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(54) **EFFICIENT COMPUTATION OF SPATIALLY VARYING ULTRASOUND ANALYTICAL POINT SPREAD FUNCTIONS**

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A61B 8/00	(2006.01)

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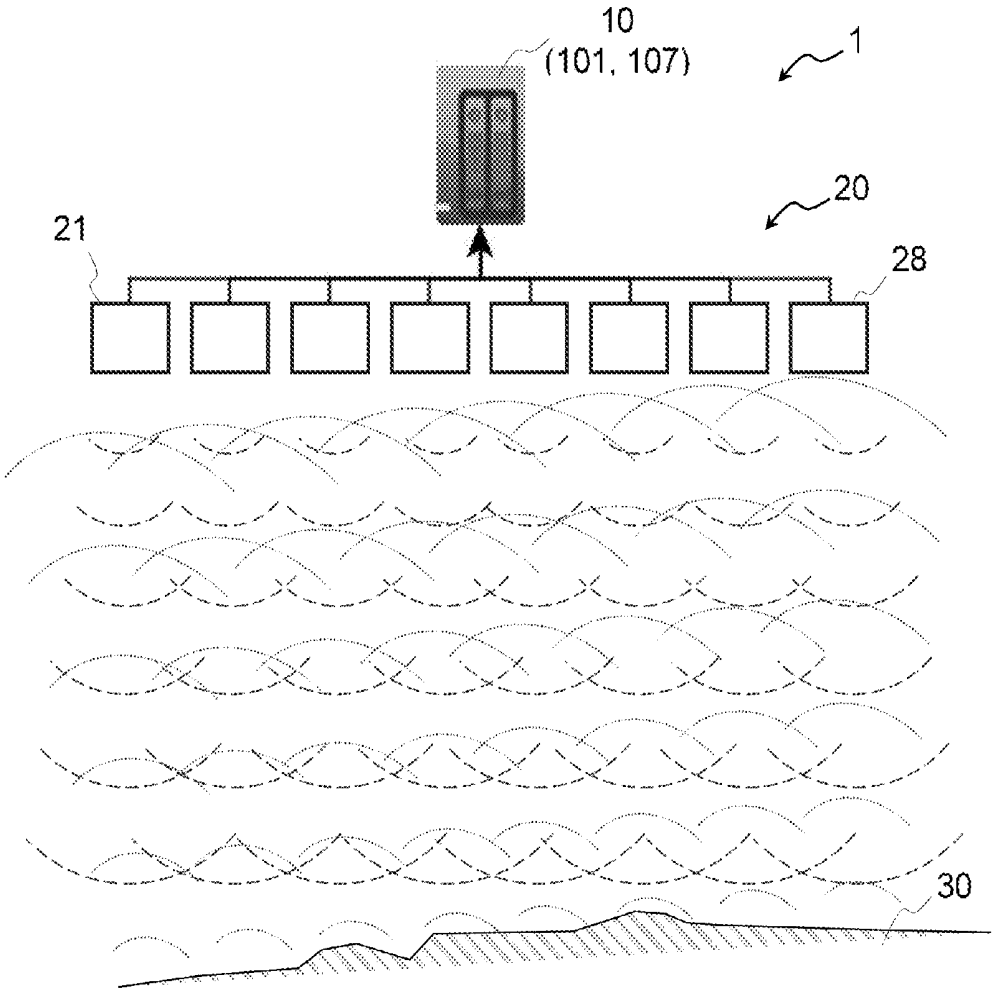
(57) **ABSTRACT**

The invention is directed to a computer-implemented method for computing a tissue reflectivity function (TRF). This method comprises accessing radio-frequency (RF) data and computing a point spread function (PSF), to obtain the TRF. The RF data accessed are data obtained by beamforming time signals R_i from an array of transducers of an ultrasound device. Next, for each pair (r, s) of given pairs of points in the imaging plane, the PSF is computed as a sum of contributions from at least some of the transducers. Each of said contributions is computed by evaluating a transducer's transfer function h, based on two outputs of a respective time-of-flight function τ. Such outputs are obtained by evaluating the time-of-flight function at a first point r and at a second point s of said each pair, respectively. Finally, the RF function can be deconvoluted, based on the computed PSF, so as to obtain the TRF.



