines are acquired which overlap spatially so that several resulting multilines are spatially co-aligned and hence from the same receive location. Spatially aligned multilines are then combined with a weighting function, e.g., apodization, if desired, and an inter-multiline delay which is generally related to the location of transmit beam centers to the received multiline location, which prevents undesired phase cancellation in the combined signals. The weighted and delayed multilines are then combined to produce a resultant line for display. This technique is advantageous because it improves the depth of field of the image by combining multiple received signals, and the effective beamforming from the received multilines causes the combination of multilines to be effectively transmit focused over a considerable depth of field. Hence the name retrospective dynamic transmit focusing.

The RDT technique as described above is a coherent signal process, as it operates on signals as a function of both amplitude and phase characteristics. Ultrasonic imaging is a coherent process *in vivo* since the echoes reflected back to the transducer elements from reflectors in the body will have their own amplitude and phase characteristics. A disadvantage of this coherent character is that the reflected signals will both constructively and destructively interfere with each other, producing a mottled pattern known as "speckle" which overlays the desired tissue image and detracts from the image contrast. Since the speckle pattern has no phase or amplitude variation over time, it cannot be suppressed simply by averaging the image

signals over time. Consequently it would be desirable to be able to conduct RDT focused imaging while at the same time suppressing the speckle pattern.

5           In accordance with the principles of the present invention, a diagnostic ultrasound system and method are described in which the RDT technique is performed incoherently, effecting both an extended transmit focus over a significant depth of field and a  
10           reduction of the speckle effect. In an illustrated example of the present invention, this is done by nonlinearly processing the multiline signals (as by detection) prior to combining. Since the multilines from different transmit signals have slightly  
15           different transmit apertures, combining the multiline signals as detected rather than r.f. data will cause a compounding effect which reduces the speckle.

          In the drawings:

          FIGURES 1a-1c illustrate beam profiles of a  
20           three-beam example of the present invention.

          FIGURES 2a-2d illustrate beam profiles of a six-beam example of the present invention.

          FIGURES 3a-3d illustrate a four-beam example of the present invention in which the first four beam  
25           patterns are offset for clarity of illustration.

          FIGURES 4a-4d illustrate a continuation of the four-beam example of FIGURE 3 showing the alignment of the receive beams.

          FIGURE 5 illustrates in block diagram form an  
30           ultrasound system constructed in accordance with the principles of the present invention.

          FIGURES 6a and 6b illustrate the delay and weighting characteristics of two different beams of the four-beam example of the present invention.

35           Referring first to FIGURES 1a-1c, overlapping

beam profiles are shown for the transmission of three transmit beams followed in each case by the reception of three beams from each transmit beam. FIGURE 1a shows the transmit beam profile 10 at a constant  
5 level below the intensity peak at the center of the beam, transmitted by and extending from a transducer array 8 that transmitted the beam. The transmit beam profile level is chosen by the designer and may be 3 dB, 6 dB, 20 dB, or some other level below the  
10 maximum intensity at the center of the beam. The beam profile is seen to be focused about a focal point 12 at the narrowest width of the beam profile by conventional transmit focusing. An orthogonal view of the beam 20 is shown below the transducer  
15 array 8 which is seen to comprise a center lobe 20a and side lobes on either side of the main lobe 20a. The transmitted beam reaches its tightest focus at the focal region 12 and diverges thereafter. In other implementations a diverging transmit beam may  
20 be used. Focusing at a considerable depth has also been found to be effective.

The transmit beam 10, 20 is transmitted with a width that encompasses multiple receive lines 14, 16, and 18. Generally a wider beam is produced by  
25 transmitting from a smaller transmit aperture. That is, a lesser number of elements of the array 8 are actuated to transmit the beam than the total number of elements across the array. Following transmission echoes are received and focused along three receive  
30 line locations 14, 16 and 18. As discussed below, the echoes received by the transducer elements of the receive aperture are delayed and summed in three different ways to form multiple lines at different line locations 14, 16, and 18 in response to one  
35 transmit beam. In this example receive line 14 is

received down the center of the transmit beam 10, 20  
and receive lines 14 and 18 are laterally steered and  
focused to be received on either side of the center  
line. In this example only the near field and far  
5 field portions of the outer lines 14 and 18 are  
within the transmit beam profile 10. In these  
regions the outer lines 14 and 18 are received from  
transmit energy on either side of the center line  
position thereby sampling targets in the image field  
10 on both sides of the center line position, thereby  
efficiently using the laterally spread energy of the  
transmit beam in the near and far fields for image  
reception and resolution.

In FIGURE 1b a second beam has been transmitted  
15 by shifting the transmit aperture to the right by the  
spacing of one receive line. The second transmit  
beam has the same beam profile as the first transmit  
beam and is outlined by beam profile curves 10'. As  
in the case of the first beam, three receive lines  
20 are simultaneously received and beamformed in  
response to the second transmission at receive line  
locations 16', 18' and 22. As a result, receive line  
16' is aligned with receive line 16 from the first  
transmission, receive line 18' is aligned with  
25 receive line 18 from the first transmission and  
receive line 22 is located to the right of the center  
line 18' of the second transmission. Like the first  
set of receive lines, the second set of receive  
multilines 16', 18', and 22 is saved for subsequent  
30 processing.

In FIGURE 1c a third beam has been transmitted  
from a center aperture location which is again  
shifted to the right by one receive line. This  
transmit beam is outlined by beam profile 10" and the  
35 transmission is followed by the simultaneous



reception of three receive lines 18", 22' and 24". These three receive lines, like the previous receive lines, are wholly or partially within the beam profile of their transmit beam with the same spacing as the lines of the preceding beams. As a result, receive line 18" is axially aligned with receive line 18' of the second transmission and receive line 18 of the first transmission, and receive line 22' is axially aligned with receive line 22 of the second transmission. The targets in the path of receive lines 18, 18' and 18" have now been sampled by three receive lines, each by a respectively different transmit beam. These co-aligned beams are combined as described below to produce a line of image data along the line which are focused over a greater depth of field than is the case of any individual line, creating an extended transmit focus effect. The focusing will be effective over a greater depth of field as the echo energy from three beam transmissions is combined to produce the resultant image data.

