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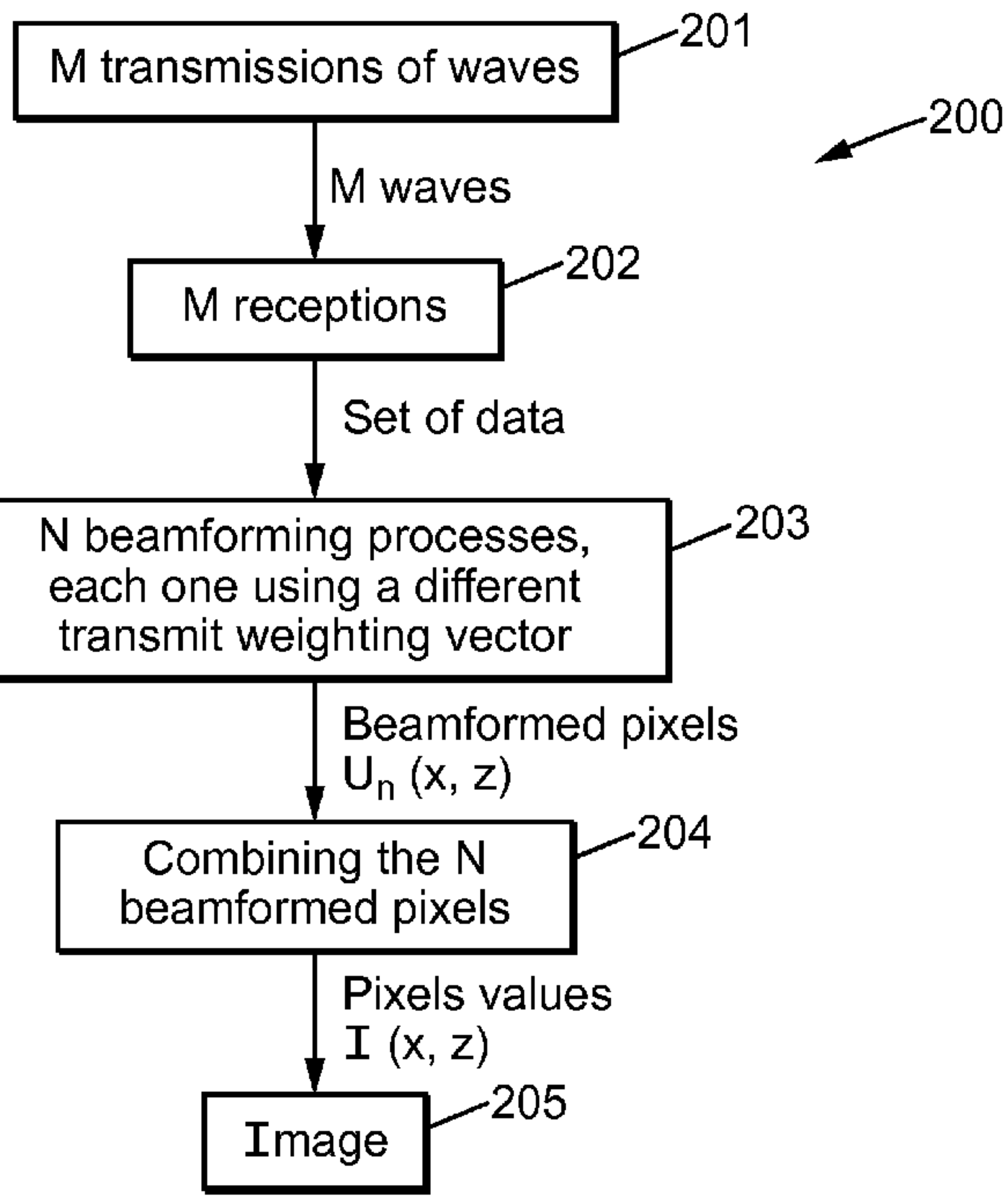

FIG. 4

(57) Abrégé/Abstract:
An imaging method for producing an image of a region inside a medium by an array (2) of transducers, and comprising the a transmission step (201) of a plurality of waves inside the medium, a reception step (202) for acquiring a set of data, a beamforming step (203) providing a plurality beamformed pixel values depending on various transmit weighting vectors, and a combining step (204) for combining the beamformed pixel values into a pixel value of each pixel in the image. The transmit weighting vectors (W_{Tn}) are different and orthogonal one to an other one.

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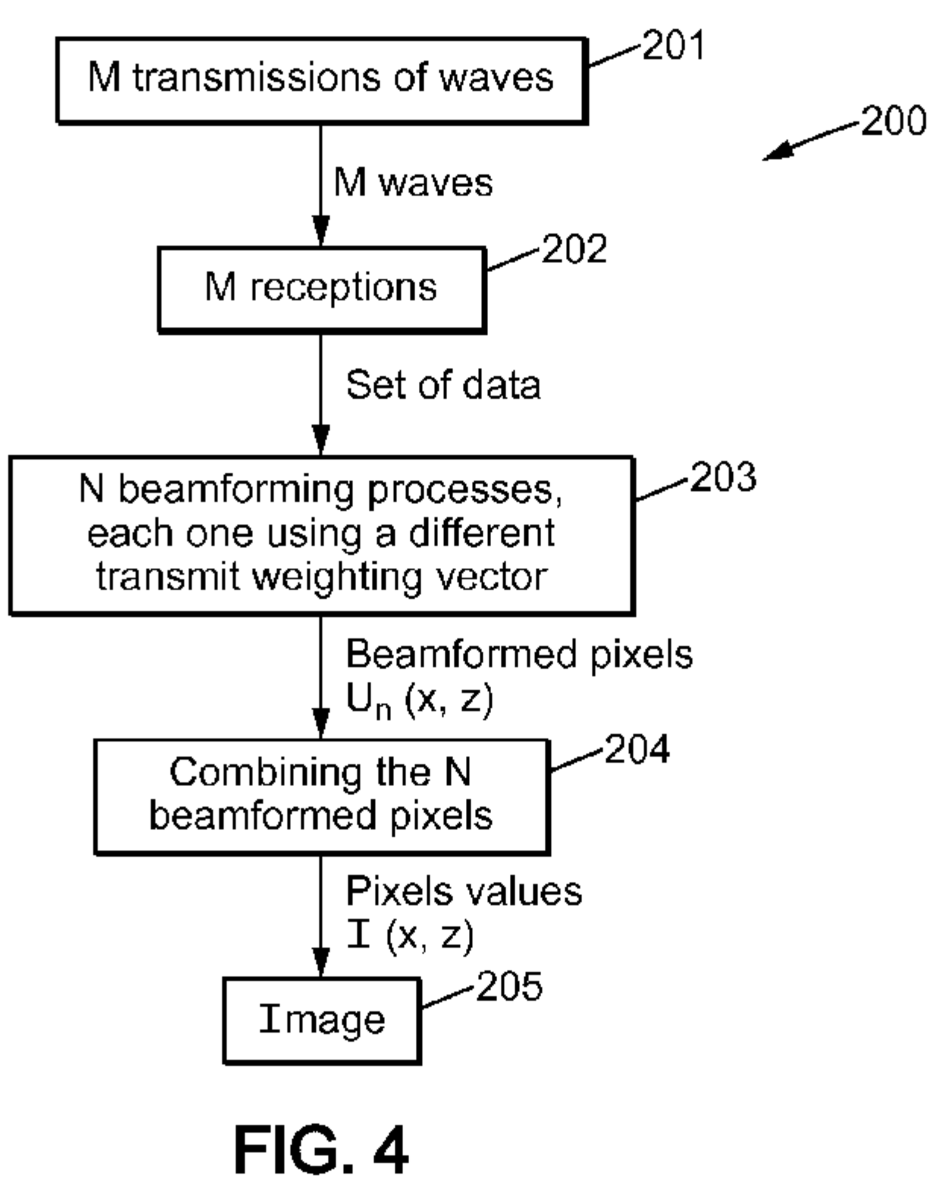

FIG. 4

(57) Abstract: An imaging method for producing an image of a region inside a medium by an array (2) of transducers, and comprising the a transmission step (201) of a plurality of waves inside the medium, a reception step (202) for acquiring a set of data, a beamforming step (203) providing a plurality beamformed pixel values depending on various transmit weighting vectors, and a combining step (204) for combining the beamformed pixel values into a pixel value of each pixel in the image. The transmit weighting vectors (W_{Tn}) are different and orthogonal one to an other one.

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An imaging method, an apparatus implementing said method, a computer program and a computer-readable storage medium

FIELD OF THE INVENTION

The present invention relates to imaging methods and apparatus implementing said methods, in particular for medical imaging.

BACKGROUND OF THE INVENTION

The present invention concerns more precisely an imaging method for producing an image of a region inside a medium, and more precisely an ultrasound imaging method.

The method is implemented by a processing unit connected to an array of transducers in relation with said medium.

This kind of image produced by reflexion waves in response to incident waves often comprise a speckle noise that corresponds to random fluctuations in the reflexion waves from the region of interest. This speckle noise causes difficulties for image interpretation.

The speckle noise can be reduced by averaging a plurality of images because each image has a speckle noise different than an other image of said plurality.

Eventually, the images for averaging can be obtained by observing the region from different angles (spatial compounding) or by varying the signal frequencies (frequency compounding).

Eventually, a plurality of different receive weighting vectors can be applied on receive beamforming so as to obtain averaged images.

However all these methods increase the number of acquisitions to be done, reduce the frame rate, and sometimes reduce the resolution of the produced image.

OBJECTS AND SUMMARY OF THE INVENTION

One object of the present invention is to provide an other imaging method for producing an image of a region inside a medium having a reduced speckle noise, and not having the drawbacks of prior art methods.

To this effect, the method comprises the following steps:

(a) a transmission step in which a first plurality of waves are transmitted inside the medium by the transducers,

(b) a reception step in which a set of data is acquired by said transducers in response to the waves,

(c) a beamforming step in which the set of data is processed by a second plurality of beamforming processes for providing beamformed pixel values of at least a portion of the image, each beamforming process either using a set of data corresponding to waves generated with a transmit weighting vector, or using a transmit weighting vector in the calculus of the beamformed pixel value, and

(d) a combining step in which the beamformed pixel values of said second plurality are combined to provide a pixel value of a pixel inside the image, and
wherein the transmit weighting vectors are different and orthogonal one to an other one.

Thanks to these features, each transmit weighting vector generates an uncorrelated speckle noise, and the combination of the weighted data allow to compute an image of the region having a reduced speckle noise.

In various embodiments of the imaging method, one and/or other of the following features may optionally be incorporated.

According to an aspect of the method:

- during the transmission step (a), each transmit weighting vector is used for generating a wave, and

- during the beamforming step (c), the beamforming process is a conventional beamforming in which the beamformed pixel values are calculated by the following formula:

$$U_n(x,z) = \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l), l, m)$$

where

$DS(k, l, m)$ is a matrix of the set of data,

W_R is a receive weighting vector,

$\tau(x, z, l)$ is a delay function adapted for the beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line, and

x, z are coordinates of a pixel inside the image.

According to an aspect of the method, the transmit weighting vectors are applied during the beamforming step (c), and

- during the beamforming step (c), the beamforming process is a synthetic beamforming in which the beamformed pixel values are calculated by the following formula:

$$U_n(x,z) = \sum_{m=1}^{M} W_{Tn}[m] \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l,m), l, m)$$

where

$DS(k, l, m)$ is a matrix of the set of data,

W_R is a receive weighting vector,

$\tau(x, z, l)$ is a delay function adapted for the beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line,

m is the index, comprised between 1 and M, M being the first plurality that is the number of transmitted waves inside medium,

W_{Tn} is the transmit weighting vector,

x, z are coordinates of a pixel inside the image.

According to an aspect of the method, the synthetic beamforming process is chosen in a list comprising synthetic aperture focusing technique (SAFT) beamforming process, virtual transducer SAFT beamforming process, spatially coded SAFT beamforming process, circular wave synthetic beamforming process, plane wave synthetic beamforming process.

According to an aspect of the method, the pixel values of the image are calculated during the combining step (d) by the following formula:

$$I(x,z) = \sum_{n=1}^{N} \left| U_n(x,z) + iHT\{U_n(x,z)\} \right|^2$$

wherein

i is the complex unit imaginary number.

n is the index, comprised between 1 and N, N being the second plurality that is the number of transmit weighting vectors,

$|X|$ is the modulus of X,

$HT\{X\}$ is the Hilbert transform of X,

$U_n(x, z)$ is a beamformed pixel value of said second plurality.

According to an aspect of the method, the transmit weighting vectors are determined by an orthogonal function chosen in a list comprising a Riedel-Sidorenko function, a Discrete prolate spheroidal function and a Hadamard function.

According to an aspect of the method, the transducers are ultrasound transducers that transmit or receive ultrasound waves, and the method produces an ultrasound image of the region inside the medium.

According to an aspect of the method, it further comprises the following steps:

- an initial imaging step wherein a first image of the region is determined by said processing unit and array,

- an evaluation step in which a metric value is determined for pixels in the first image,

- an imaging step in which, if the metric value is comprised in a first range, a pixel value in the image is computed without using a transmit weighted vector, and if the metric value is comprised in a second range different than said first range, a pixel value in the image is computed with using transmit weighting vectors, said transmit weighting vectors being different and orthogonal one to an other one.

According to an aspect of the method, the metric value is determined for distinguishing a pixel in the first image corresponding to a significant reflective signal from a pixel in the first image corresponding to a non-significant speckle signal.

According to an aspect of the method, the metric value is determined via a calculus of an autocorrelation function.

According to an aspect of the method, the metric value is a mean value of the autocorrelation function for lags comprised between 10 degrees and 30 degrees.