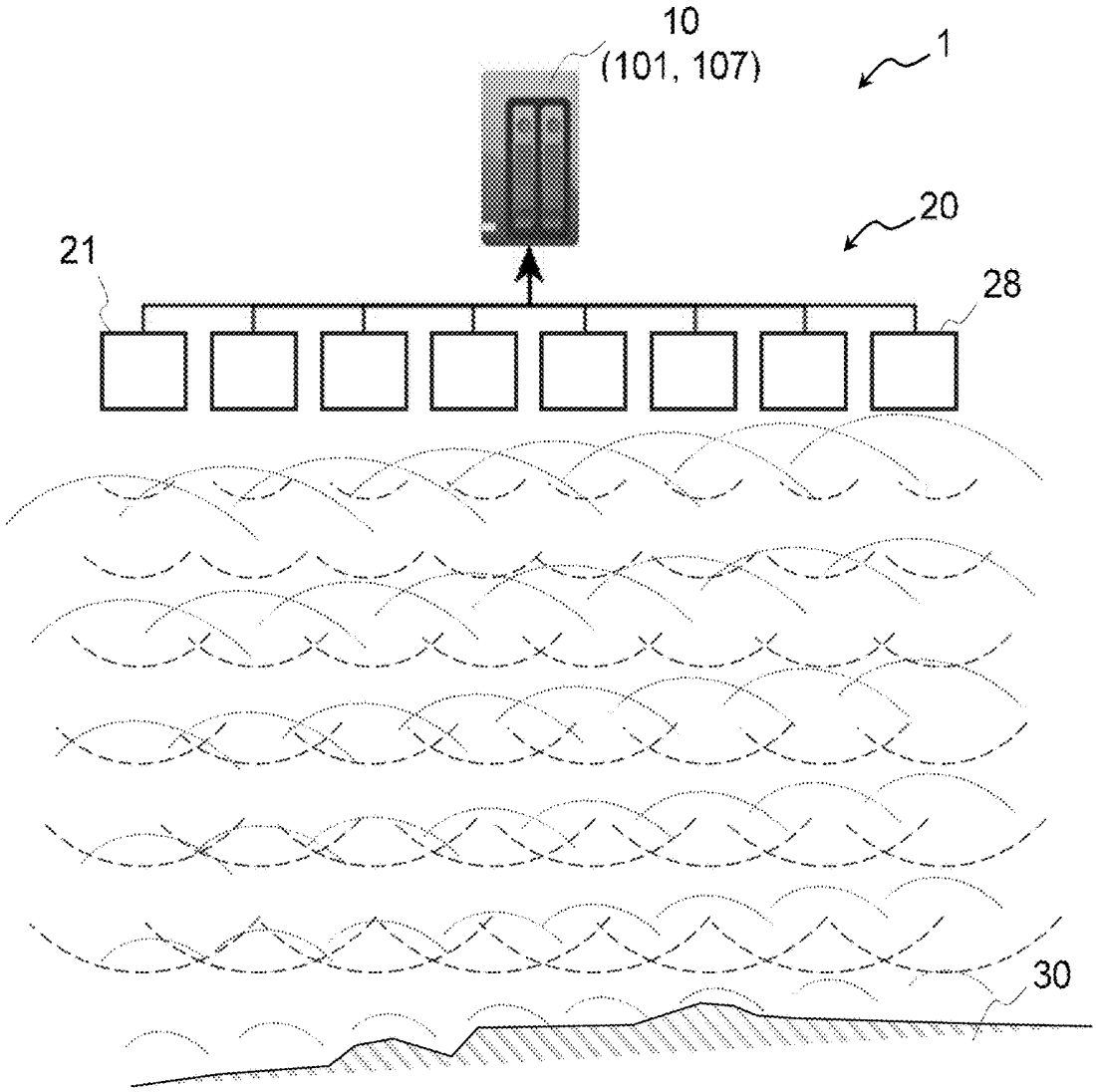


FIG. 1

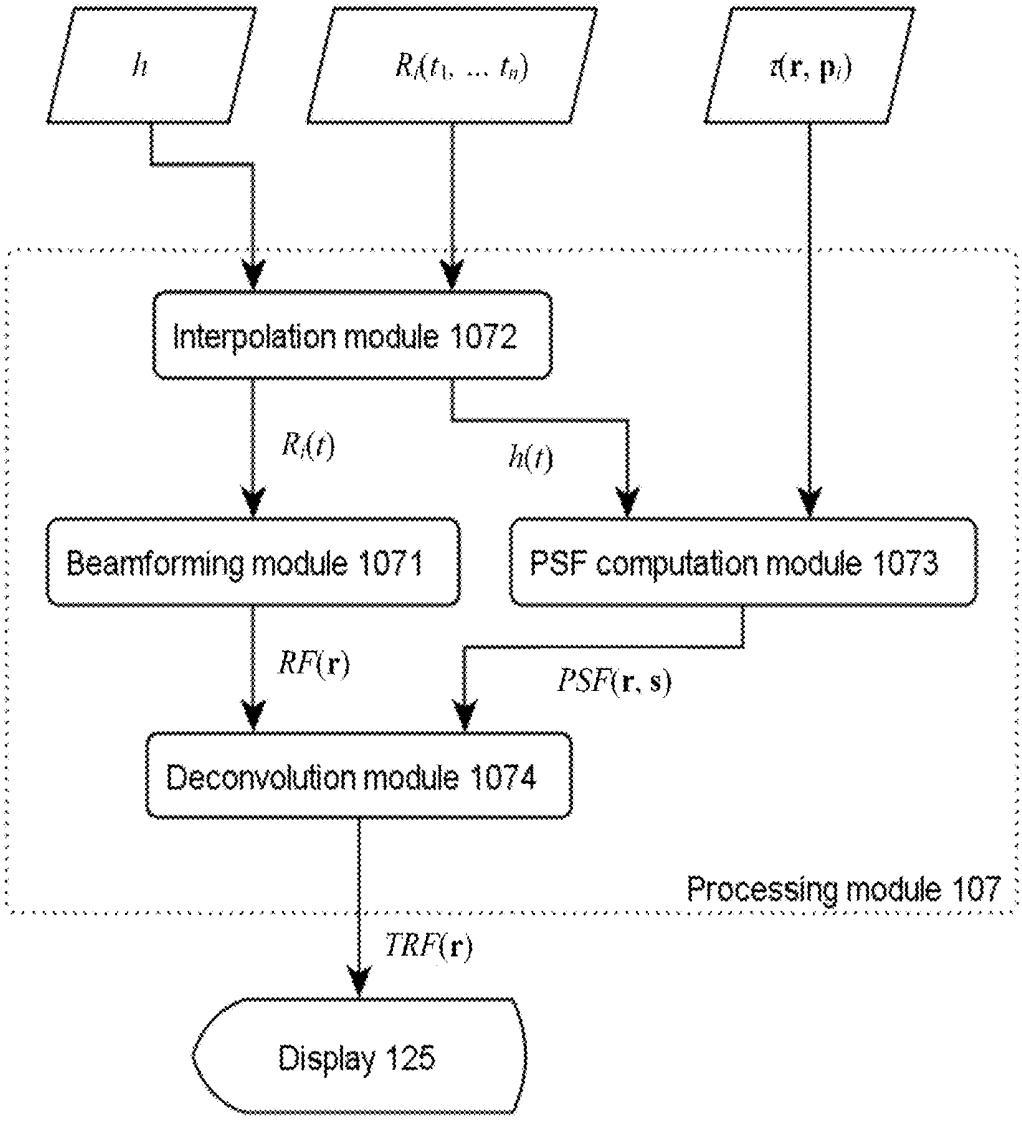

h
$R_i(t_1, \ldots t_n)$
$z(\mathbf{r}, \mathbf{p}_i)$
Interpolation module 1072
$R_i(t)$
$h(t)$
Beamforming module 1071
PSF computation module 1073
$RF(\mathbf{r})$
$PSF(\mathbf{r}, \mathbf{s})$
Deconvolution module 1074
Processing module 107
$TRF(\mathbf{r})$
Display 125