Transmission and reception continues across the image field in this manner until the full image field has been scanned. Each time the maximum number of receive lines for a given line location has been acquired, three in this example, the receive lines are processed together to produce a line of image data at that location. There is thus no need to store pre-summed r.f. data from any transmission as the received r.f. signals are beamformed into multiple lines as they are received, and there is only a limited need to store previous lines at a line location until all of the receive lines at the location have been acquired, at which time they can be processed and the line storage freed up for

storage of subsequent lines.

FIGURES 2a-2d give another example of the present invention in which the transmit beam profile 30 includes all or portions of receive lines at six  
5 receive line locations, identified at 31-36 in FIGURE 2a. In this example, unlike the first, there is no receive line at the center of the transmit beam. Instead, central receive lines 33 and 34 are spaced one-half of a receive line spacing on either side of  
10 the center of the transmit beam. The outer receive lines 32 and 35 are within the beam profile 30 in the near and far fields, and only near field portions of the outermost receive lines 31 and 36 are within the transmit beam profile. It may be decided not to use  
15 these near field line portions 31 and 36 in image data formation as explained below.

The next transmit beam is transmitted to the right of the first transmit beam by one receive line spacing as shown by the profile 30' of the second  
20 transmit beam in FIGURE 2b. Six receive lines are again received and beamformed simultaneously at receive line locations 32', 33', 34', 35', 36' and 37. The first five of these receive lines are seen to be aligned with receive lines 32, 33, 34, 35 and  
25 36 of the first transmit beam, thus providing a second receive line for processing at each of these line locations. FIGURE 2c shows the results following transmission of a third transmit beam and reception of six receive lines within that beam  
30 profile 30". There now have been all or parts of three receive lines received at line locations 33", 34", 35" and 36", two receive lines at location 37', and a portion of one receive line at location 38. Following a fourth transmission, indicated by beam  
35 profile 30"' in FIGURE 2d, there have been all or

portions of four receive lines received at line locations 34'", 35'" and 36'", three receive lines received at line location 37", two receive lines received at line location 38' and a portion of one receive line received at line location 39. It can be seen that, when scanning continues in this manner, there will be all or portions of six receive lines received at the line locations across most of the aperture, except at the extremes where fewer lines will have been received as shown in this example. The greater number of samplings of each receive line location results in better effective transmit focusing when the receive line data is combined to form the image data.

Higher numbers of simultaneously received lines may be used, such as eight, twelve or sixteen spaced apart, simultaneously received lines, for which a lower F number on transmit should be used to insonify the greater expanse of receive line locations.

FIGURES 3 and 4 illustrate another example of the present invention using four receive lines from every transmit beam. In these drawings the successive beam and receive line groups are not overlapping but are vertically aligned for clarity of illustration. Each transmit beam 40-1, 40-2, 40-3, etc. is indicated by a dashed arrow pointing downward, and the receive lines from each transmit beam are shown as solid line arrows on either side of the respective transmit beam. FIGURES 3a-3d illustrate the first four transmit-receive sequences, with the transmit beam 40-n being shifted to the right by one receive line spacing for each successive transmit interval. At the end of this transmit-receive sequence it is seen that four receive lines have been received which are aligned with receive

line 44: receive line 44-1 from the second beam,  
receive line 44-2 from the third beam, and receive  
line 44-3 from the fourth beam. These four receive  
lines are combined to produce a line of image data at  
5 the location of these receive lines in the image  
field.

FIGURES 4a-4d show a continuation of the  
previous transmit-receive sequence with four more  
transmit-receive intervals of four simultaneously  
10 received lines for each transmit beam. The next four  
transmit beams are identified as 40-5, 40-6, 40-7,  
and 40-8 in these drawings. As these drawings  
illustrate, there now have been four receive lines  
received at line locations 44, 45, 46, 47 and 48.  
15 After the four receive lines at each of these  
locations has been received the four lines can be  
combined to form one line of image data and the  
stored receive lines deleted so that subsequent lines  
can be stored in the same storage locations. Each  
20 time another fourth line of a group of four aligned  
lines has been received, the four lines of the group  
can be combined to form the line of image data at  
that location and the storage used for subsequent  
lines. The sequence continues in this manner,  
25 receiving four receive lines for each transmitted  
beam across the image field so that four receive  
lines may be combined at each line location over all  
but the lateral extremities of the image field.

FIGURE 5 illustrates in block diagram form an  
30 ultrasonic imaging system constructed in accordance  
with the principles of the present invention. An  
ultrasonic probe 102 includes a transducer array 104  
of transducer elements. Selected groups of the  
transducer elements are actuated at respectively  
35 delayed times by the transmit beamformer 106 to

transmit beams focused at selected focal regions in the desired directions and from the desired origin(s) along the array. The transmit beamformer is coupled to the transducer elements by a transmit/receive  
5 switch which may comprise a crosspoint switch that protects the receiver inputs from the high voltage transmit pulses applied. The echoes received by each transducer element of the array 104 in response to each transmit beam are applied to the inputs of  
10 multiline processors 110a-110n. Each multiline processor comprises a receive beamformer which applies its own set of delays and, if desired, apodization weights to weight the received echoes from the array elements to form a differently steered  
15 receive beam from the same transmit beam. Suitable multiline beamformers for the multiline processors 110a-110n may be found, for instance, in US Pat. 6,695,783 (Henderson et al.) and US Pat. 5,318,033 (Savord). The outputs of the multiline processors  
20 110a-110n are coupled to a line store 112 which stores the received multilines at least until all of the multilines needed to form a line of display data have been acquired. The group of multilines used to form a particular line of display data are applied to  
25 respective ones of multipliers 116a-116n to produce the display data for the corresponding line location. The echo data from each line may, if desired be weighted by apodization weights 114a-114n. In general, these weights will weight each line as a  
30 function of its round-trip impulse response. A suitable weighting algorithm can be derived by letting the term *amplitude(x,z)* be theinsonification amplitude of a point at location (x,z) in the image field by the transmit wave-front, the azimuth  
35 position  $x=0$  corresponding to the center axis of the

transmit beam. Let  $X$  be the azimuth of the received multiline with respect to the transmit beam axis. The weight applied to this received multiline to form a point of the image at depth  $Z$  is:

5

$$\text{Weight}(X,Z) = \text{amplitude}(X,Z)$$

For determination of an appropriate delay characteristic, let  $\text{propagation\_time}(x,z)$  be the  
10 propagation time needed by the transmit wavefront to reach a point at location  $(x,z)$ , the azimuth  $x=0$  corresponding again to the center axis of the transmit beam. Let  $X$  be the azimuth of the receive line with respect to the transmit beam axis. The  
15 delay applied to this received multiline to form a point of the image at depth  $Z$  is:

$$\text{Delay}(X,Z) = \text{propagation\_time}(X,Z) - \text{propagation\_time}(0,Z)$$

20 where  $\text{propagation\_time}(0,Z)$  is the time to reach a point at the same depth but on-axis.