Another object of the invention is to provide an apparatus implementing said imaging method. Said apparatus for producing an image of a region inside a medium, comprises a processing unit connected to an array of transducers in relation with said medium, and wherein the array and the processing unit implements the flowing steps:

(a) a transmission step in which a first plurality (M) of waves are transmitted inside the medium by the transducers,

(b) a reception step in which a set of data is acquired by said transducers in response to the waves, and wherein the processing unit implements the following step:

(c) a beamforming step in which the set of data is processed by a second plurality of beamforming processes for providing beamformed pixel values of at least a portion of the image, each beamforming process either using a set of data corresponding to waves generated with a transmit weighting vector, or using a transmit weighting vector in the calculus of the beamformed pixel values, and

(d) a combining step in which the beamformed pixel values of said second plurality are combined together to provide a pixel value of each pixel in the image, and wherein the transmit weighting vectors are different and orthogonal one to an other one.

In various embodiments of the apparatus, one and/or other of the following features may optionally be incorporated.

According to an aspect of the apparatus, the transmit weighting vectors are applied during the beamforming step (c), and

- during the beamforming step (c), the beamforming process is a synthetic beamforming in which the beamformed pixel values are calculated by the following formula:

$$U_n(x,z) = \sum_{m=1}^{M} W_{Tn}[m] \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l,m),l,m)$$

where

$DS(k, l, m)$ is a matrix of the set of data,

W_R is a receive weighting vector,

$\tau(x, z, l)$ is a delay function adapted for the beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line,

m is the index, comprised between 1 and M, M being the first plurality that is the number of transmitted waves inside medium,

W_{Tn} is the transmit weighting vector,

x, z are coordinates of a pixel inside the image.

According to an aspect of the apparatus, the synthetic beamforming process is chosen in a list comprising synthetic aperture focusing technique (SAFT) beamforming process, virtual transducer SAFT beamforming process, spatially coded SAFT beamforming process, circular wave synthetic beamforming process, plane wave synthetic beamforming process.

According to an aspect of the apparatus, it further implements the following steps:

- an initial imaging step wherein a first image of the region is determined by said processing unit and array, and
- an evaluation step in which a metric value is determined for pixels in the first image,
- an imaging step in which, if the metric value is comprised in a first range, a pixel value in the image is computed without using a transmit weighted vector, and if the metric value is comprised in a second range different than said first range, a pixel value in the image is computed with using transmit weighting vectors, said transmit weighting vectors being different and orthogonal one to an other one.

Another object of the invention is to provide a computer program including instructions for executing the steps of the above imaging method when said program is executed by a computer.

Another object of the invention is to provide a computer-readable storage medium on which is stored computer program including instructions for execution of the steps of the above imaging method when said program is executed by a computer.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the invention will be apparent from the following detailed description of two of its embodiments given by way of non-limiting example, with reference to the accompanying drawings. In the drawings:

- Figure 1 is a schematic drawing showing an ultrasound imaging apparatus according to one embodiment of the invention;
- Figure 2 is a block diagram showing part of the apparatus of figure 1;
- Figure 3 is a diagram showing a first example of imaging method according to the invention and implemented in the apparatus of figure 1;
- Figure 4 is a diagram showing a second example of imaging method according to the invention and implemented in the apparatus of figure 1;
- Figures 5a to 5c are first examples of three transmit weighting vectors that are orthogonal one to another one, said vectors corresponding to Riedel-Sidorenko functions;
- Figures 6a to 6c are second examples of three transmit weighting vectors that are orthogonal one to another one, said vectors corresponding to Discrete prolate spheroïdal functions;
- Figures 7a to 7c are third examples of three transmit weighting vectors that are orthogonal one to another one, said vectors corresponding to Hadamard functions;
- Figure 8 is a third example of imaging method according to the invention, said third example being an adaptive method;
- Figure 9 shows an example of a decision image computed for a sample and corresponding to metric evaluation decisions in the method of figure 8;

- Figure 10 shows an example of an image computed for the same sample as in figure 9; and

- Figure 11 shows an example of autocorrelation function used in the third example of imaging method of figure 8.

MORE DETAILLED DESCRIPTION

In the Figures, the same references denote identical or similar elements.

The apparatus shown on **Figure 1** is adapted for imaging of a region 1, for instance living tissues and in particular human tissues of a patient. The apparatus may include for instance:

- a transducer array 2, for instance a linear array typically including a few tens of transducers (for instance 100 to 300) juxtaposed along an axis X (horizontal or array direction X) as already known in usual probes (the array 2 is then adapted to perform a bidimensional (2D) imaging of the region 1, but the array 2 could also be a bidimensional array adapted to perform a 3D imaging of the region 1);

- an electronic bay 3 controlling the transducer array and acquiring signals therefrom;

- a microcomputer 4 for controlling the electronic bay 3 and viewing images obtained from the electronic bay (in a variant, a single electronic device could fulfill all the functionalities of the electronic bay 3 and of the microcomputer 4).

The axis Z on figure 1 is an axis perpendicular to the axis X, and it is usually the direction of ultrasound beams generated by the transducers of the array. This direction is designated in present document as a vertical or axial direction.

The transducer array 2 may also be a convex array including a plurality of transducer aligned along a curved line.

As shown on **Figure 2**, the electronic bay 3 may include for instance:

- L analog/digital converters 5 (A/D_1-A/D_L) individually connected to the L transducers (T1-TL) of the transducer array 2;
- L buffer memories 6 (B_1-B_n) respectively connected to the n analog/digital converters 5,
- a central processing unit 8 (CPU) communicating with the buffer memories 6 and the microcomputer 4,
- a memory 9 (MEM) connected to the central processing unit 8;
- a digital signal processor 10 (DSP) connected to the central processing unit 8.

The apparatus herein disclosed is a device for ultrasound imaging, the transducers are ultrasound transducers, and the implemented method is for producing ultrasound images of region 1.

However, the apparatus may be any imaging device using other waves than ultrasound waves (waves having a wavelength different than an ultrasound wavelength), the transducers and the electronic bay components being then adapted to said waves.

Figure 3 and 4 show two examples of implementation of the method with the apparatus of Figures 1 and 2. The method steps are controlled mainly by the central processing unit 8 eventually with the help of the digital signal processor 10, or any other means.

The method includes the following main steps:

(a) a transmission step (101; 201) in which a first plurality of waves are transmitted by the transducers inside the region of the medium;

(b) a reception step (102; 202) in which a set of data is acquired by said transducers in response to the waves;

(c) a beamforming step (103; 203) in which the set of data, that is acquired during the reception step, is processed by a second plurality of beamforming processes to provide a second plurality of beamformed pixel values $U_n(x,z)$ for at least a portion of the image, and

(d) a combining step (104; 204) in which the N beamformed pixel values are combined to provide a pixel value of each pixel in the image.

The first plurality is the number of waves transmitted inside the region of the medium for processing the image. This is a number of successive firings of the transducers to generate said waves.

The second plurality is the number of transmit weighting vectors W_{Tn} that is used in the method.

The method according the invention uses a second plurality (a number N) of transmit weighting vectors W_{Tn}, that are different one to an other one.

Moreover, the transmit weighting vectors W_{Tn} used in the method are orthogonal one to an other one, i.e.:

for any indexes i, j belonging to $1 \ldots N$,

index i being different of index j

$W_{Ti}.W_{Tj} = 0$.

i.e.: $\sum_{l=1}^{L} W_{Ti}(l).W_{Tj}(l) = 0$

The transmit weighting vector W_{Tn} is a vector comprising a number of L components, each component corresponding to an amplification coefficient to be applied to the signal that is usually sent to a transducer of the array 2 during the transmission step (a). The components of transmit weighting vectors W_{Tn} can be defined to be values lower or equal to one:

$W_{Tn}(l) <= 1$, for $l=1$ to L.

According to a first variant illustrated on figure 3, the transmit weighting vector is applied on the transmitted waves during the transmission step a) (101) so as to provide a set of data comprising data corresponding to the plurality of transmit weighting vectors.

Then, this set of data is used during the beamforming step c), each beamforming process of this step using data corresponding to a specific transmit weighting vector (a specific transmission wave).

In this first variant, the amplitude wave transmitted in the medium may be small because of weighting effect of each transmit weighting vector, and therefore signal to noise ratio of the received set of data may be low. Additionally, this first variant requires MxN transmissions and acquisitions of waves, and therefore, it also lowers the imaging frame rate. Furthermore, it generates an image having a speckle noise that is not optimal into the overall scanned region as it is only adapted to the beam focal depth.

According to a second variant illustrated on figure 4, the transmit weighting vector is applied on the set of data (not weighted) inside the calculus of each beamforming process during the beamforming step (c) (203).

In that case, the weighting effect of first variant is obtained by an appropriate calculus (summation) during the beamforming step (c) (203), said calculus using a transmit-receive beamforming formula for each beamforming process.

In this second variant, the wave is transmitted inside the medium with unit amplification coefficients (except coefficients concerning windowing or aperture). The transmit weighting coefficients are only applied by calculation on the set of data acquired during the reception step (b).

Thanks to this transmit-receive beamforming process, the amplitudes of waves that are really transmitted inside the medium are not decreased, and the signal to noise ration (SNR) of the received signals digitized into the set of data is preserved.

In all variants of the method, the transducer array 2 is put into contact with the medium to be imaged (e.g. a patient's body).

The number of the transmitted waves may be comprised for instance between 2 and 100. The frequency of the ultrasound waves may be comprised for instance between 0.5 and 100 MHz, for instance between 1 and 10 MHz.

The number N of transmit weighting vectors W_{Tn} is for instance a small number, for instance comprised between 2 and 10, and for example $N=3$. There are lots of orthogonal functions that can be used to determined such transmit weighting vectors W_{Tn}.

Figures 5a to 5c show a first example of 3 transmit weighting vectors W_{Tn}. In these figures, the abscissa is a transducer index, and the ordinate is the value of the component in each vector.

These transmit weighting vectors W_{T1-3} are vectors of Riedel-Sidorenko functions that are orthogonal one to an other one.

Figures 6a to 6c show a second example of 3 transmit weighting vectors W_{Tn} using Discrete prolate spheroidal functions, also orthogonal one to an other one.

Figures 7a to 7c show a second example of 3 transmit weighting vectors W_{Tn} using Hadamard functions, also orthogonal one to an other one.

The number N of transmit weighting vectors is preferably lower or equal to the number waves transmitted into the medium (the first plurality).

Demonstration concerning the effect of the invention

Thanks to the use of orthogonal transmit weighting vectors, the speckle noise in the image is smoothed, because each transmit vector generates an uncorrelated speckle.

This can be mathematically proved. We use in this section, the formalism and notations used in the document "The van Cittert-Zernike theorem in pulse echo measurements", Raoul Mallart and Mathias Fink, J. Acoust. Soc. Am. 90(5), November 1991.

The incident pressure field at point X_1 and at frequency f is given by:

$$H_k(X_1,f) = \iint_O O_k(X)\frac{\exp(\frac{j2\pi fr}{c})}{r}dX$$

where

O(X) is the transmit aperture function of a focused aperture; and

X=(x,y,0), where x,y are coordinates in the image.

The goal of this section is to show that orthogonal transmit apertures $O_k(X)$ and $O_l(X)$ produce uncorrelated speckle patterns. The pressure field scattered by an individual scatterer located at point X_1 is a spherical wave.

The received pressure field at point X_0 is expressed as:

$$P_k(X_0,X_1,f) = \chi(X_1,f)H_k(X_1,f)\frac{\exp(^{j2\pi fr_{01}}/_c)}{r_{01}}$$

where $r_{01}=|X_0-X_1|$.

The assumption is made that the scattering medium is incoherent, i.e., its structure is random and finer than the smallest wavelength used by the imaging system. The medium is unresolved and the autocorrelation of its scattering function R_M is of the form:

$$R_M(X_1-X_2,f) = \chi(X,f)\delta(X_1-X_2)$$

where χ is the local scattering coefficient in the neighbourhood of the point coordinate (x, z).

The pressured field backscattered from the whole medium in response to a Dirac pulse sensed at point X_0 is given by:

$$P_k(X_0,f) = \iiint_V \chi(X_1,f)H_k(X_1,f)\frac{\exp(^{j2\pi fr_{01}}/_c)}{r_{01}}d^3X_1 .$$

The cross-correlation $R_{kl}(X_0,f)$ of the pressure fields $P_k(X_0,f)$ and $P_l(X_0,f)$ is given by:

$$R_{kl}(X_0,f) = \mathrm{E}\{P_k(X_0,f)P_l(X_0,f)\}$$

where

E{.} denotes mathematical expectation.

One can express the product $P_k(X_0,f).P_l(X_0,f)$ with the above equations, as:

$$P_k(X_0,f)P_l(X_0,f) = \iiint_V \iiint_V \chi(X_1,f)\chi^*(X_2,f)H_k(X_1,f)\,H_l^*(X_1,f)\frac{\exp(^{j2\pi f(r_{01}-r_{02})}/_c)}{r_{01}r_{02}}d^3X_1d^3X_2$$

With the above equations, it can be derived that:

$$R_{kl}(X_0,f) = \chi_0(f)\iiint_V \iiint_V \delta(X_1-X_2)H_k(X_1,f)\,H_l^*(X_1,f)\ldots$$

$$\frac{\exp(^{j2\pi f(r_{01}-r_{02})}/_c)}{r_{01}r_{02}}d^3X_1d^3X_2$$

Thus the cross-correlation of the pressure fields $P_k(X_0,f)$ and $P_l(X_0,f)$ is given by:

$$R_{kl}(X_0,f) = \chi_0(f)\iiint_V H_k(X_1,f)\,H_l^*(X_1,f)d^3X_1$$

From the above cited publication of Mallart et al., the incident pressure field at point X_1 is then approximately:

$$H_k(X_1,f) = \varphi_k\iint_O O_k(x)\exp(\frac{j\pi f}{zc}x.x)\exp(\frac{j\pi f}{zc}x.X_1)d^2x$$

Where φ_k is a phase term.