FIG. 2

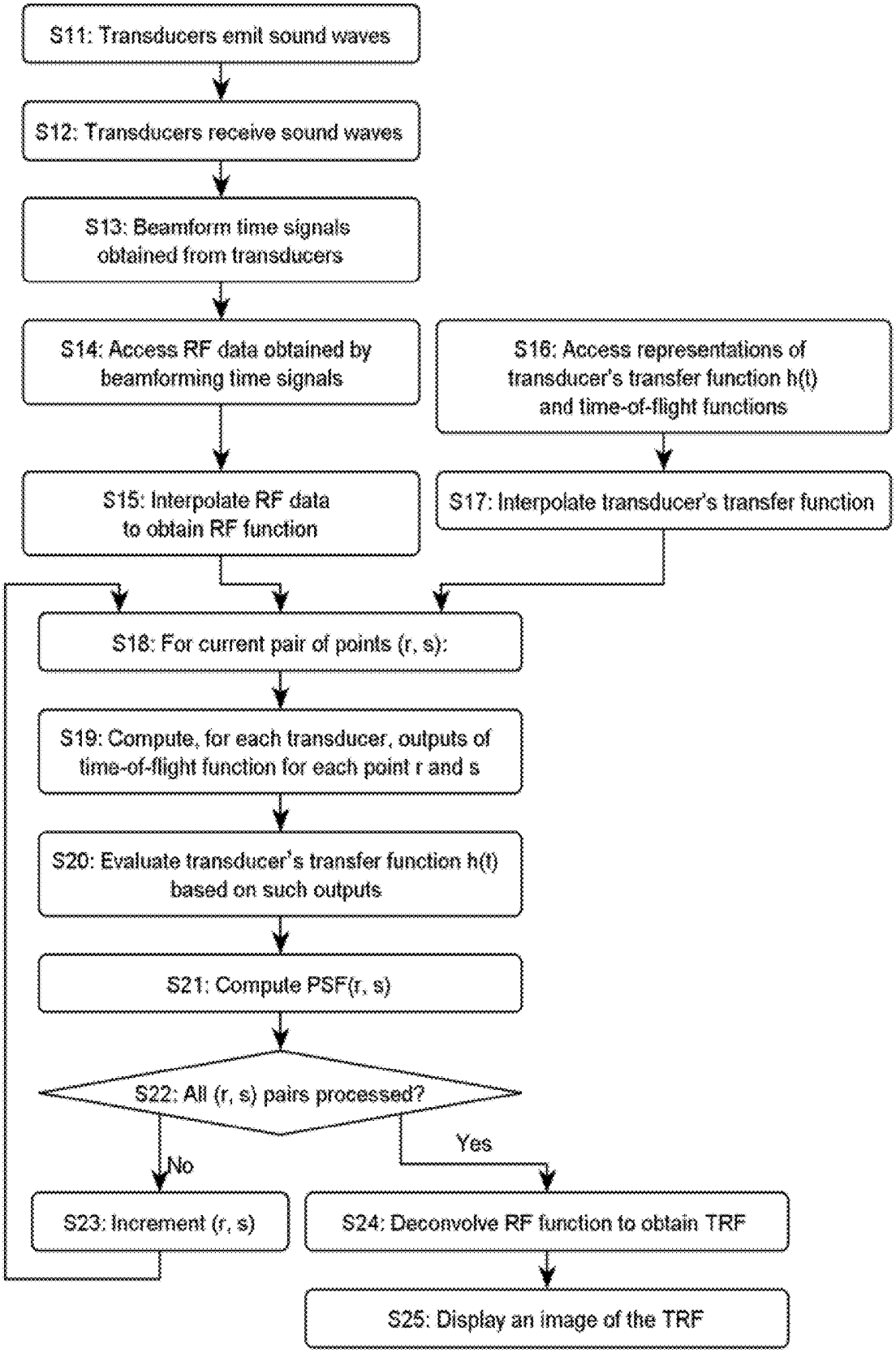

S11: Transducers emit sound waves
S12: Transducers receive sound waves
S13: Beamform time signals obtained from transducers
S14: Access RF data obtained by beamforming time signals
S16: Access representations of transducer's transfer function h(t) and time-of-flight functions
S15: Interpolate RF data to obtain RF function
S17: Interpolate transducer's transfer function
S18: For current pair of points (r, s):
S19: Compute, for each transducer, outputs of time-of-flight function for each point r and s
S20: Evaluate transducer's transfer function h(t) based on such outputs
S21: Compute PSF(r, s)
S22: All (r, s) pairs processed?
No
Yes
S23: Increment (r, s)
S24: Deconvolve RF function to obtain TRF
S25: Display an image of the TRF

FIG. 3

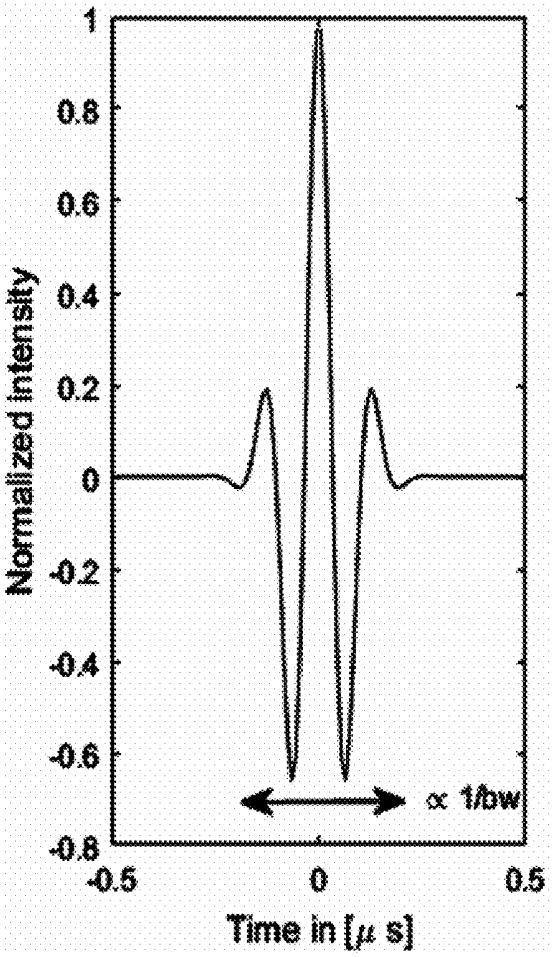

Normalized intensity
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.5
0
0.5
Time in [μ s]
∝ 1/bw