The functions  $\text{amplitude}(X,Z)$  and  $\text{propagation\_time}(X,Z)$  may, for example, be obtained from a simulation of the transmit field. An  
25 appropriate way to compute the propagation time is to use the phase delay of the field from monochromatic simulation at several frequencies. The amplitude may be computed by averaging the amplitude of the field at several frequencies. In addition, a depth-  
30 dependent normalization can be applied to the weights. This multiplies all the weights at a given depth by a common factor. For example, the normalization can be chosen so that speckle regions have uniform brightness with depth. By varying the  
35 weights as a function of depth, it is possible to

vary the size and shape (apodization) of the aperture dynamically with depth.

5 The amplitude and propagation time do not need to be derived from a simulation of the exact transmit characteristics used in the system. The designer may choose to use a different aperture size or a different apodization for example.

10 The echoes from each line are weighted by the multipliers 116a-116n and delayed by delay lines 118a-118n. In general, these delays will be related to the location of the transmit beam center to the receive line location as shown above. The delays are used to equalize the phase shift variance that exists from line to line for the multilines with differing  
15 transmit-receive beam location combinations, so that a loss of precision will not be caused by misalignment of the combined signals. It will be appreciated that in a digital system the delay lines may be effected by storing the weighted multiline  
20 echo data in memory and reading the data out at later times which effect the necessary delay. Shift registers of differing lengths and clock signals may also be used to effect a digital delay, or an interpolating beamformer such as that described in  
25 the aforementioned US Pat. 6,695,783 may be used.

In accordance with the principles of the present invention the multiline signal are nonlinearly processed before being combined. In the example of  
30 FIGURE 5 this is accomplished by amplitude detection of the r.f. signals by detectors 130a-130n. Since each received multiline bears a slightly different relation to its transmit beam center than the other multilines in the combination, each multiline exhibits a slightly different speckle pattern.  
35 Detection removes the phase information from the

signals so that the incoherent combining of the multilines will effect an averaging of the speckle characteristics, improving the desired signal to speckle noise ratio by approximately the square root of N, where N is the number of independent multilines being combined. The delayed and detected signals are combined by a summer 120 and the resultant signals are coupled to an image processor 122. The image processor may perform scan conversion or other processing to improve the displayed image. The resultant image is displayed on an image display 124.

In the system of FIGURE 5 the combining of the respectively delayed multilines effect a refocusing of the signals received from the several receive multilines which are co-aligned in a given direction. The refocusing adjusts for the phase differences resulting from the use of different transmit beam locations for each multiline, effecting signal alignment in the combined signals. At the same time, the detection enables the speckle patterns of the respective multilines to be averaged and reduced while causing but a small diminution from the loss of coherent refocusing. The weights 114 weight the contributions of the multilines in relation to the proximity of the transmit beam to the multiline location, giving higher weight to receive beams with higher signal-to-noise ratios. This results in an extended depth of field along each receive line and an enhanced penetration (improved signal-to-noise and signal-to-speckle-noise ratios) due to the combination of multiple samplings in each receive line direction.

In the example of FIGURES 4a-4d it is seen that each received multiline is only used once in combination with other co-aligned multilines. This



means that an implementation of the present invention does not require the second set of weights 114 multipliers 116 and delays 118, because these weighting and delay effects can be implemented with the weights and delays of the multiline processors 110, which can focus the multiline in the proper receive direction and account for phase and transmit beam variation with respect to the multilines with which it is to be combined, all in one process step. After all the multilines for a given line location have been received they are simply detected and summed to provide the display line data. Alternatively each received multiline for a given line location is detected and then stored in a line accumulator for that line. Each subsequently received multiline at that line location is detected and then added to the contents of the accumulator until the full complement of multilines at that location has been combined in the accumulator. The accumulator contents are then forwarded to the image processor, freeing the accumulator for use for another line location.

FIGURES 6a and 6b illustrate examples of the weighting and delay characteristics that may be used in combining the received multilines for a given display line location. FIGURE 6a illustrates example weighting and delay characteristics for a received multiline that is relatively distant from the transmit beam center such as received multiline 33' of FIGURE 2b. The received multiline 33' is shown extending in the z direction from the face of the transducer array at  $z=0$  to the maximum scan depth on the right side of the drawing. The center of the multiline is drawn as dotted where that portion of the multiline 33' is outside of the selected beam

profile 30' and its response is below that which the designer has deemed to be acceptable. The weighting characteristic 82 thus weights this multiline with a weight which is at a minimum where it is beyond the beam profile and at nonzero levels where the multiline is to be used for refocusing. In other implementations the weighting characteristic 82 may drop to zero in the near field. This is because the echoes may be too close to or behind the array after the necessary delay has been applied and thus not susceptible to accurate reception. Thus the multilines from laterally distant multilines are not used in the multiline combination in the very near field.

The phase characteristic 84 is seen to cross through a zero phase adjustment at the focal point of the transmit beam, staying nearly constant in the near field and gradually decreasing in the far field.

FIGURE 6b illustrates exemplary weighting and delay characteristics for a received multiline 33 that is closer to the center of its transmit beam. Due to this closer proximity the multiline is given greater overall weighting in the combination as shown by the weighting characteristic 86. The weighting increases in the vicinity of the focal region to balance the falloff of the weighting of the more remote multilines such as 33' in this region. The phase adjustment characteristic 88 is drawn as a straight line because the delay characteristic 84 for the more laterally remote multiline is calculated from the phase of the more central multiline 33. In this example the multiline 33 is used for refocusing over the full image depth, although in a given implementation the designer may elect to use the echoes of a single line from a transmit beam in close

proximity to the line location in the very near field.