For an aperture focusing at depth z, the aperture function O(x) contains the phase term $\exp(-\frac{j\pi f}{zc}x.x)$, thus $O_k(x)\exp(\frac{j\pi f}{zc}x.x)$ is a real value.

Let $\widetilde{O_k}(x) \triangleq O_k(x)\exp(\frac{j\pi f}{zc}x.x)$, the product of incident fields is expressed as:

$$H_k(X_1,f)H_l^*(X_1,f) = \varphi_k\iint_O \iint_O \widetilde{O_k}(x_1)\widetilde{O_l}(x_2)\ldots$$

$$\exp\left(\frac{j\pi f}{zc}(x_1-x_2).X_1\right)dx_1^2dx_2^2$$

And, injecting the last equation in the previous one, one can derive that:

$$R_{kl}(X_0,f) = \chi_0(f)\varphi_k\varphi_l^* \iint_O \iint_O \widetilde{O_k}(x_1)\widetilde{O_l}(x_2) \iiint_V \exp\left(\frac{j\pi f}{zc}(x_1-x_2).X_1\right) d^3X_1 d^2x_1 d^2x_2$$
$$= \chi_0(f)\varphi_k\varphi_l^* \iint_O \iint_O \widetilde{O_k}(x_1)\widetilde{O_l}(x_2)\ \delta(x_1-x_2) d^2x_1 d^2x_2$$
$$= \chi_0(f)\varphi_k\varphi_l^* \iint_O \widetilde{O_k}(x_1)\widetilde{O_l}(x_1)\ d^2x_1$$

The above equation shows that, orthogonal apertures, i.e. $\left(\widetilde{O_k}(x_1), \widetilde{O_l}(x_1)\right)$ that are so that $\iint_O \widetilde{O_k}(x_1)\widetilde{O_l}(x_1)\ d^2x_1 = 0$, yields to uncorrelated acquired data, i.e. $R_{kl}(X_0,f) = 0$.

Therefore, the cross-correlation of the pressure fields is null, and the speckle noise is uncorrelated.

Consequently, the method of the invention leads to a reduced speckle noise compared to prior art method. In fact, the speckle noise according to the method is minimal.

The method of the invention may be applied to any ultrasound imaging method. The following description will explains some of them.

Example 1: Conventional imaging

A first example corresponding to a conventional imaging method, usually called conventional focussing aperture or conventional B-mode imaging, is now explained.

During the transmission step (a), a number of M waves are successively transmitted into the region by the transducers. These waves are focused beams transmitted inside the medium according to a vertical direction (Z) substantially perpendicular to the array direction (X), and focused at a focal distance (or focal depth) from the transducer array 2.

The M successive focused beams are moved transversally one to an other according to a lateral direction corresponding to the array direction (X), so as to scan the region.

According to the present invention, each focused beam is also repeated N times, i.e. one focussed beam for each transmit weighting vector W_{Tn} of index n. The transmit weighting vector W_{Tn} are directly applied to the transducers: Each component of index l of the transmit weighting vector is used for amplifying or reducing the signal sent to the transducer of index l of the array 2.

In this first example, the first plurality (the number of waves transmitted inside the medium) is therefore equal to MxN.

Each wave propagates inside the region, where it interacts with diffusing particles which are reflective for the ultrasound waves. A wave is then backscattered as a reflexion wave (comprising echoes) towards the transducer array 2.

During the reception step (b), each reflexion wave is received by the transducers, acquired or converted into data by an analog to digital converter, and stored into a memory. Then, all the reflexion waves are all stored into the memory as a set or group of data.

The set of data from the acquired waves can be organized as a matrix $DS(k, l, m)$, where

k is an index of a sample over time,

l is an index of transducer among the array,

m is an index of the transmission wave among the number of MxN fired or transmitted waves (the number corresponding to the first plurality).

During the beamforming step (c), one or several lines (vertical lines or axial lines) of an image are calculated by a beamforming process. These lines are parallel to the vertical or axial direction Z (direction of the focused beam), and are included inside the focused beam.

For each one of the N transmit weighting vectors W_{Tn}, beamformed pixel values $U_n(x,z)$ of the pixels inside the lines can be calculated by the following beamforming formula, corresponding to a receive beamforming:

$$U_n(x,z) = \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l), l, m)$$

where

$DS(k,l,m)$ is a matrix storing all the set of data,

W_R is a receive weighting vector,

$\tau(x,z,l)$ is a delay function for the beamforming process, i.e. corresponding to the present conventional beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line,

m is an index pointing to a unique or determined transmit weighting vector W_{Tn} of index n and corresponding to a beam focussed near a point having coordinates (x, z) inside the medium, and

x, z are coordinates of a pixel inside the image.

During the combining step (d), the N (second plurality) beamformed pixel values $U_n(x,z)$ are computed for each transmit weighting vector, and are combined to provide a pixel value $I(x,z)$ of each pixel inside the image.

Then, the pixel value $I(x,z)$ can be calculated by the following sum formula:

$$I(x,z) = \sum_{n=1}^{N} \left| U_n(x,z) + iHT\{U_n(x,z)\} \right|^2$$

wherein

i is the complex unit imaginary number.

n is the index, comprised between 1 and N, N being the number of transmit weighting vectors in the second plurality,

$|X|$ is the modulus of X,

$HT\{X\}$ is the Hilbert transform of X,

$U_n(x,z)$ is the beamformed pixel value for index n.

Unfortunately, the above method:

- requires MxN transmission and acquisition of waves, and therefore the steps a) and b) may take some time,

- generates an image having a speckle noise that is not optimal into the overall scanned region, as it is only adapted to the beam focal depth.

Example 2 Synthetic imaging

A second example corresponding to a synthetic imaging method is now explained.

As synthetic imaging method, it should be understand any method known synthetic method, and at least any method of following list:

1) Synthetic aperture focusing technique method (SAFT),
2) Virtual transducer SAFT method,
3) Spatial coded SAFT method,
4) Circular wave synthetic method, and
5) Plane wave synthetic method.

1) The SAFT method is for example detailed in published document of J. A. Jensen, S. I. Nikolov, K. L. Gammelmark, M. H. Pedersen, "Synthetic Aperture Ultrasound Imaging", Ultrasonics 44, e5-e15, 2006.

This method implements:

- a transmission step (a) wherein at least one transmission of a wave is done (fired) for each transducer of the array 2: Each transducer of the array 2 is excited one after an other one, and

- a reception step (b) wherein all the transducers signals are acquired, recorded (stored) into memory as a set of data.

The set of data can also be organized as a matrix $DS(k, l, m)$, usually called the "full data set", where

k is an index of a sample over time,

l is an index of transducer among the array,

m is an index of the transmission wave among the number of fired waves (the number corresponding to the first plurality).

Therefore, the number M of fired waves is usually equal to the number L of transducers in the array 2. However, this number can be lower than this number L of transducers if not using all the transducers of the array, or it can be higher than the number L of transducers if doing averaging for some of them.

Then, the beamforming step (c) and combining step (d) differs from the known SAFT method, and are explained bellow.

During the beamforming step (c), the beamformed pixel values $U_n(x,z)$ can be calculated by the following beamforming formula comprising a double summation (one for the number of used transducers having index l, and one for the number of transmitted waves having index m):

$$U_n(x,z) = \sum_{m=1}^{M} W_{Tn}[m] \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l,m),l,m)$$

where

$DS(k,l,m)$ is a matrix of the sets of data,

W_R is a receive weighting vector,

$\tau(x,z,l)$ is a delay function for the beamforming process, i.e. corresponding to the present SAFT beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line,

m is the index, comprised between 1 and M, M being the first plurality that is the number of transmitted waves inside medium,

W_{Tn} is a transmit weighting vector of index n,

x, z are coordinates of a pixel inside the image.

During the combining step (d), the beamformed pixel values $U_n(x,z)$ calculated for all the number N (second plurality) of transmit weighting vectors are also combined to provide a pixel value $I(x,z)$ of each pixel inside the image.

Then, the pixel value $I(x,z)$ can be also calculated by the same sum formula as disclosed above:

$$I(x,z)=\sum_{n=1}^{N}\left|U_n(x,z)+iHT\{U_n(x,z)\}\right|^2 .$$

The transmit weighting vectors W_T being applied by calculus during the beamforming step (c), this method do not need additional firings (transmission of waves into the medium).

The image produced with SAFT method is usually of a high quality inside the entire region that is scanned: good resolution and good contrast. The signal to noise ratio (SNR) is not optimal, because each firing uses only one transduced of the array, and the firing energy is low compared to other methods.

Thanks to the orthogonal transmit weighting vectors W_{Tn}, the above modified SAFT method is able to reduce the image speckle noise.

2) The Virtual transducer SAFT method improves the SAFT method in terms of signal to noise ratio. This method is for example disclosed in published document of J. Kortbek, J. A. Jensen, K. L. Gammelmark, "Synthetic Aperture Sequential Beamforming", IEEE International Ultrasonics Symposium Proceedings, p.p. 966-969, 2008.

Compared to the previous SAFT method, the transmission waves are not generated by only one transducer of the array, but by a plurality of transducers of the array so that the transmission wave is a focused beam focused to a predetermined focal zone inside the region.

Then, in this virtual transducer SAFT method:

- during the transmission step (a), a plurality of transmission waves, each one corresponding to focused beam to a focal zone inside the region is transmitted by a plurality of transducers, and

- during the reception step (b), the set of data is acquired for a plurality of focal zones, and the set of data can be organized as a matrix $DS(k, l, m)$, usually called the "full data set" equivalent to the one of the SAFT method.

Then, the beamforming step (c) and the combining step (d) of present invention are applied to the Virtual transducer SAFT method and are identical or similar to those applied for the above modified SAFT method.

Thanks to this modified virtual transducer SAFT method, using a second plurality of transmit weighting vectors W_{Tn}, the produced image has a reduced speckle noise.

3) **The spatially coded SAFT method** also improves the SAFT method in terms of signal to noise ratio.

In this method,

- during the transmission step (a), a wave is fired by applying a transmission matrix *TM* to the transducers signals of the SAFT method: For each one of the *M* transmission waves (the first plurality), the signals to the transducers are multiplied by the transmission matrix *TM*, said transmission matrix being an invertible matrix, and

- during the reception step (b), the set of data acquired in response to the transmission waves is stored into a receive matrix *RM(k, l, m)* and the matrix of the set of data *DS(k, l, m)* can be obtained by using the receive matrix *RM* and the transmission matrix *TM* by the following inversion formula:

$$DS(k,l,m)\big|_{k=\mathrm{constant}} = TM^{-1} \bullet RM(k,l,m)\big|_{k=\mathrm{constant}},$$

$$\textit{for } k=1 \textit{ to } K.$$

The matrix *DS* of the set of data is then equivalent to the same one above described in the SAFT method.

Then, the beamforming step (c) and the combining step (d) of present invention is applied to the spatially coded SAFT method, and are similar to those applied for the above modified SAFT method.

Thanks to this modified spatially coded SAFT method, using a second plurality of transmit weighting vectors W_{Tn}, the produced image has a reduced speckle noise.

4) **The circular wave synthetic method** also improves the SAFT method in terms of signal to noise ratio. It is also similar to the virtual transducer SAFT method, but differs in that the focussed beam is focussed behind the array, which leads to circular waves transmitted inside the medium.

Details of this method can be found in the published document M. Couade, M. Pernot, M. Tanter, E. Messas, A. Bel, M. Ba, A.-A. Hagege, M. Fink, "Ultrafast Imaging of the Heart Using Circular Wave Synthetic Imaging with Phased Arrays", IEEE Ultrason. Symposium, pp. 515-518, 2009.

Then, the beamforming step (c) and the combining step (d) of present invention applied to this circular wave synthetic method are identical or similar to those applied for the above modified SAFT method.

Thanks to this modified circular wave synthetic method, using a second plurality of transmit weighting vectors W_{Tn}, the produced image has a reduced speckle noise.

5) **The plane wave synthetic method** also improves the SAFT method in terms of signal to noise ratio.

Details of this method can be found in the published patent US 6,551,246 or published patent application US 2009/0234230.

In this method:

- during the transmission step (a), a first plurality (M) of plane waves is fired into the medium, and

- during the reception step (b), the transducers signals are acquired, recorded (stored) into a memory as a matrix $DS(k, l, m)$ of the set of data , m being the index of the transmitted plane wave into the medium.

Therefore, the method differs from the SAFT method in that a number M of plane waves is transmitted (emitted, fired) inside the medium.

Then, the beamforming step (c) and the combining step (d) of present invention are applied to this plane wave synthetic method, and are identical or similar to those applied for the above modified SAFT method.

During the beamforming step (c), the beamformed pixel values $U_n(x,z)$ can be calculated by the following beamforming formula:

$$U_n(x,z) = \sum_{m=1}^{M} W_{Tn}[m] \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l,m),l,m).$$

In the plane wave synthetic method, each plane wave is weighted by a different transmit weighting vector W_{Tn}.

In all the above beamforming process, the delay function $\tau(x,z,l,m)$ is a well known function depending on each type of beamforming process and each type of probe (shape, dimension).

According to a third variant of the imaging method, illustrated on **figure 8**, the imaging method is not using a plurality of transmit weighting vectors for all pixels in the image. Thanks to this feature lateral resolution is not reduced for these pixels (without transmit weighting vectors compounding), and speckle noise is reduced for the other pixels in the image (with transmit weighting vectors compounding).

In this third variant, the imaging method further comprises the following steps.