FIG. 4A

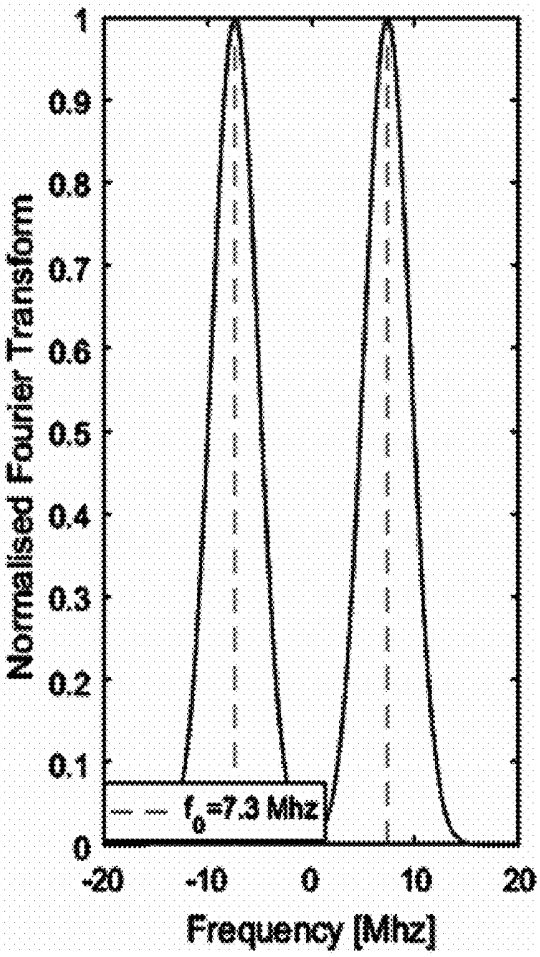

Normalised Fourier Transform
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-20
-10
0
10
20
Frequency [Mhz]
f0=7.3 Mhz

FIG. 4B

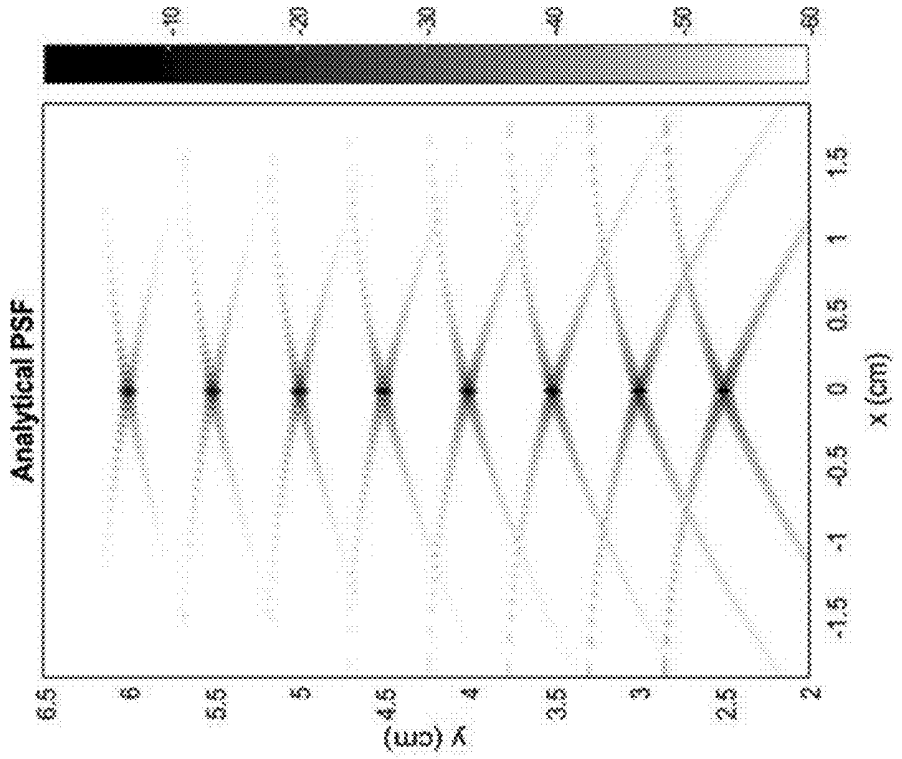

Analytical PSF
-10
-20
-30
-40
-50
-60
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
y (cm)
-1.5
-1
-0.5
0
0.5
1
1.5
x (cm)