An implementation of the present invention can be used with a variety of receive functions. For instance an implementation can operate on signals from focused sub-apertures. In another variation, instead of forming receive beams *per se*, a limited number of orthogonal functions such as Fourier components can be used. It is then possible to combine the different transmits in Fourier space. The signals being combined do not correspond exactly to received image lines. Thereafter receive beams are formed by combining the Fourier components or sub-apertures. Various combinations of several beams and functions derived from a beam by a change of apodization are also within the scope of the present invention. In other implementations a small number of received multilines can be increased by interpolating additional intermediate multilines, then performing the inventive processing with the increased number of multilines.

It will be appreciated that, rather than do one summation of all of the detected signals, the summation process can be partitioned as illustrated in FIGURE 7. In this example the delayed multiline data is combined in two partial summations referred to as Summation 1 and Summation 2. Each partial sum is then detected by a detector. The detected partial sums are then combined by Summation 3. An implementation with partial summation prior to detection requires fewer detectors.

FIGURE 8 provides an example of an ultrasound system of the present invention in which the delays are partitioned with some of the delay applied to detected data. In this example the coherent

multiline data is delayed, then partially summed. The two partial sums are detected as in FIGURE 7, then a further delay is applied to the two detected partial sums before the final summation. The first  
5 delay stages can align the signals within each sub-aperture, then the second stages align the signals across the sub-apertures. Another variation of this implementation is to apply the second delay stages to the partial sums before detection.

10 Variations of the examples above will readily occur to those skilled in the art and are within the scope of the present invention. For example, instead of transmitting along successive line locations, transmission can skip lines (multiplex) between  
15 multiline transmission. Transmission can be done along every other line position, every fourth line position, or other intervals of multi-line spacing, thus reducing the number of transmit events needed to form the image and increasing the acquisition  
20 rate. This is also a way to reduce motion artifacts. Receiving multilines at more widely spaced line intervals with a fewer number of transmit beams is another way to address the problem of motion. This approach can be augmented with interpolated lines as  
25 mentioned above to increase the number of lines which are combined. This will also increase the depth of field improvement for a given number of multilines. The sampling used is generally a function of the F number of the transmit aperture, which determines the  
30 Nyquist sampling requirement. Scanning does not have to be done sequentially across the image; other transmission sequences can be used, which will have different responses in the presence of motion. While the examples above are shown with apodization, it is  
35 not necessary to apodize on transmission, reception,

or multiline combination. It is not necessary that the multilines to be combined all be precisely axially aligned. Multilines which are to be combined can be offset laterally from each other, effecting an interpolation when the multilines are combined. The principles of the present invention are also applicable to three dimensional imaging by performing the processing in both the elevation and azimuth dimensions, and to phased array (sector scan) imaging as well as linear array (orthogonal scan) imaging and by use of curved arrays. The reduction of the effects of motion through detection of the relative image motion and adjustment of the multiline order in response to the presence of motion, discussed in previously mentioned application serial number 60/747148, is also applicable to implementations of the present invention.

WHAT IS CLAIMED IS:

1. An ultrasonic diagnostic imaging system comprising:

5 a probe including an array of transducer elements;

a transmit beamformer, coupled to the array of transducer elements, and operable to transmit a beam insonifying a plurality of laterally spaced line positions;

10 a multiline receive beamformer, coupled to the array of transducer elements, which is operable to produce a plurality of receive lines at the line positions in response to one transmit beam;

15 a multiline combining circuit, responsive to a plurality of receive lines which relate to a common line position produced by the multiline receive beamformer in response to a plurality of transmit beams, which is operable to nonlinearly combine the plurality of receive lines to produce image data; and

20 a display which produces an image utilizing the image data.

2. The ultrasonic diagnostic imaging system of Claim 1, wherein the multiline combining circuit includes a detector and a summer which is operable to combine detected data from different multilines.

3. The ultrasonic diagnostic imaging system of Claim 2, wherein the multiline combining circuit further includes a plurality of delays responsive to the data of different multilines and operable to adjust phase variations between the multilines.

35 4. The ultrasonic diagnostic imaging system of

Claim 3, wherein the multiline combining circuit further includes a plurality of weighting circuits which are operable to weight multiline data.

5           5.    The ultrasonic diagnostic imaging system of Claim 1, wherein the probe comprises a linear array probe.

10           6.    The ultrasonic diagnostic imaging system of Claim 1, wherein the probe comprises a phased array probe.

15           7.    The ultrasonic diagnostic imaging system of Claim 1, wherein the transmit beamformer is further variable to transmit a beam from a selected transmit aperture.

20           8.    The ultrasonic diagnostic imaging system of Claim 7, wherein the transmit beamformer is operable to transmit a sequence of beams from a sequence of different apertures along the transducer array.

25           9.    The ultrasonic diagnostic imaging system of Claim 8, wherein the transmit beamformer is further operable to transmit a sequence of beams from a sequence of different apertures selected such that at least some of the laterally spaced line positions of one beam are aligned with at least some of the laterally spaced line positions of another beam.

30           10.   The ultrasonic diagnostic imaging system of Claim 9, wherein the transmit beamformer is further operable such that at least some of the laterally spaced line positions of one beam are coaxially  
35 aligned with at least some of the laterally spaced

line positions of another beam.

11. The ultrasonic diagnostic imaging system of Claim 1, wherein the multiline receive beamformer  
5 includes a plurality of multiline processors, each of which applies a set of delays to signals received from a plurality of transducer elements to focus a receive multiline in a selected line direction.

10 12. The ultrasonic diagnostic imaging system of Claim 11, wherein the multiline receive beamformer exhibits a variable multiline order.

13. The ultrasonic diagnostic imaging system of  
15 Claim 1, further including a line store coupled to the multiline receive beamformer and operable to store receive lines produced in response to a plurality of transmit beams.