- an initial imaging step (301) wherein a first image of the region is determined by said processing unit and array,

- an evaluation step (302) in which a metric value is determined for the pixels inside the first image,

- an imaging step (303, 304, 305) in which, if the metric value is comprised in a first range, a pixel value in the image is computed directly without using a plurality of transmit weighted vectors, and if the metric value is comprised in a second range different than said first range, a pixel value in the image is computed with using a plurality (second plurality, N) of transmit weighting vectors, said transmit weighting vectors being different and orthogonal one to an other one in the (second) plurality.

Then, the imaging method can build the final image 307 by combining the pixels computed in the imaging steps (303, 304, 305). The final image pixel value is eighter calculated at step 304 without using transmit weighting vectors, or at step 305 with using transmit weighting vectors according to one of the above explained methods.

Advantageously, the metric value is determined for distinguishing a pixel in the first image corresponding to a significant reflective signal from a pixel in the first image corresponding to a non-significant speckle signal. A significant reflective signal from a pixel in the first image is usually a pixel corresponding to a location inside the medium having a strong reflector element. In that case, the imaging method does not use transmit weighting vectors that reduces lateral resolution. A non-significant speckle signal from a pixel in the first image is usually a pixel corresponding to a location inside the medium not having a strong reflector element. This location corresponds to a speckle noise location in the image. In that case, the imaging method can use transmit weighting vectors that reduces said speckle noise that is not satisfying for the user and that is not significant.

Figures 9 and 10 are an example of images generated by the third variant of imaging method. Figure 9 is a binary image 303 in which black pixels are pixels without transmit weighting (step 304 of the method) and white pixels are pixels with transmit weighting (step 305 of the method). Figure 10 is the final image provided by the third variant imaging method 300.

Thanks to the above hybrid adaptive method, this image 307 is an image having an reduced speckle noise and a good lateral resolution.

The metric value can be determined via a calculus of an autocorrelation function $R(\theta, x, z)$.

For example, the autocorrelation function may be determined by:

$$R(\theta,x,z) = E\{I_{m1}(x,z).I_{m2}(x,z)\}$$

where E{} is a mathematical expected value, and

$$I_m(x,z) = \left|V_m(x,z) + iHT\{V_m(x,z)\}\right|^2$$

$$V_m(x,z) = \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l,m),l,m)$$

DS(k, l, m) is a matrix of the sets of data,

k is an index over time,

l is an index of a transducer among the array,

m is an index of a transmitted wave (e.g. plane wave) for synthetic beamforming,

W_R is a receive weighting vector,

τ(x, z, l, m) is a delay function for the beamforming process, e.g. corresponding to plane wave beamforming process.

The lag θ is an angle that is a difference between a first angle corresponding to a first firing of index *m1* and a second angle corresponding to a second firing of index *m2*. The first and second firings are plane wave firings and the first and second angles are angles of said plane waves relative to the array of transducers.

Figure 11 is showing two examples of such autocorrelation functions: a first autocorrelation function curve 401 established at a location inside the medium corresponding to a strong reflector, and a second autocorrelation function 402 established at a location inside the medium corresponding to speckle noise.

The two autocorrelation functions 401, 402 differ in a lag range comprised between 10 degrees and 30 degrees. This difference may be used to distinguish between the two types of pixels in the first image, and to choose (step 303) between the use or not use (steps 304, 305) of the transmit weighting vectors for computing or calculating a pixel of the final image of the imaging method.

CLAIMS

1. **An imaging method** for producing an image of a region inside a medium, wherein said method is implemented by a processing unit (8) connected to an array (2) of transducers in relation with said medium, and said method comprising the following steps:

(a) a transmission step (101; 201) in which a first plurality (M) of waves are transmitted inside the medium by the transducers,

(b) a reception step (102; 202) in which a set of data is acquired by said transducers in response to the waves,

(c) a beamforming step (103; 203) in which the set of data is processed by a second plurality of beamforming processes for providing beamformed pixel values ($U_n(x, z)$) of at least a portion of the image, each beamforming process either using a set of data corresponding to waves generated with a transmit weighting vector (W_{Tn}), or using a transmit weighting vector (W_{Tn}) in the calculus of the beamformed pixel values, and

(d) a combining step (104; 204) in which the beamformed pixel values of said second plurality are combined together to provide a pixel value ($I(x, z)$) of a pixel inside the image, and

wherein the transmit weighting vectors (W_{Tn}) are different and orthogonal one to an other one.

2. The method according to claim 1, wherein:

- during the transmission step (a), each transmit weighting vector (W_{Tn}) is used for generating a wave, and

- during the beamforming step (c), the beamforming process is a conventional beamforming in which the beamformed pixel values ($U_n(x, z)$) are calculated by the following formula:

$$U_n(x,z)=\sum_{l=l1}^{l2}W_R[l]DS(k-\tau(x,z,l),l,m)$$

where

$DS(k, l, m)$ is a matrix of the set of data,

W_R is a receive weighting vector,

$\tau(x, z, l)$ is a delay function adapted for the beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line, and

x, z are coordinates of a pixel inside the image.

3. The method according to claim 1, wherein the transmit weighting vectors (W_{Tn}) are applied during the beamforming step (c), and

- during the beamforming step (c), the beamforming process is a synthetic beamforming in which the beamformed pixel values ($U_n(x, z)$) are calculated by the following formula:

$$U_n(x,z)=\sum_{m=1}^{M}W_{Tn}[m]\sum_{l=l1}^{l2}W_R[l]DS(k-\tau(x,z,l,m),l,m)$$

where

$DS(k, l, m)$ is a matrix of the set of data,

W_R is a receive weighting vector,

$\tau(x, z, l)$ is a delay function adapted for the beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line,

m is the index, comprised between 1 and M, M being the first plurality that is the number of transmitted waves inside medium,

W_{Tn} is the transmit weighting vector,

x, z are coordinates of a pixel inside the image.

4. The method according to claim 3, wherein the synthetic beamforming process is chosen in a list comprising synthetic aperture focusing technique (SAFT) beamforming process, virtual transducer SAFT beamforming process, spatially coded SAFT beamforming process, circular wave synthetic beamforming process, plane wave synthetic beamforming process.

5. The method according to any one of the claims 1 to 4, wherein the pixel values ($I(x,z)$) of the image are calculated during the combining step (d) by the following formula:

$$I(x,z) = \sum_{n=1}^{N} \left| U_n(x,z) + iHT\{U_n(x,z)\} \right|^2$$

wherein

i is the complex unit imaginary number.

n is the index, comprised between 1 and N, N being the second plurality that is the number of transmit weighting vectors,

$|X|$ is the modulus of X,

$HT\{X\}$ is the Hilbert transform of X,

$U_n(x,z)$ is a beamformed pixel value of said second plurality.

6. The method according to any one of the claims 1 to 5, wherein the transmit weighting vectors (W_{Tn}) are determined by an orthogonal function chosen in a list comprising a Riedel-Sidorenko function, a Discrete prolate spheroidal function and a Hadamard function.

7. The method according to any one of the claims 1 to 6, wherein the transducers are ultrasound transducers that transmit or receive ultrasound waves, and the method produces an ultrasound image of the region inside the medium.

8. The imaging method according to any one of claims 3 to 7, further comprising the following steps:

- an initial imaging step (301) wherein a first image of the region is determined by said processing unit and array,
- an evaluation step (302) in which a metric value is determined for pixels in the first image,
- an imaging step (303, 304, 305) in which, if the metric value is comprised in a first range, a pixel value in the image is computed without using a transmit weighted vector, and if the metric value is comprised in a second range different than said first range, a pixel value in the image is computed with using transmit weighting vectors, said transmit weighting vectors being different and orthogonal one to an other one.

9. The imaging method according to claim 8, wherein the metric value is determined for distinguishing a pixel in the first image corresponding to a significant reflective signal from a pixel in the first image corresponding to a non-significant speckle signal.

10. The imaging method according to claim 8 or claim 9, wherein the metric value is determined via a calculus of an autocorrelation function.

11. The imaging method according to claim 10, wherein the metric value is a mean value of the autocorrelation function for lags comprised between 10 degrees and 30 degrees.

12. **An apparatus** for producing an image of a region inside a medium, comprising a processing unit (8) connected to an array (2) of transducers in relation with said medium, and

wherein the array and the processing unit implements the flowing steps:

(a) a transmission step (101; 201) in which a first plurality (M) of waves are transmitted inside the medium by the transducers,

(b) a reception step (102; 202) in which a set of data is acquired by said transducers in response to the waves, and

wherein the processing unit implements the following step:

(c) a beamforming step (103; 203) in which the set of data is processed by a second plurality of beamforming processes for providing beamformed pixel values ($U_n(x, z)$) of at least a portion of the image, each beamforming process either using a set of data corresponding to waves generated with a transmit weighting vector (W_{Tn}), or using a transmit weighting vector (W_{Tn}) in the calculus of the beamformed pixel values, and

(d) a combining step (104; 204) in which the beamformed pixel values of said second plurality are combined together to provide a pixel value ($I(x,z)$) of each pixel in the image, and

wherein the transmit weighting vectors (W_{Tn}) are different and orthogonal one to an other one.

13. The apparatus according to claim 12, wherein the transmit weighting vectors (W_{Tn}) are applied during the beamforming step (c), and

- during the beamforming step (c), the beamforming process is a synthetic beamforming in which the beamformed pixel values ($U_n(x, z)$) are calculated by the following formula:

$$U_n(x,z) = \sum_{m=1}^{M} W_{Tn}[m] \sum_{l=l1}^{l2} W_R[l] DS(k - \tau(x,z,l,m),l,m)$$

where

$DS(k, l, m)$ is a matrix of the set of data,

W_R is a receive weighting vector,

$\tau(x, z, l)$ is a delay function adapted for the beamforming process,

l is an index of a transducer in the array 2, comprised between $l1$ and $l2$, an aperture for beamforming a line,

m is the index, comprised between 1 and M, M being the first plurality that is the number of transmitted waves inside medium,

W_{Tn} is the transmit weighting vector,

x, z are coordinates of a pixel inside the image.

14. The apparatus according to claim 13, wherein the synthetic beamforming process is chosen in a list comprising synthetic aperture focusing technique (SAFT) beamforming process, virtual transducer SAFT beamforming process, spatially coded SAFT beamforming process, circular wave synthetic beamforming process, plane wave synthetic beamforming process.

15. The apparatus according to any one of claims 12 to 14, further implementing the following steps:

- an initial imaging step (301) wherein a first image of the region is determined by said processing unit and array, and

- an evaluation step (302) in which a metric value is determined for pixels in the first image,

- an imaging step (303, 304, 305) in which, if the metric value is comprised in a first range, a pixel value in the image is computed without using a transmit weighted vector, and if the metric value is comprised in a second range different than said first range, a pixel value in the image is computed with using transmit weighting vectors, said transmit weighting vectors being different and orthogonal one to an other one.

16. **A computer program** including instructions for executing the steps of the method according to any one of the claims 1 to 15 when said program is executed by a computer.

17. **A computer-readable storage medium** on which is stored computer program including instructions for execution of the steps of the method according to any one of the claims 1 to 15 when said program is executed by a computer.