FIG. 5B

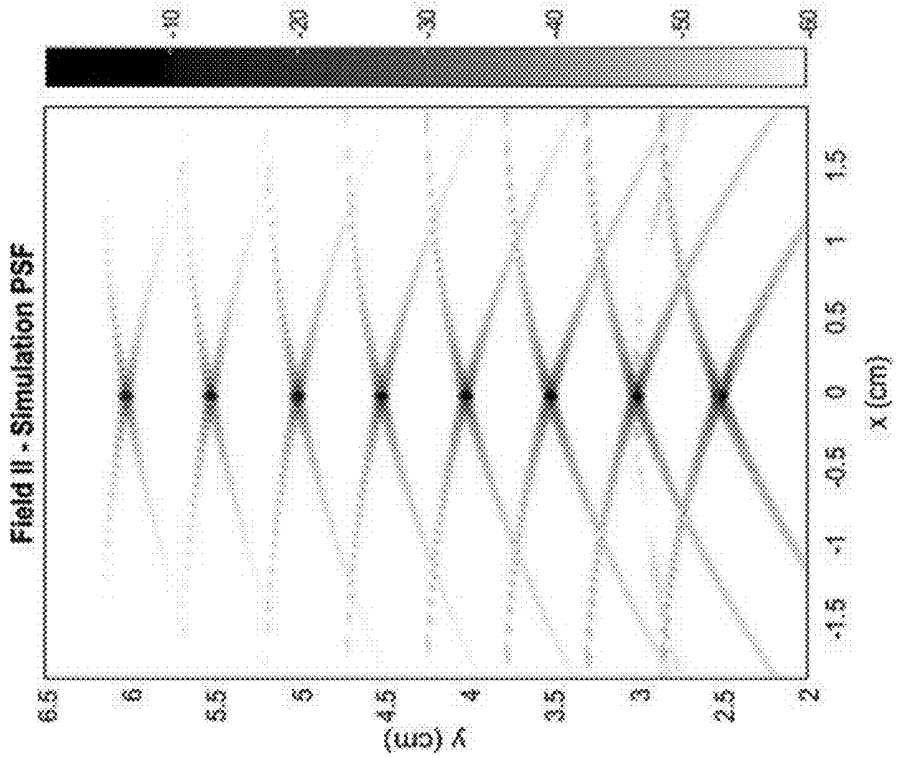

Field II - Simulation PSF
-10
-20
-30
-40
-50
-60
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
y (cm)
-1.5
-1
-0.5
0
0.5
1
1.5
x (cm)