20 14. A method for producing an ultrasound image with an extended focal range, comprising:

transmitting a plurality of transmit beams from an array transducer, each transmit beam being centered at a different position along the array and  
25 each transmit beam encompassing a plurality of laterally spaced line positions which are spatially related to laterally spaced line positions of another beam;

receiving echo signals with the array  
30 transducer;

concurrently processing the echo signals received in response to one transmit beam to produce a plurality of receive lines of echo signals at the laterally spaced line positions of the beam;

35 repeating the concurrently processing for



additional transmit beams;

incoherently combining echo signals of receive lines from different transmit beams which are spatially related to produce image data; and

5 producing an image using the image data.

15 15. The method of Claim 14, further comprising relatively delaying the signals of receive lines from different transmit beams prior to combining.

10

16. The method of Claim 15, further comprising relatively weighting the signals of receive lines from different transmit beams prior to combining.

15

17. The method of Claim 14, further comprising detecting the signals of receive lines from different transmit beams prior to combining.

20

18. The method of Claim 14, wherein transmitting further comprises transmitting a sequence of transmit beams which are centered at a sequence of successive line positions along the array.

25

19. The method of Claim 14, wherein transmitting further comprises transmitting a sequence of transmit beams which are centered at a sequence of successive inter-line positions along the array.

30

20. The method of Claim 14, further comprising storing the receive lines from a plurality of transmit beams prior to combining.