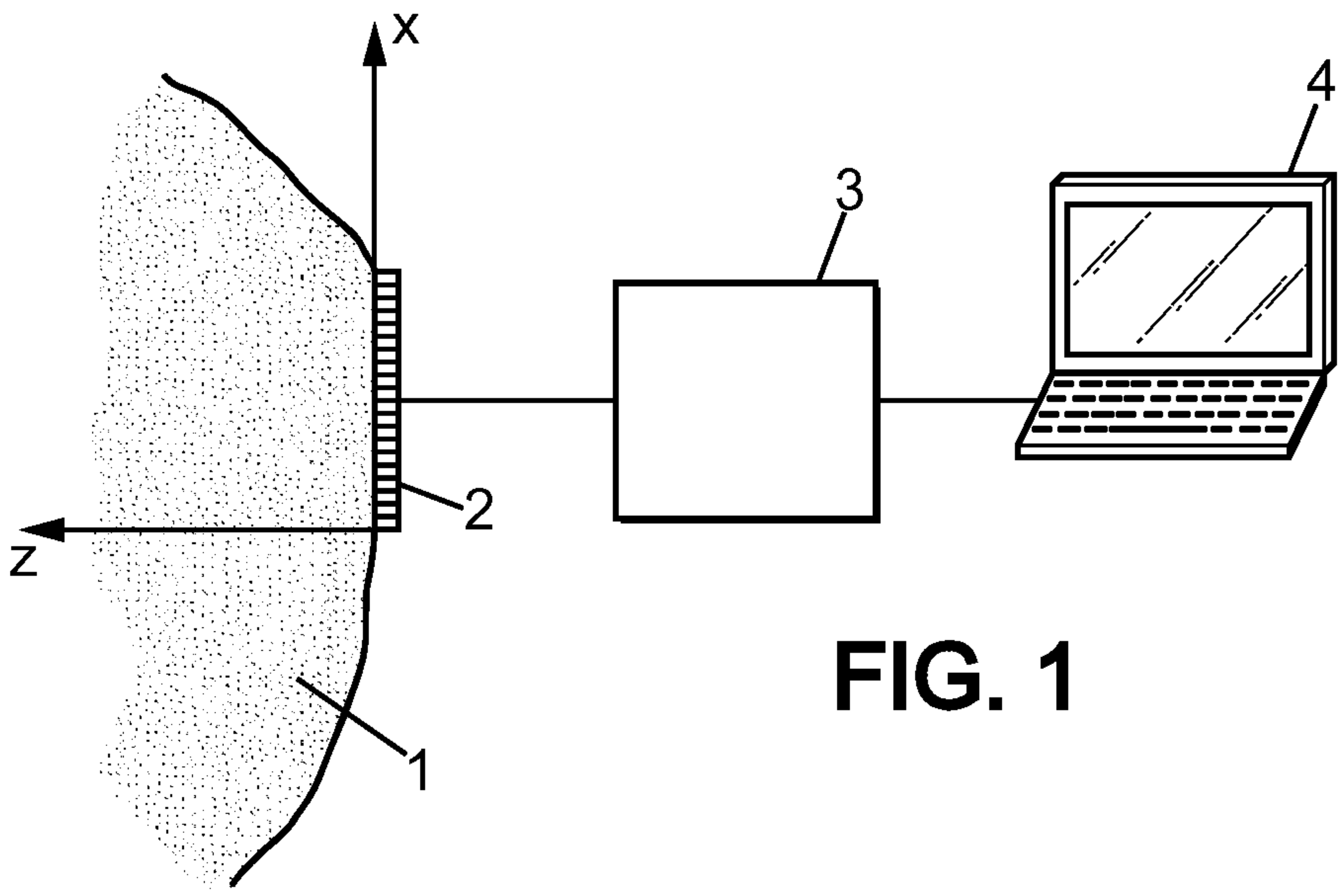

FIG. 1

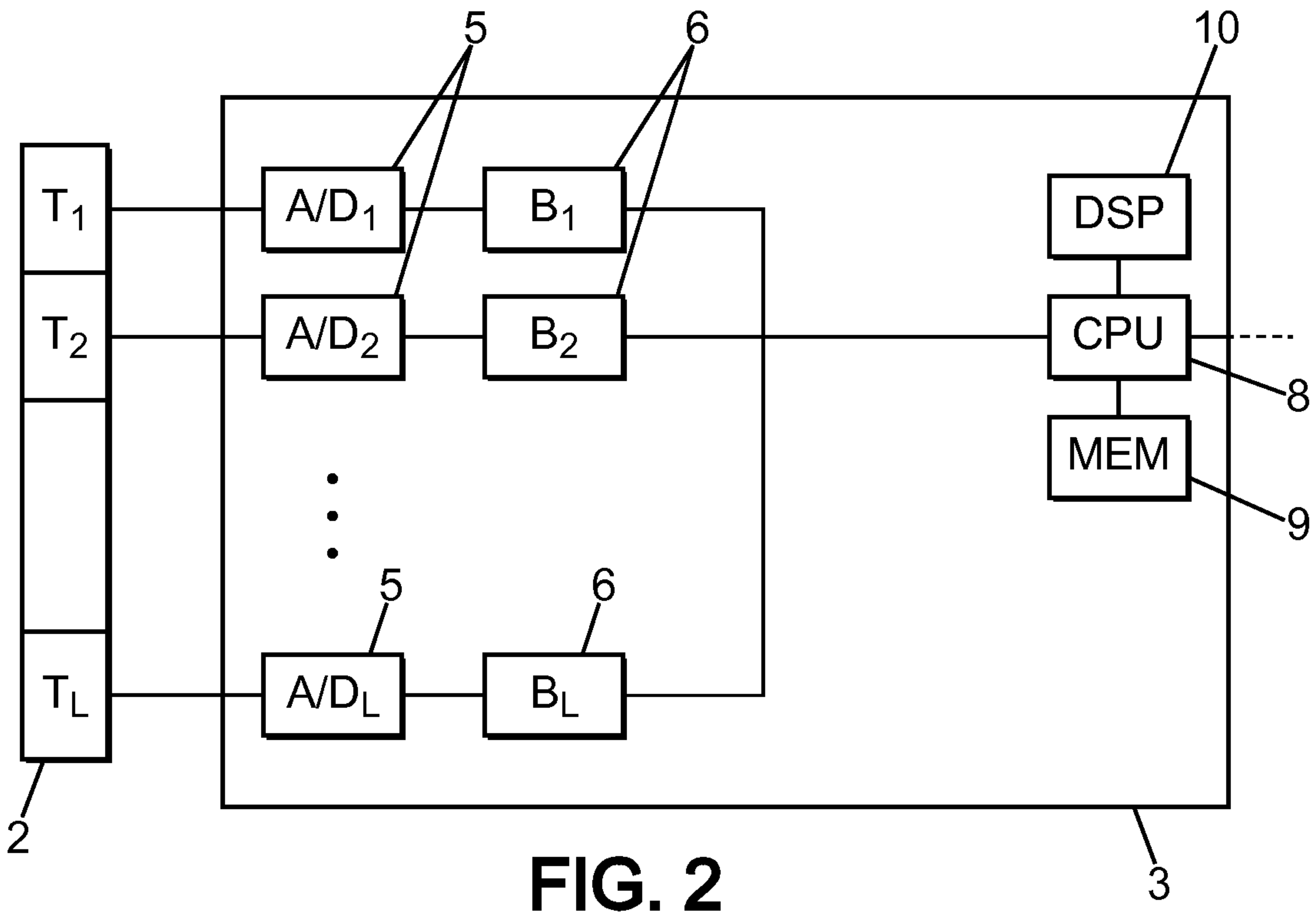

FIG. 2

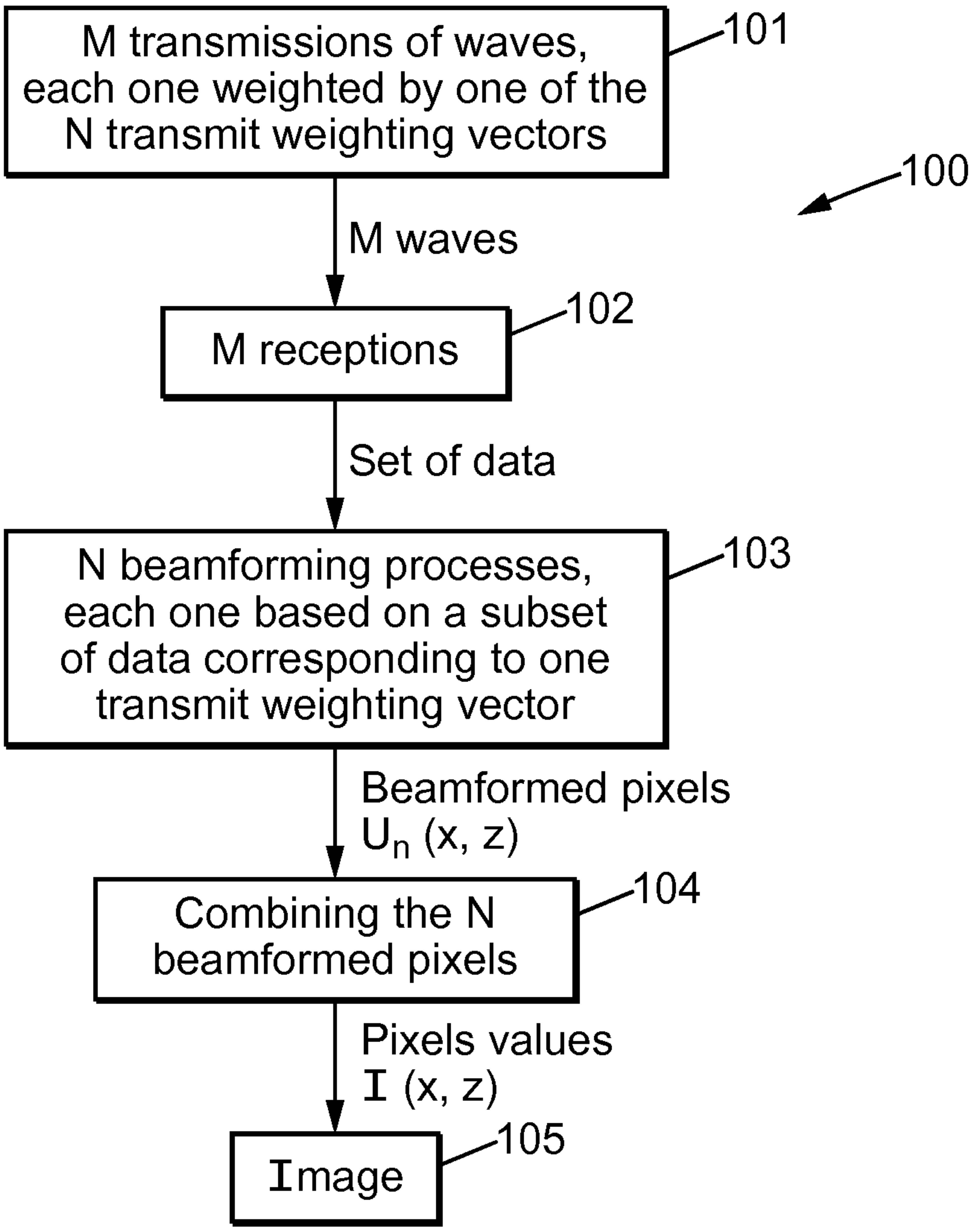
M transmissions of waves, each one weighted by one of the N transmit weighting vectors
101
100
M waves
M receptions
102
Set of data
N beamforming processes, each one based on a subset of data corresponding to one transmit weighting vector
103
Beamformed pixels
U_n (x, z)
Combining the N beamformed pixels
104
Pixels values
I (x, z)
Image
105

FIG. 3

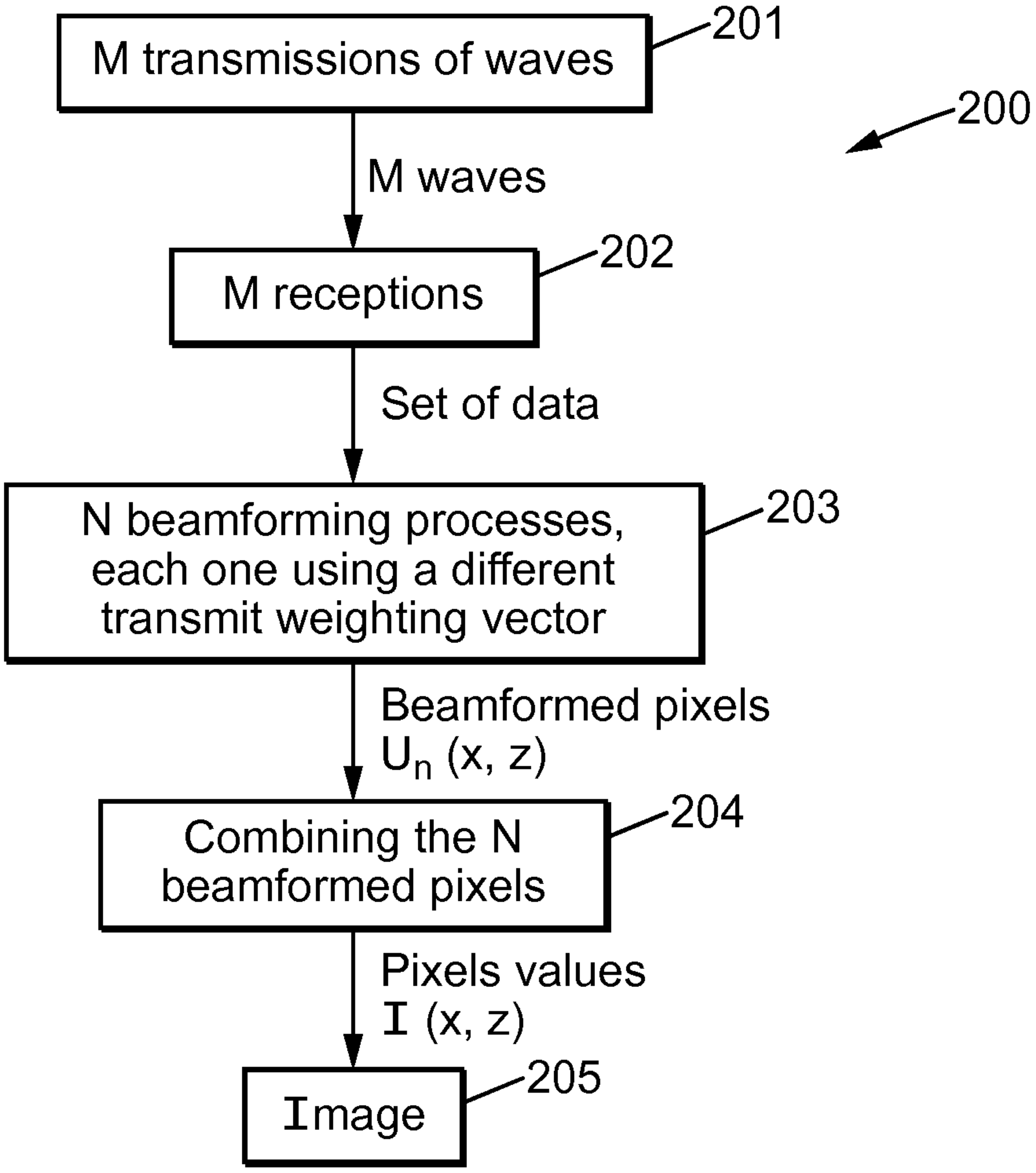
M transmissions of waves
201
200
M waves
M receptions
202
Set of data
N beamforming processes, each one using a different transmit weighting vector
203
Beamformed pixels $U_n (x, z)$
Combining the N beamformed pixels
204
Pixels values I (x, z)
Image
205