FIG. 5A

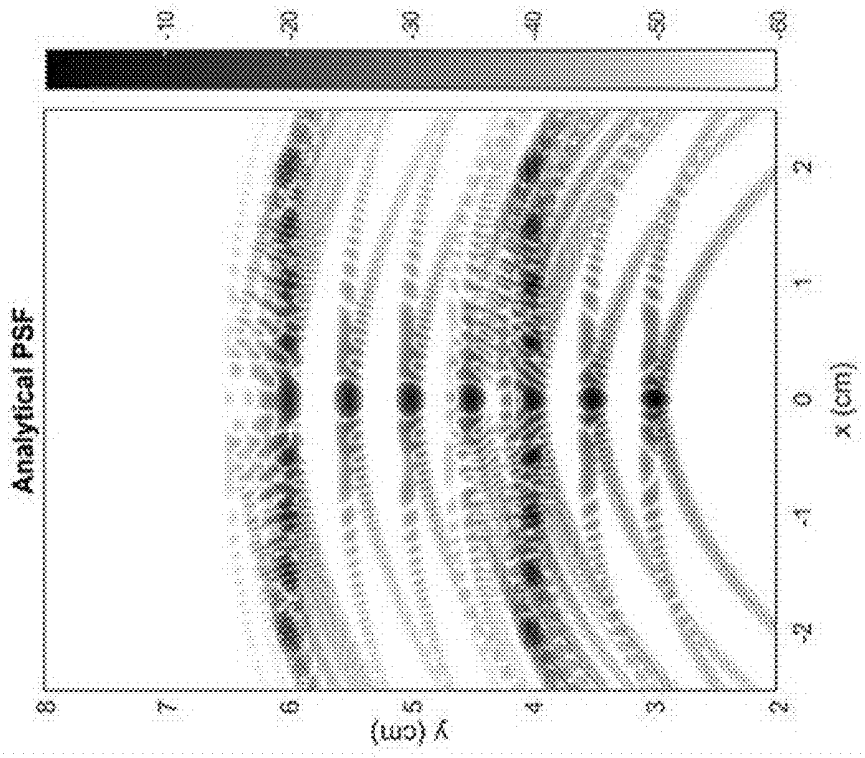

Analytical PSF
y (cm)
x (cm)
-10
-20
-30
-40
-50
-60

FIG. 6B

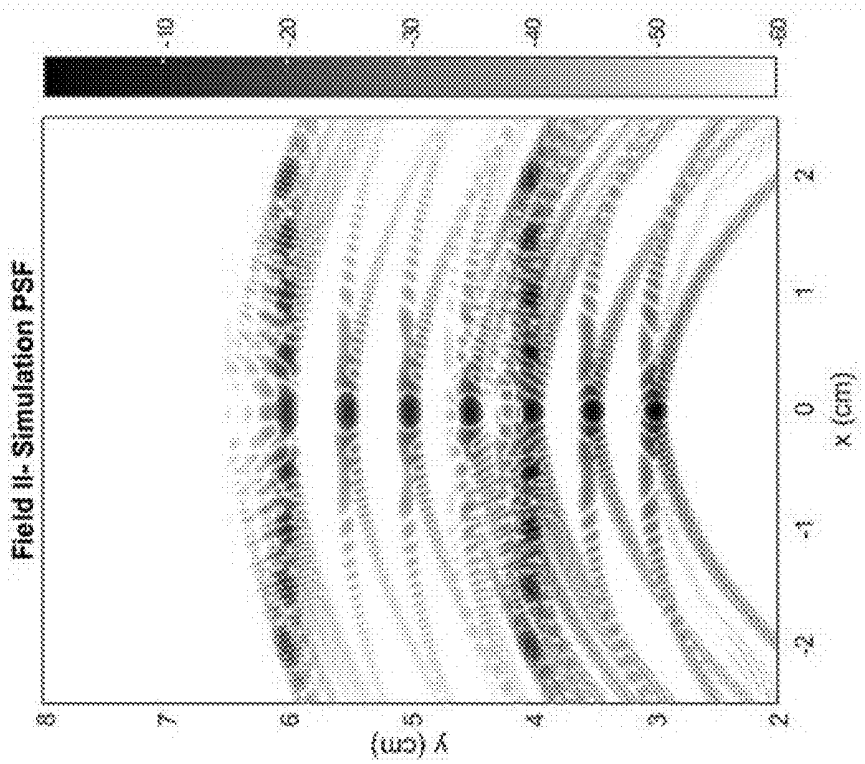

Field II- Simulation PSF
y (cm)
x (cm)
-10
-20
-30
-40
-50
-60