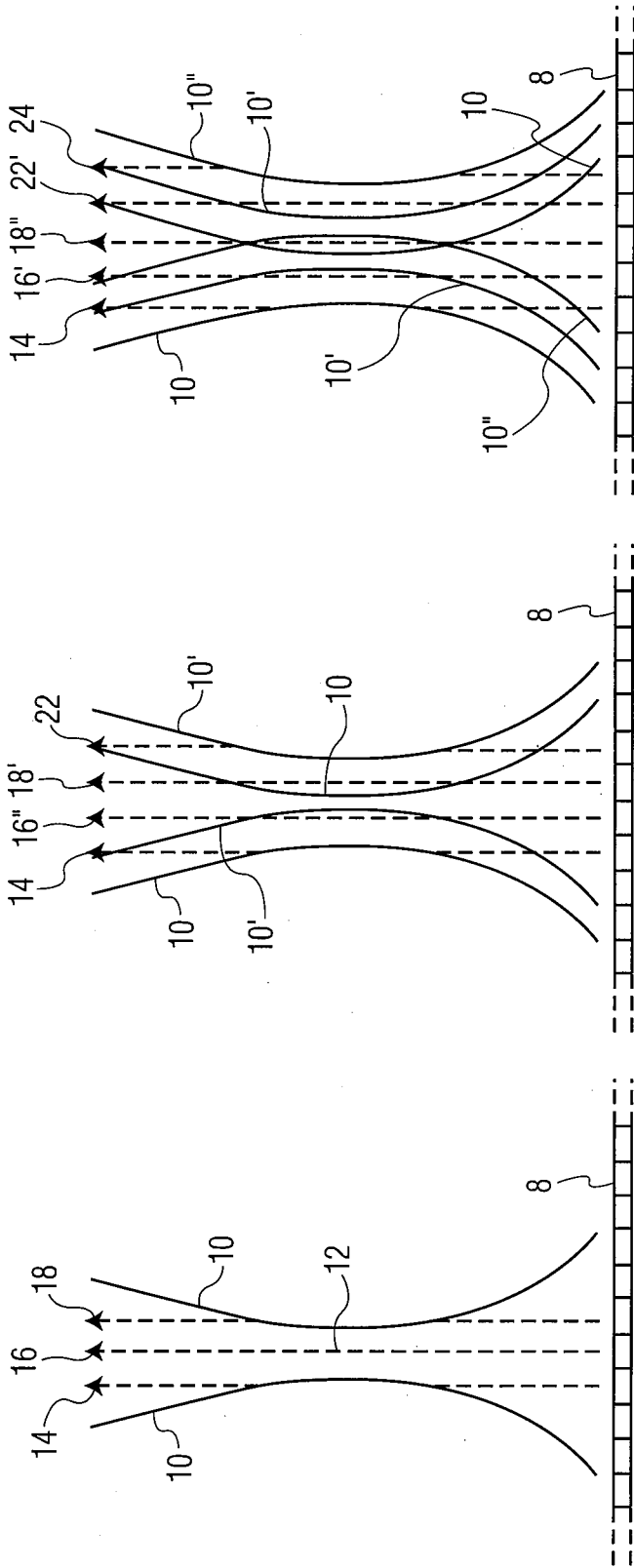


FIG. 1C

FIG. 1B

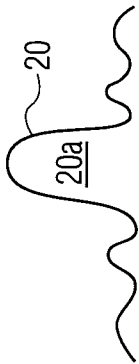


FIG. 1A

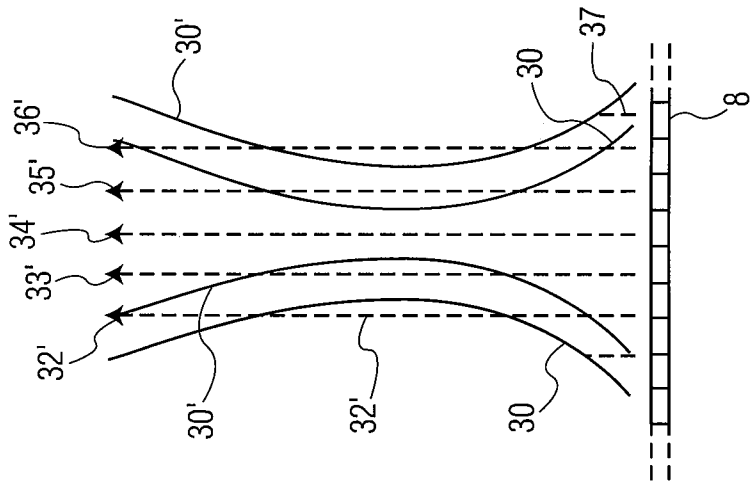


FIG. 2B

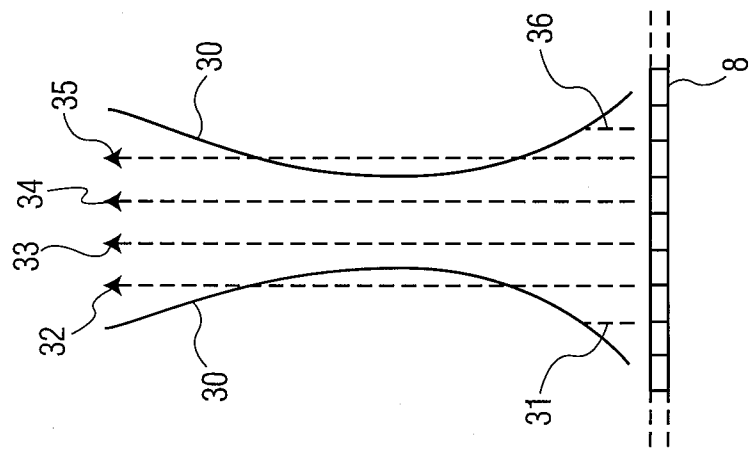


FIG. 2A

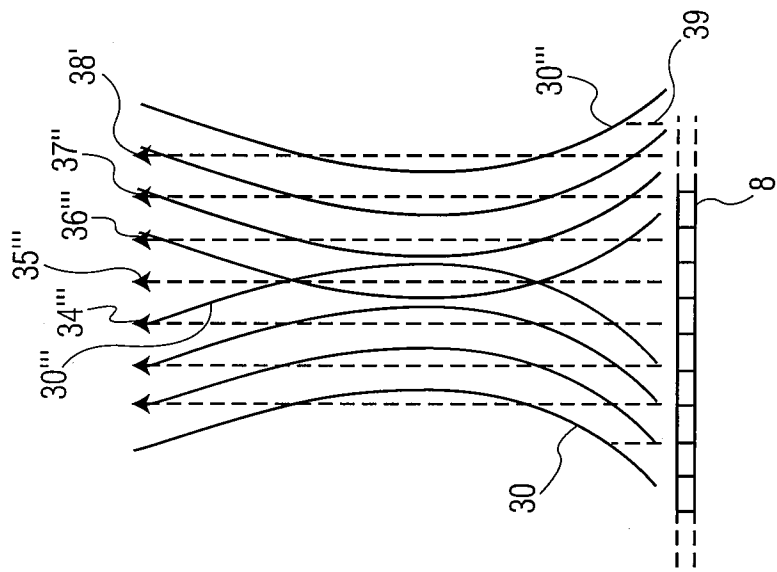


FIG. 2D

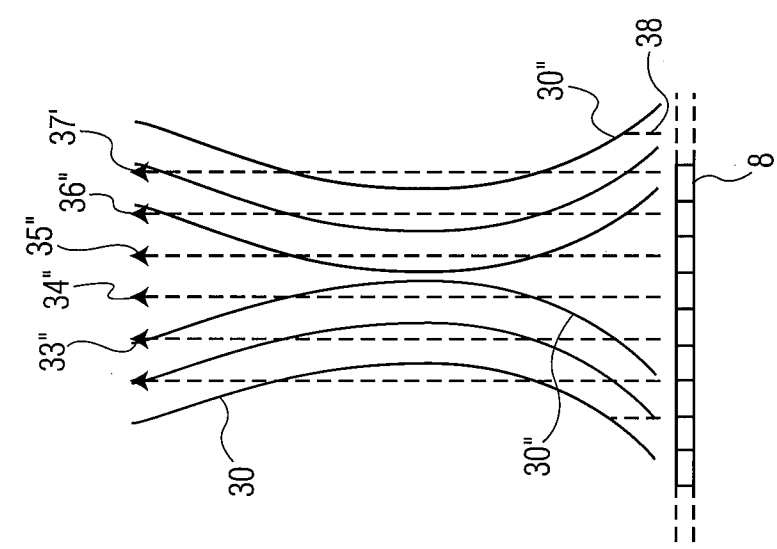


FIG. 2C