FIG. 4

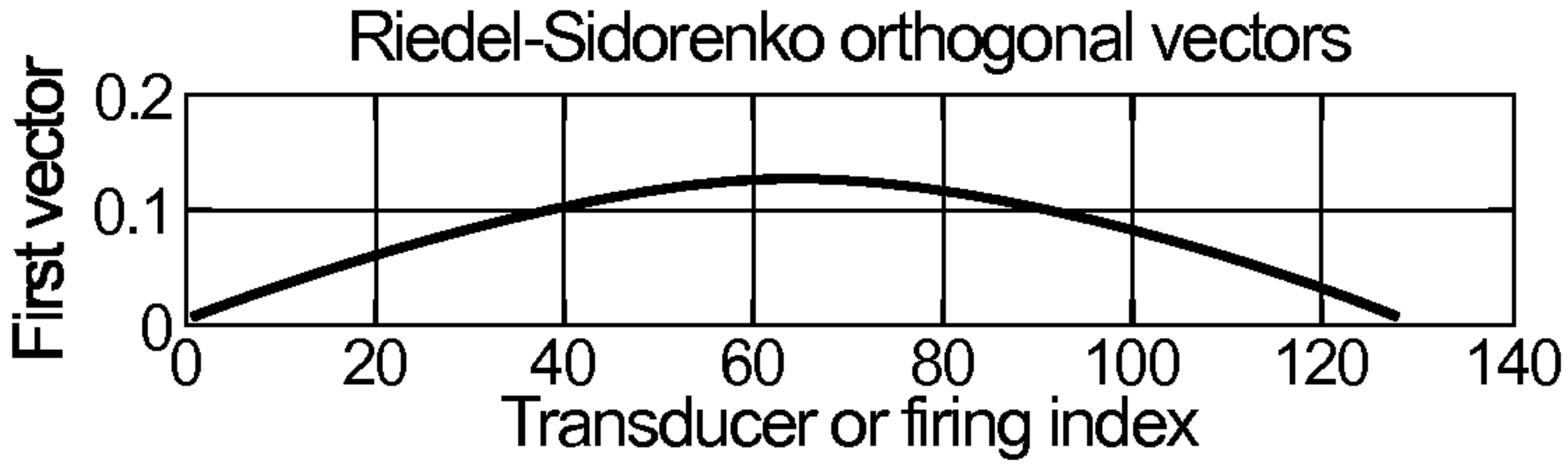

FIG. 5a

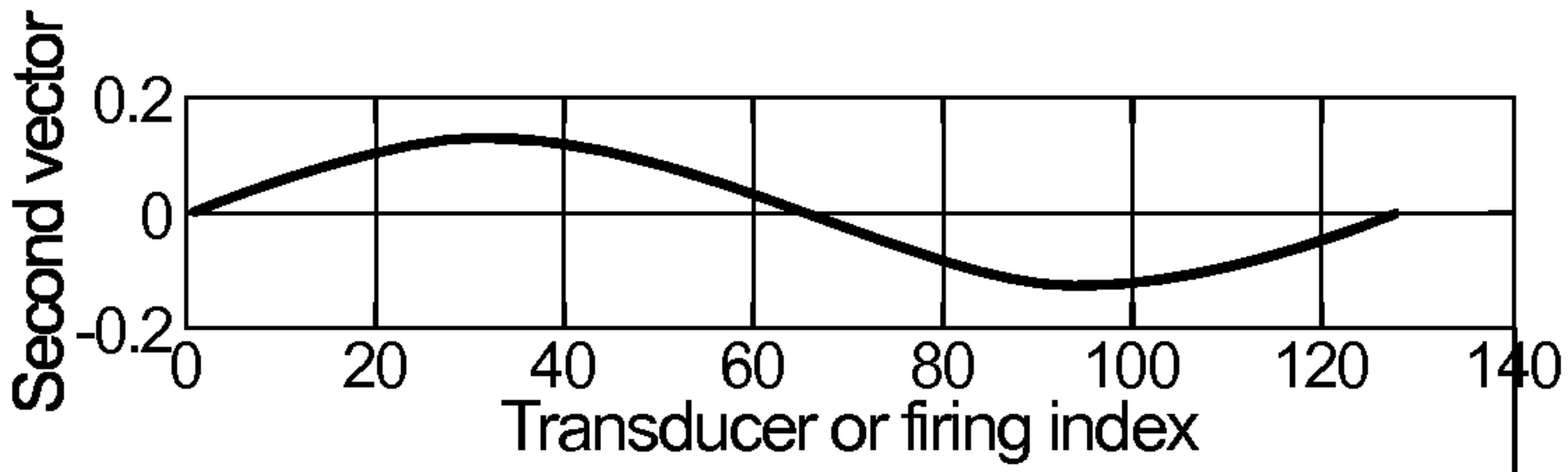

FIG. 5b

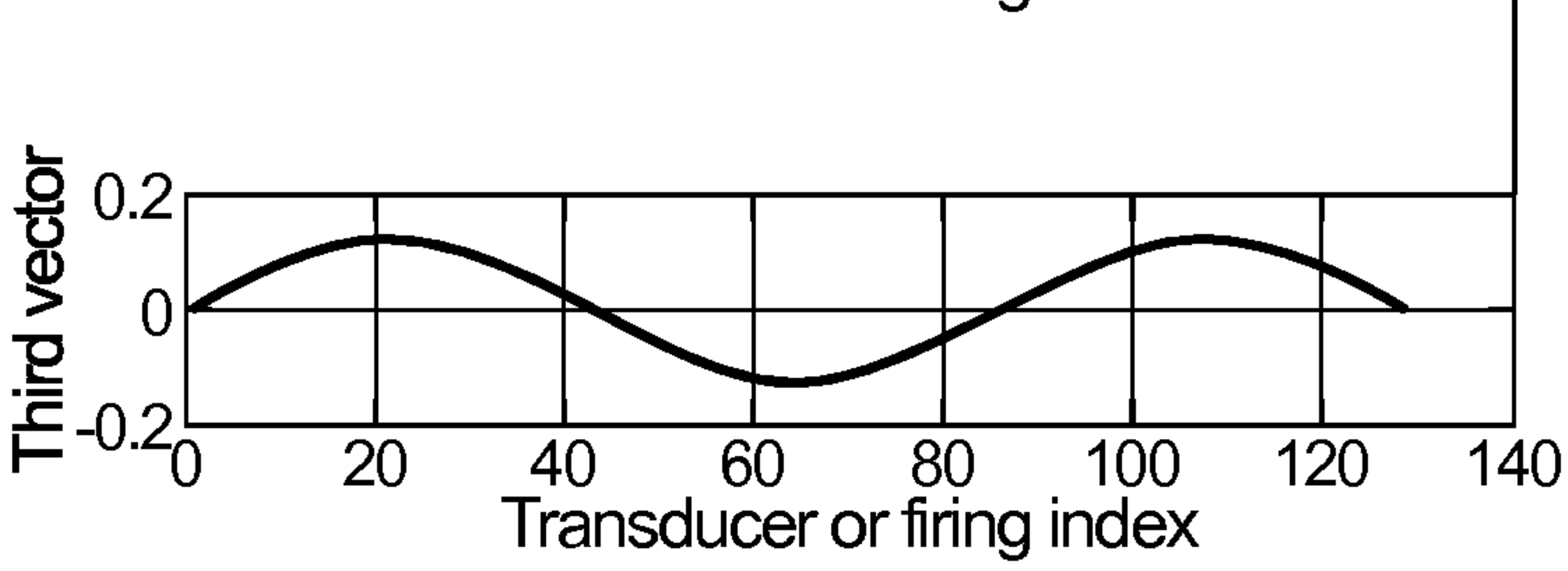

FIG. 5c

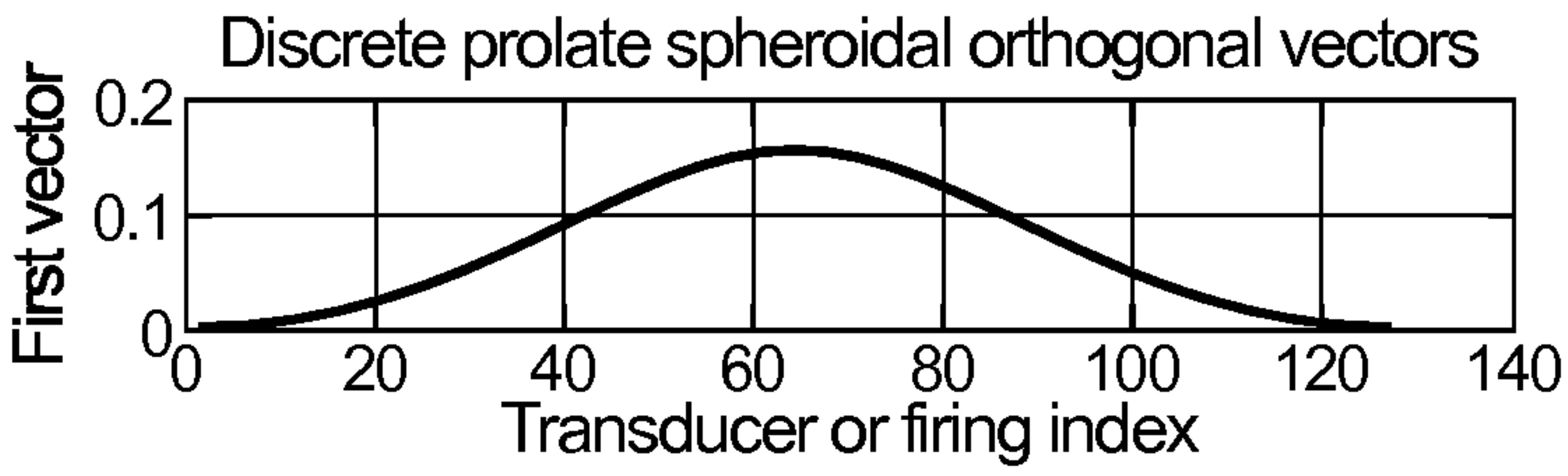

FIG. 6a

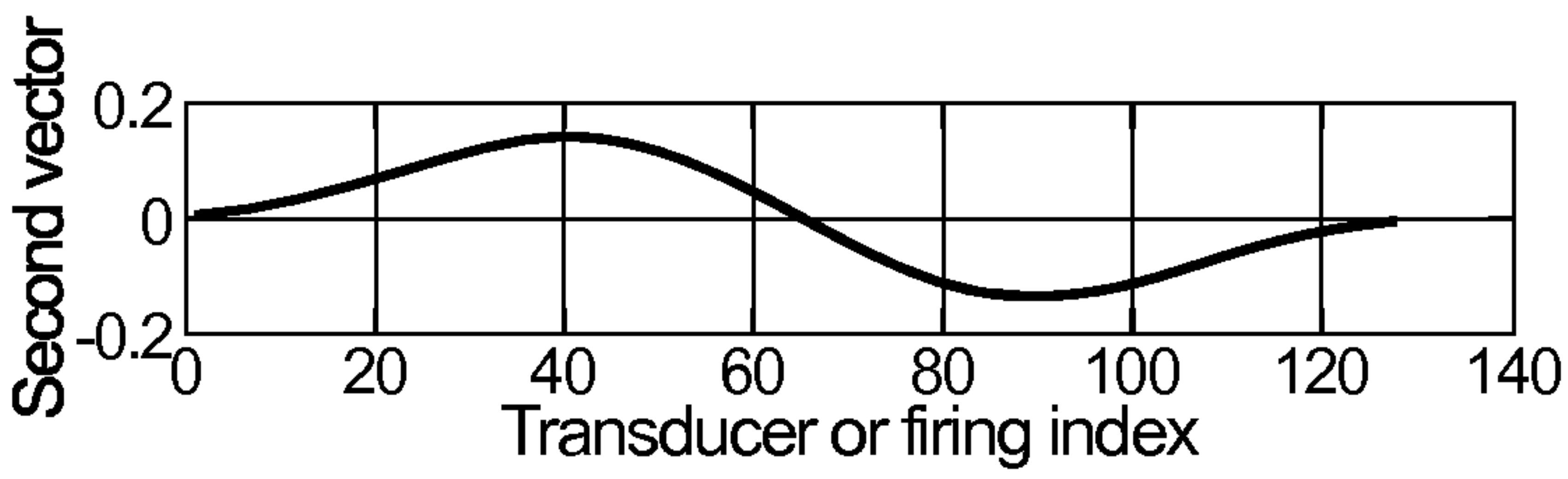

FIG. 6b

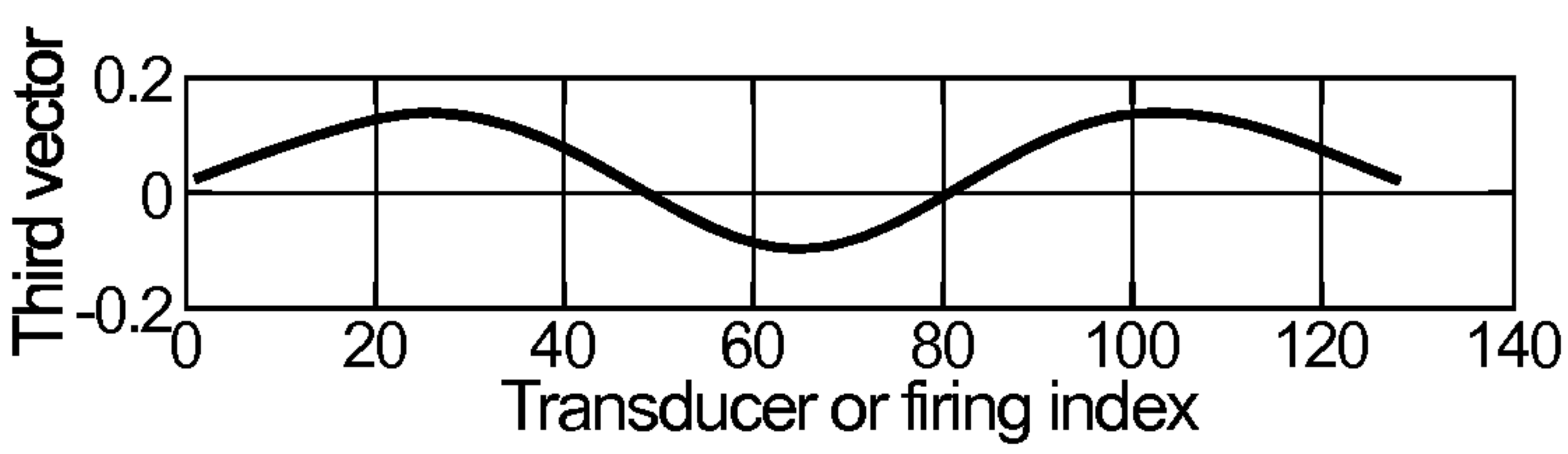

FIG. 6c

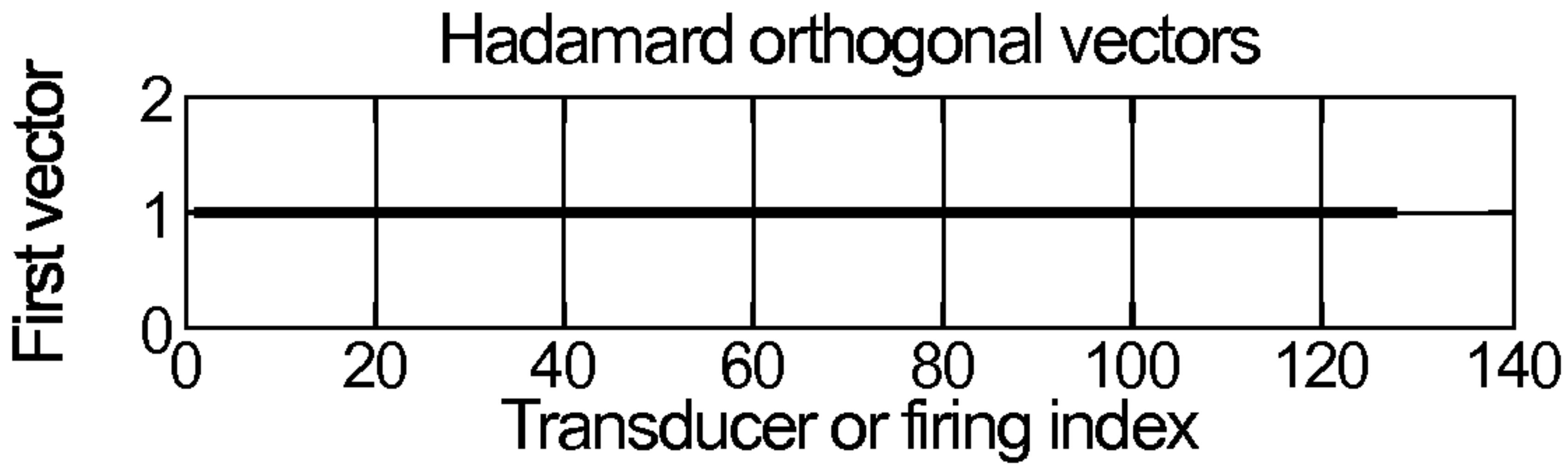

FIG. 7a

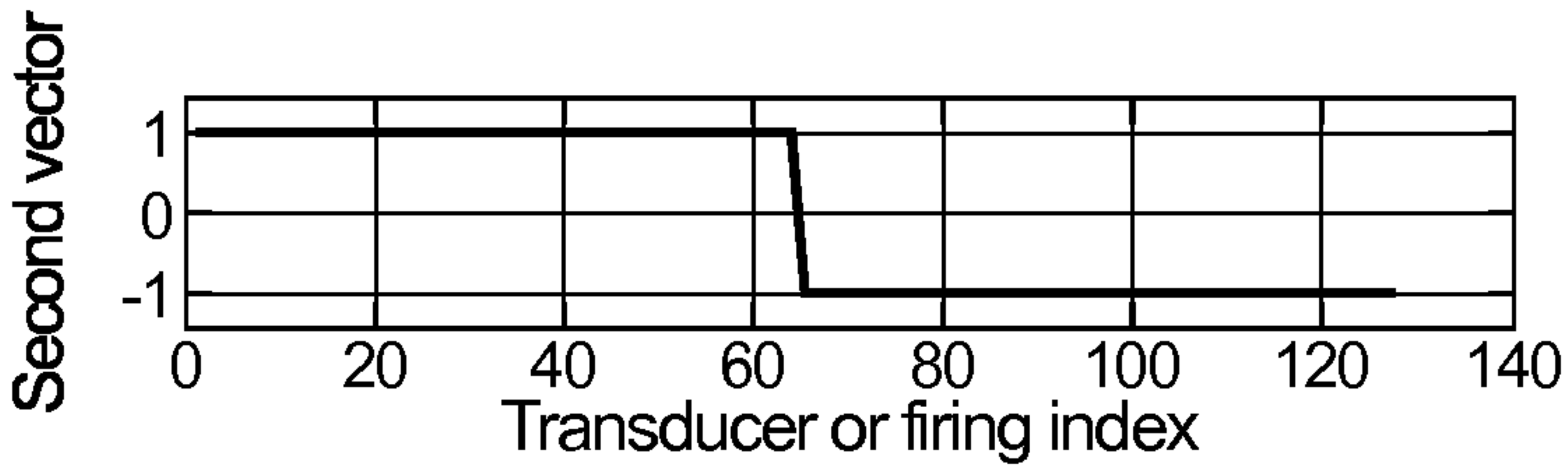

FIG. 7b