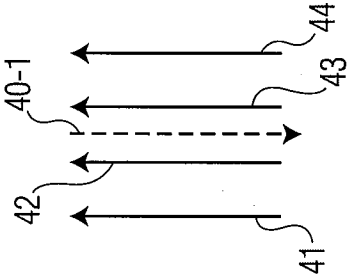


FIG. 3A

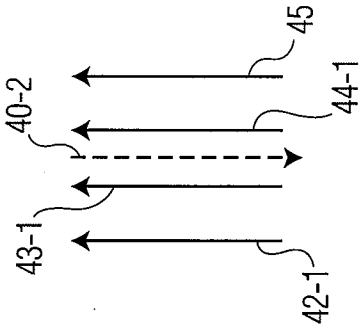


FIG. 3B

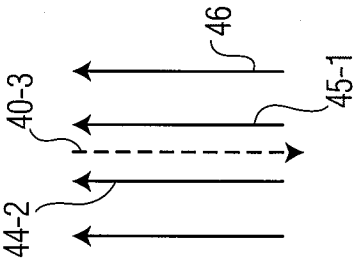


FIG. 3C

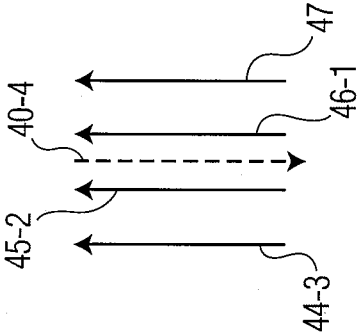


FIG. 3D

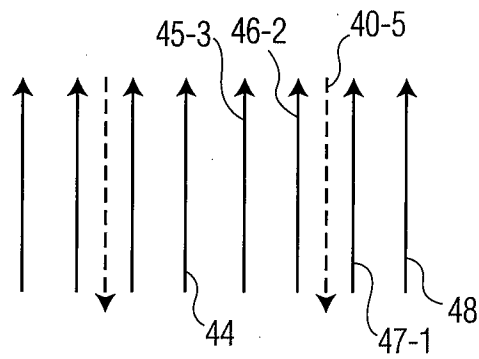


FIG. 4A

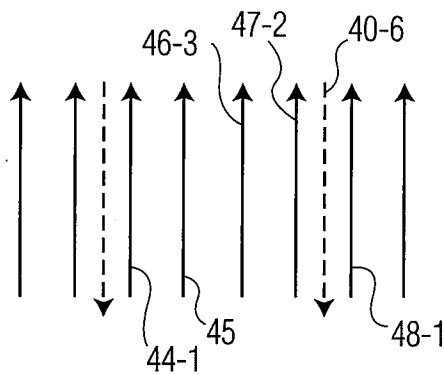


FIG. 4B

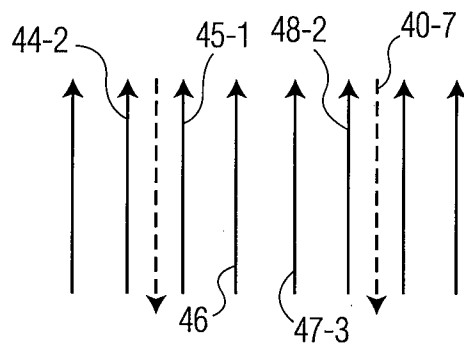


FIG. 4C

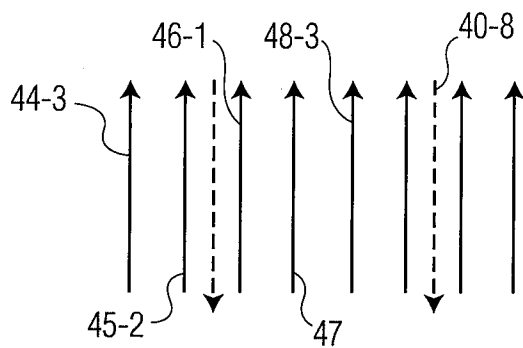


FIG. 4D

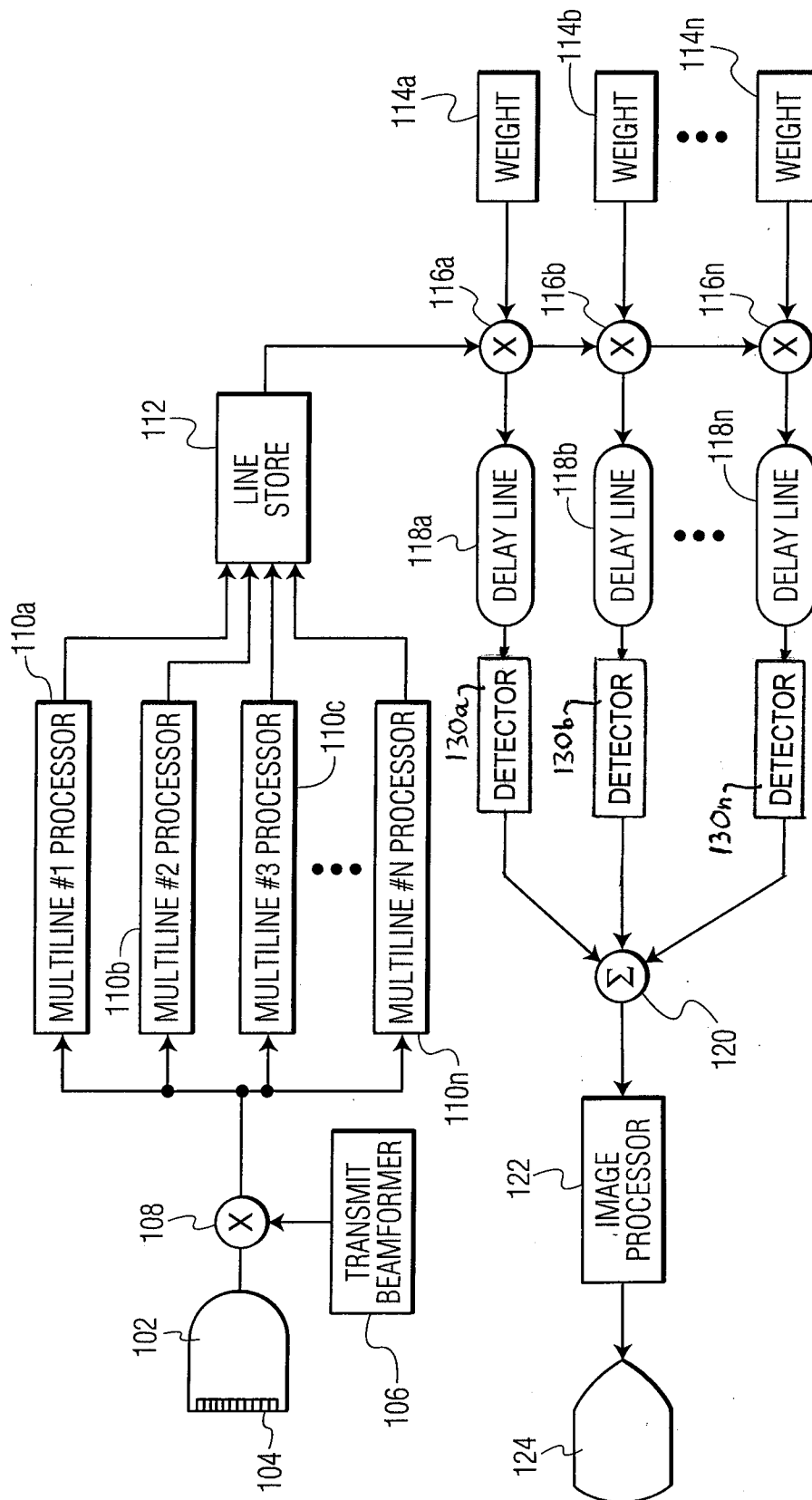


FIG. 5

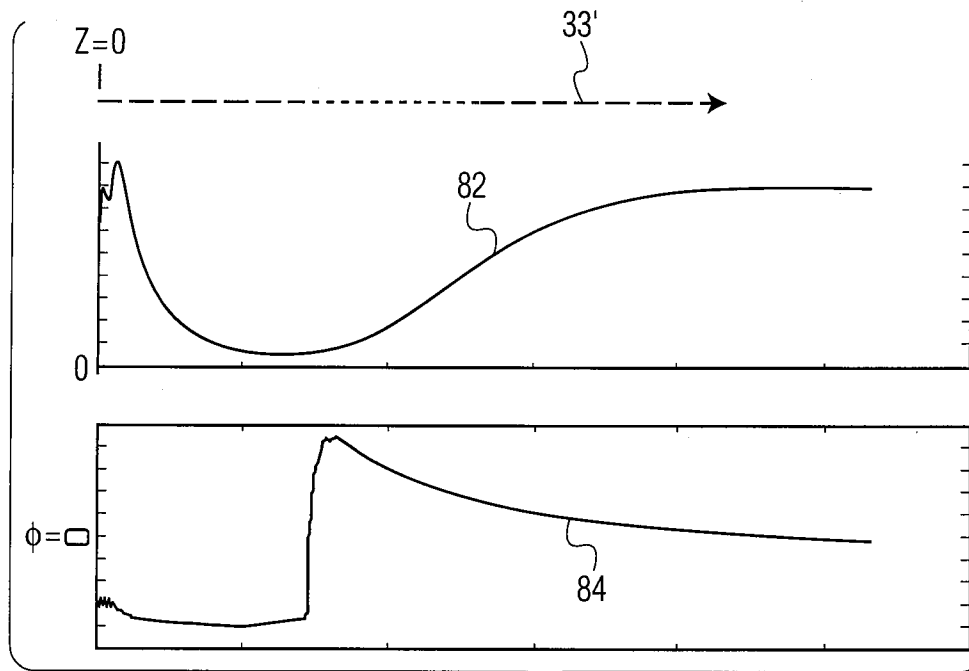


FIG. 6A

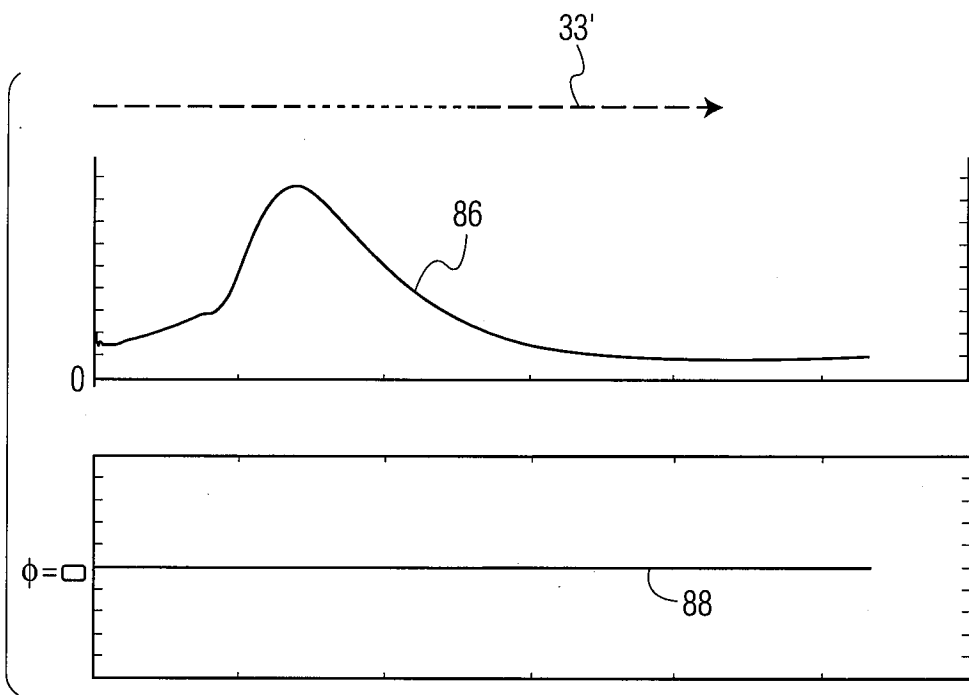


FIG. 6B



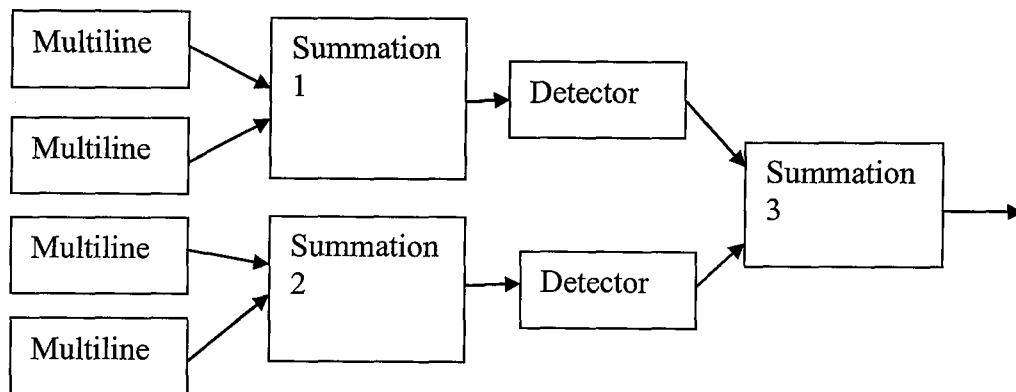


FIG. 7

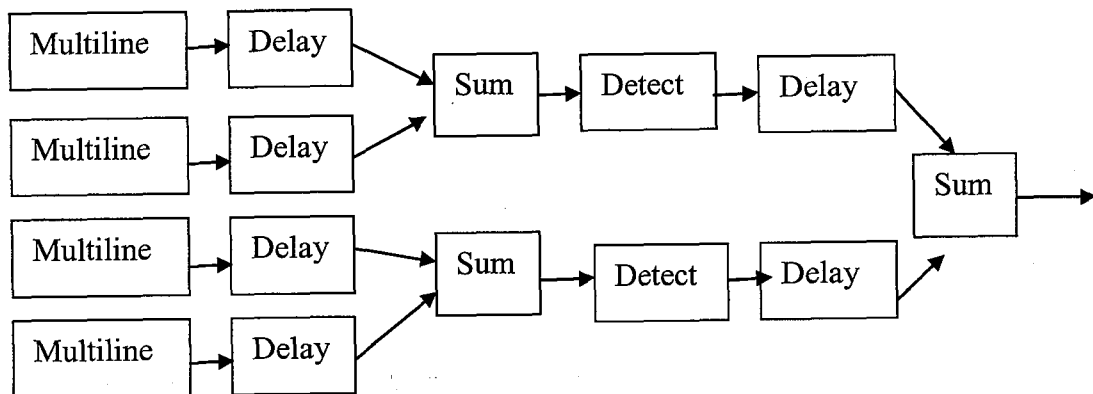


FIG. 8