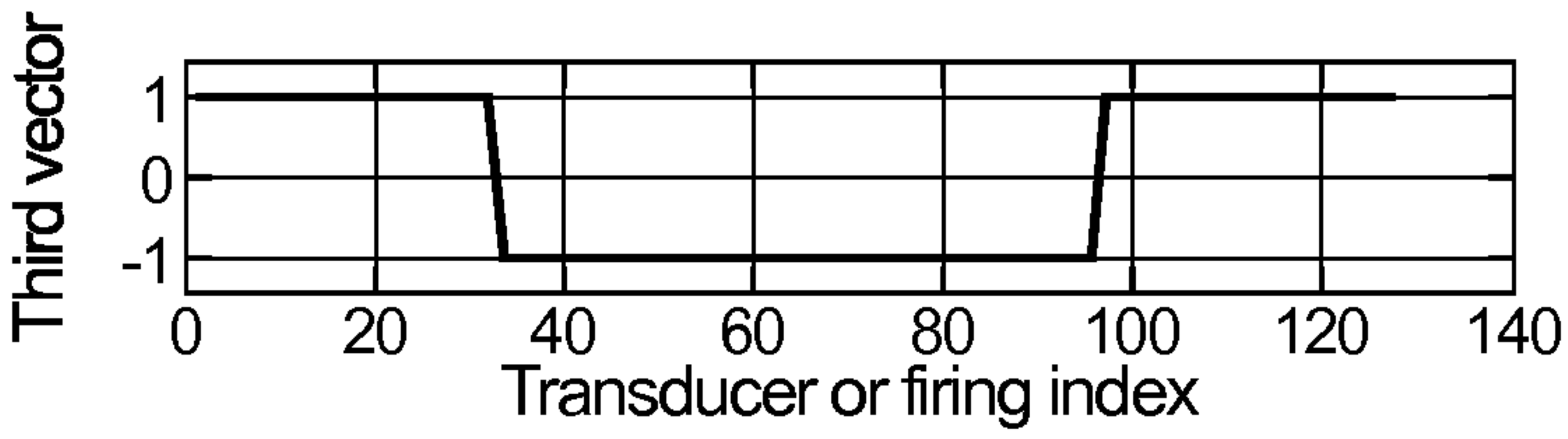

FIG. 7c

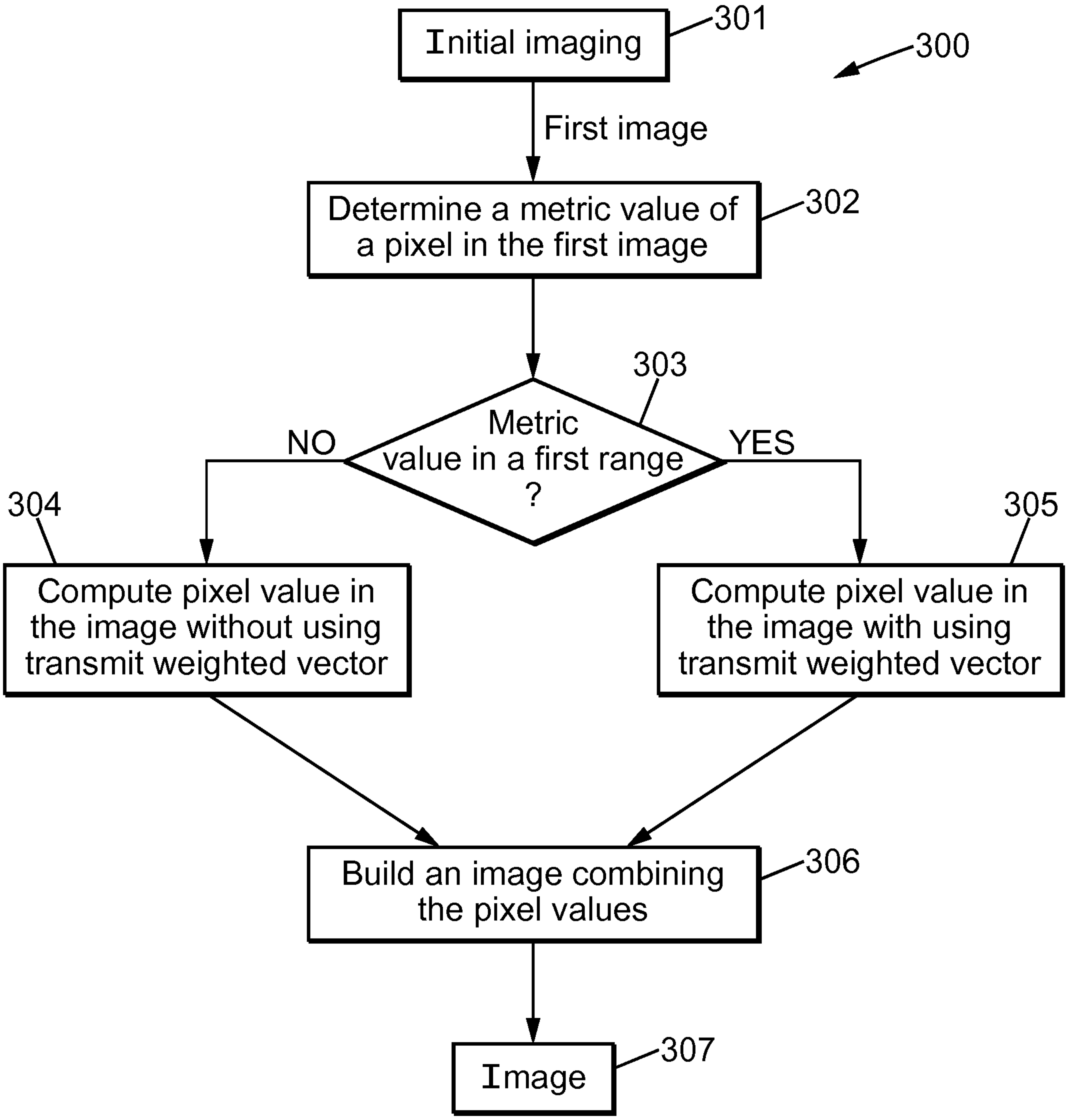
Initial imaging
301
300
First image
Determine a metric value of a pixel in the first image
302
303
Metric value in a first range ?
NO
YES
304
305
Compute pixel value in the image without using transmit weighted vector
Compute pixel value in the image with using transmit weighted vector
Build an image combining the pixel values
306
Image
307

FIG. 8

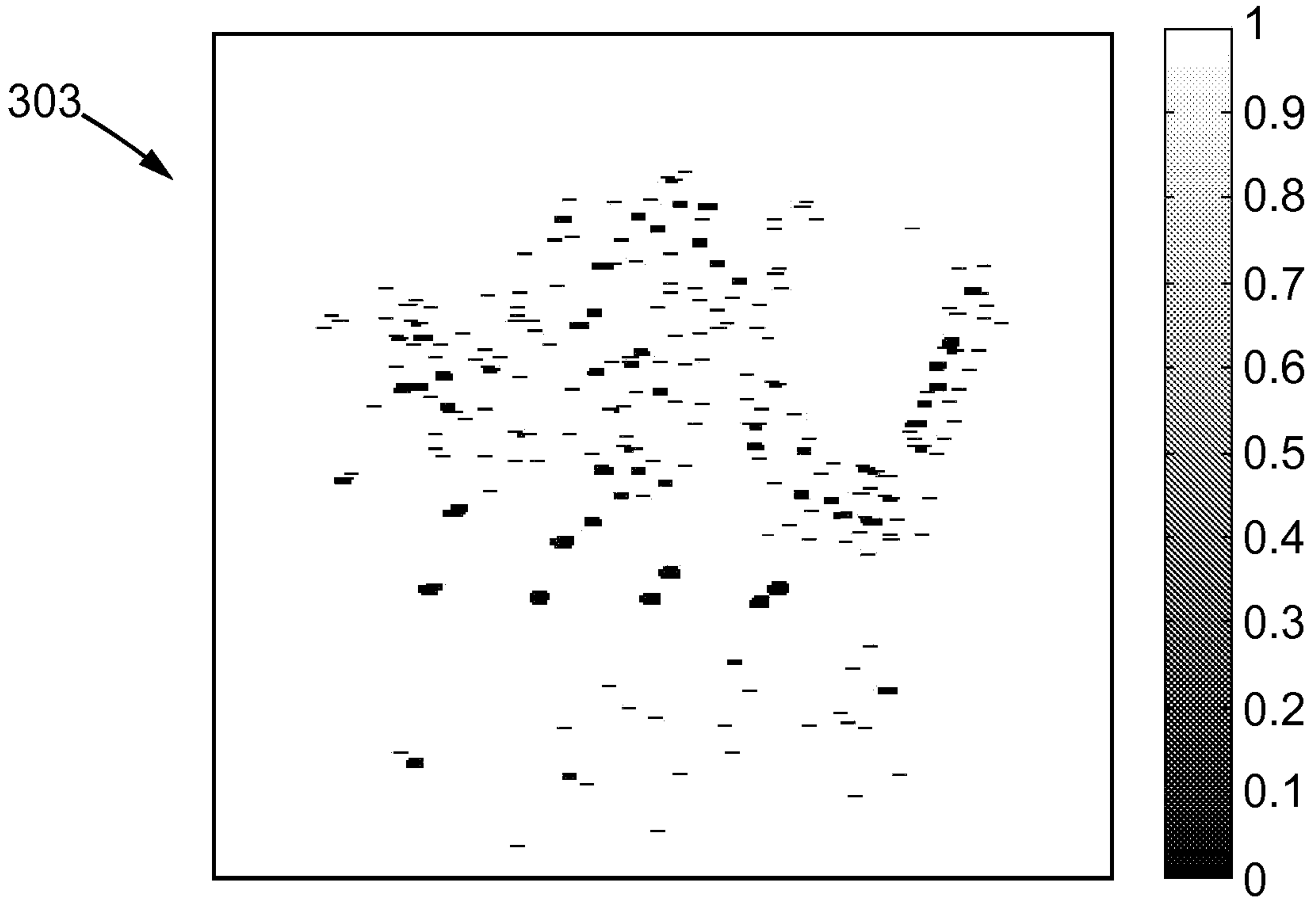

FIG. 9

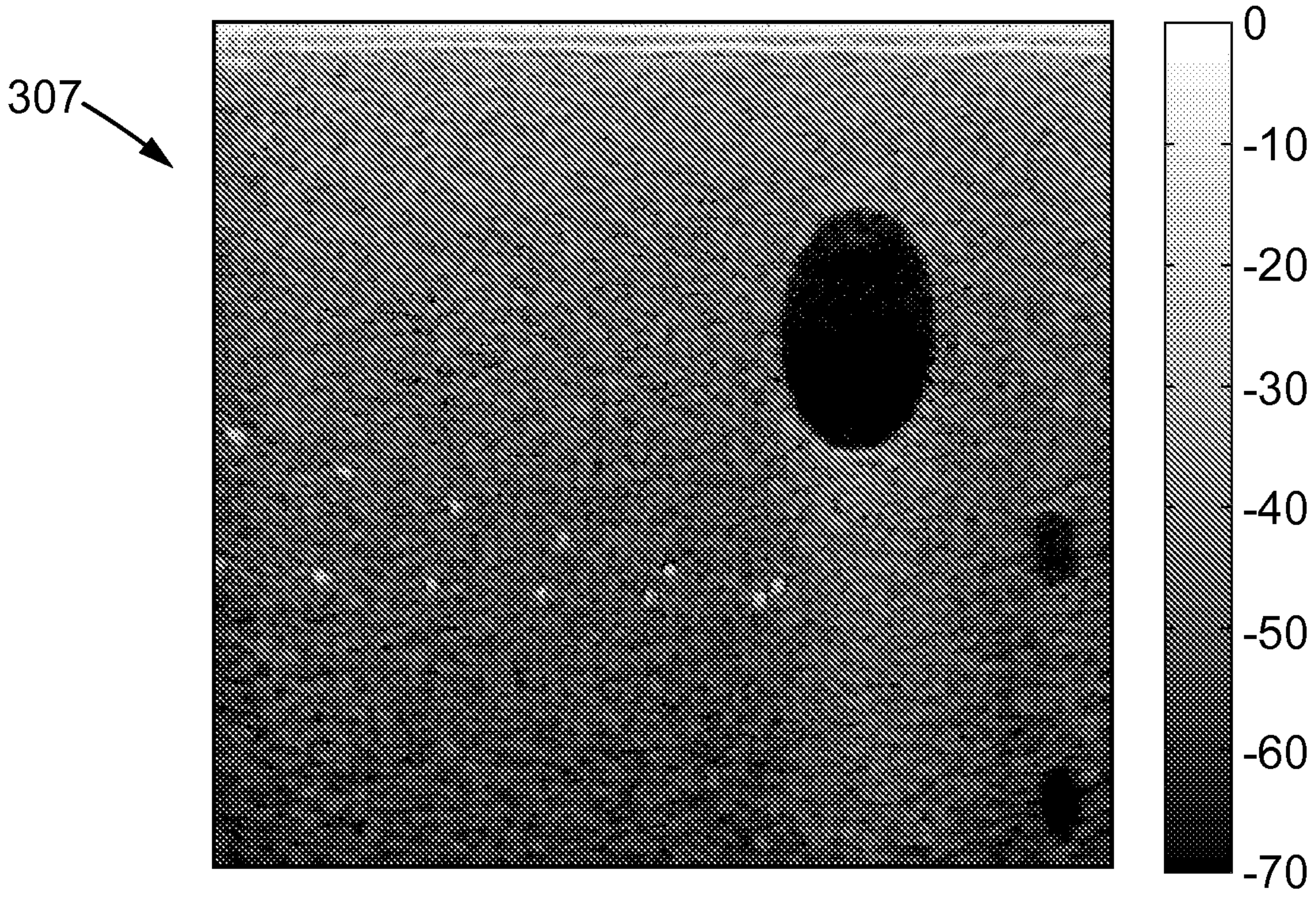

FIG. 10

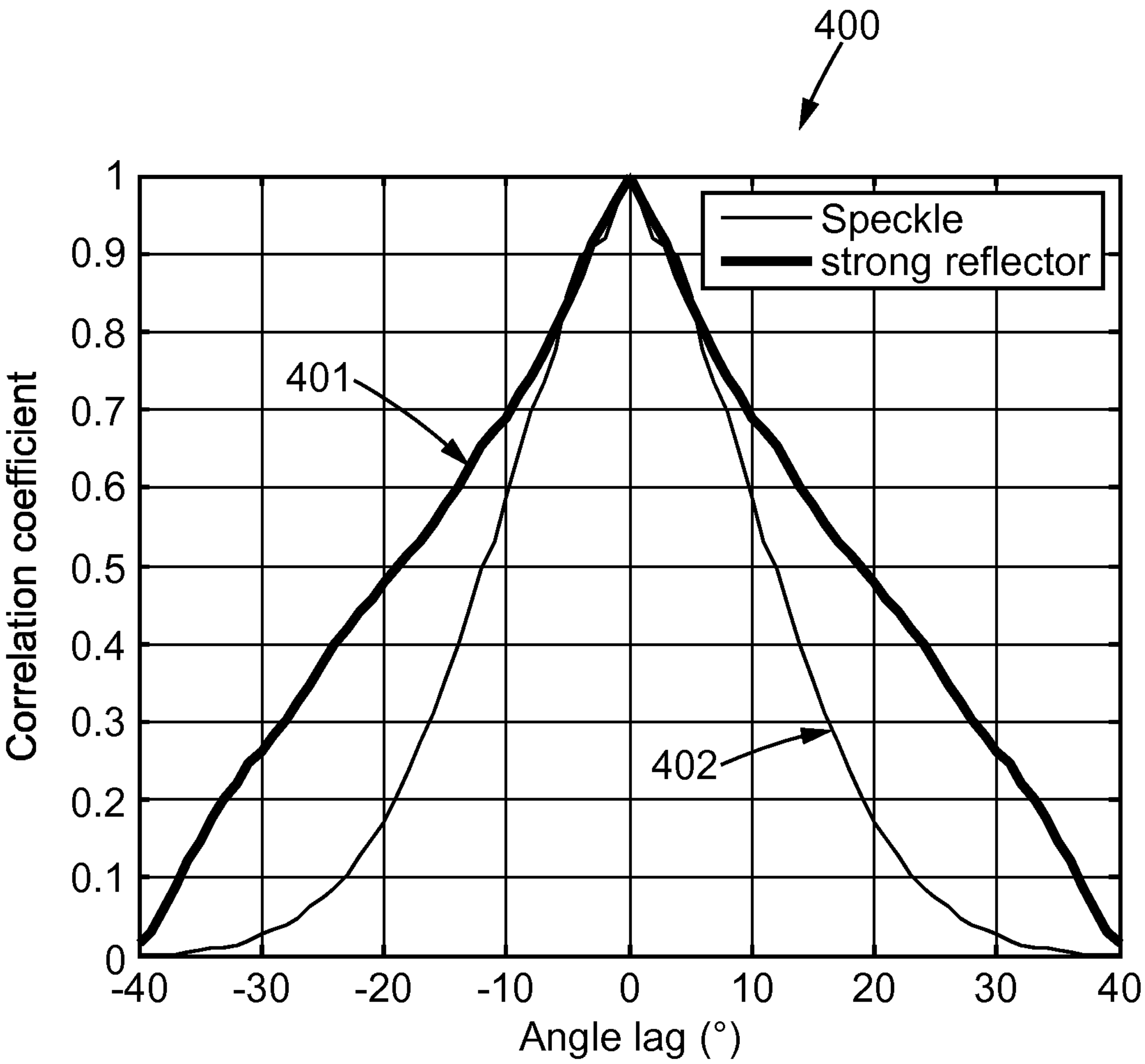
400
Speckle
strong reflector
401
402
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Correlation coefficient
-40
-30
-20
-10
0
10
20
30
40
Angle lag (°)

FIG. 11

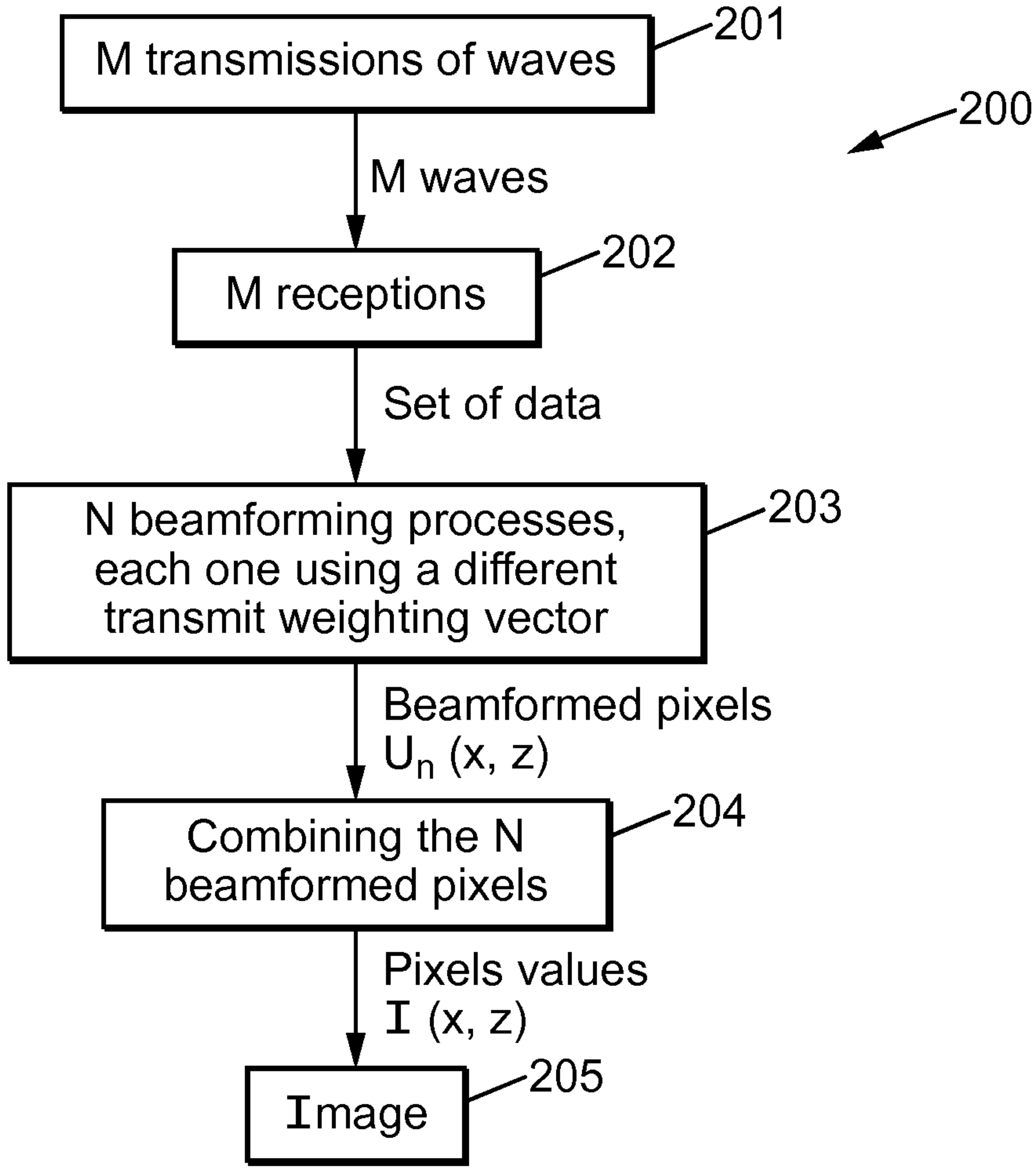
M transmissions of waves
201
200
M waves
M receptions
202
Set of data
N beamforming processes, each one using a different transmit weighting vector
203
Beamformed pixels
U_n (x, z)
Combining the N beamformed pixels
204
Pixels values
I (x, z)
Image
205

FIG. 4