FIG. 6A

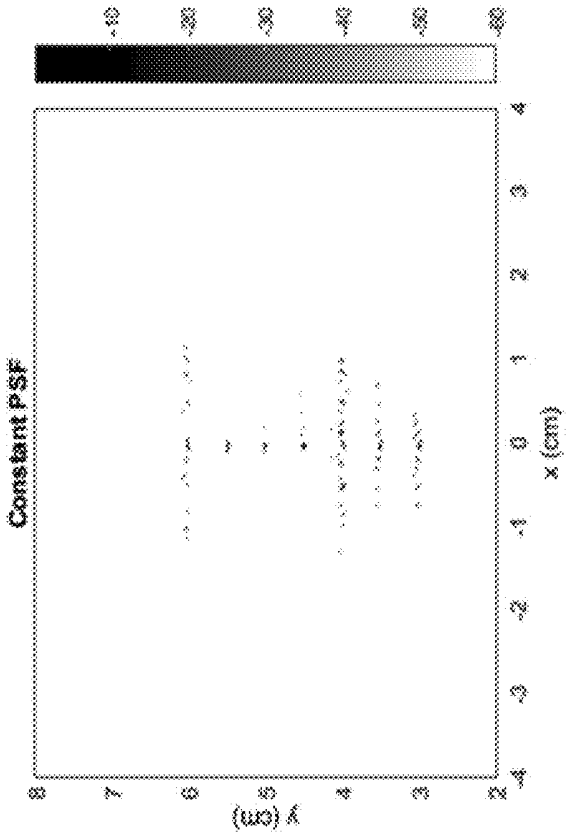


FIG. 7B

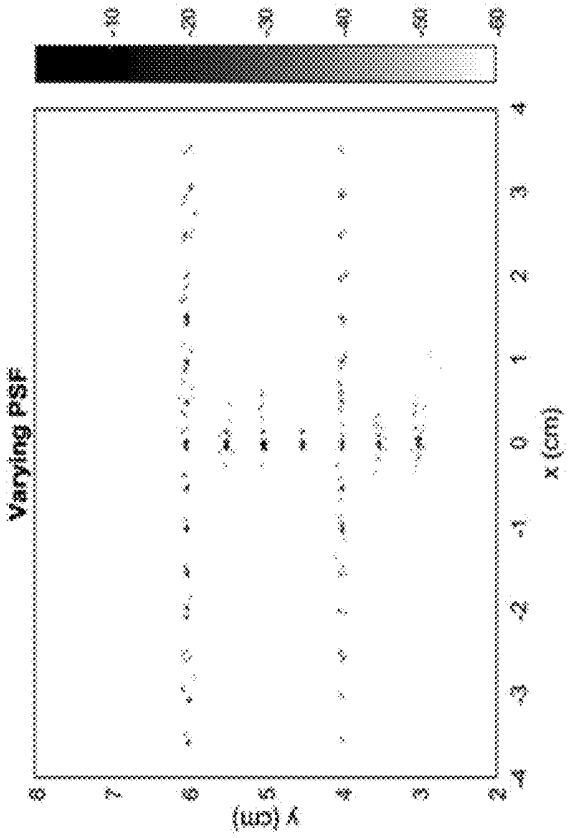


FIG. 7A

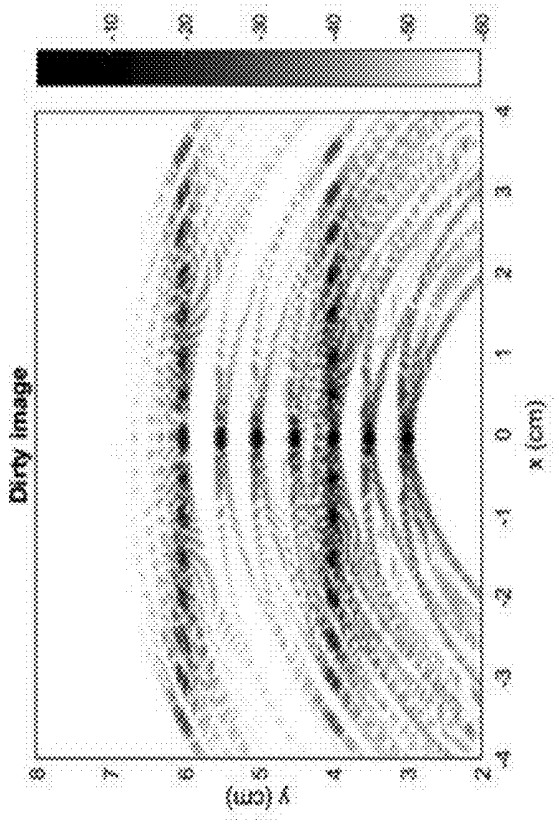


FIG. 7D

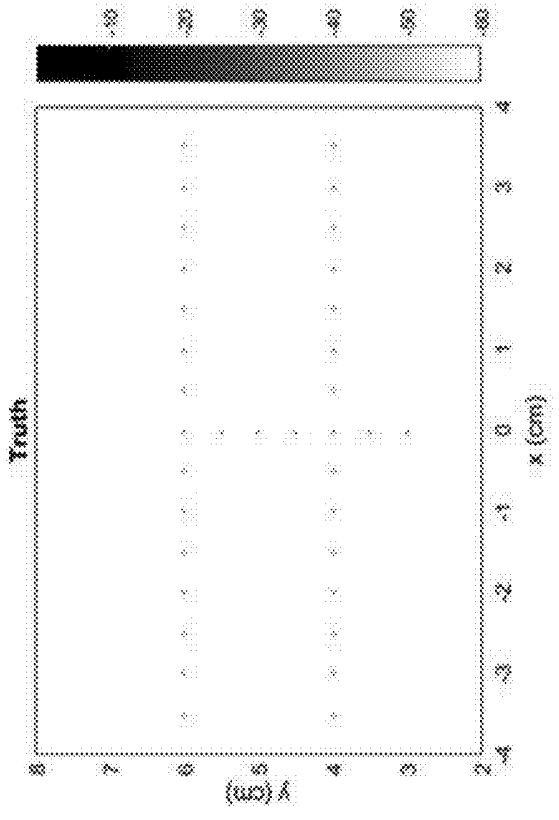


FIG. 7C

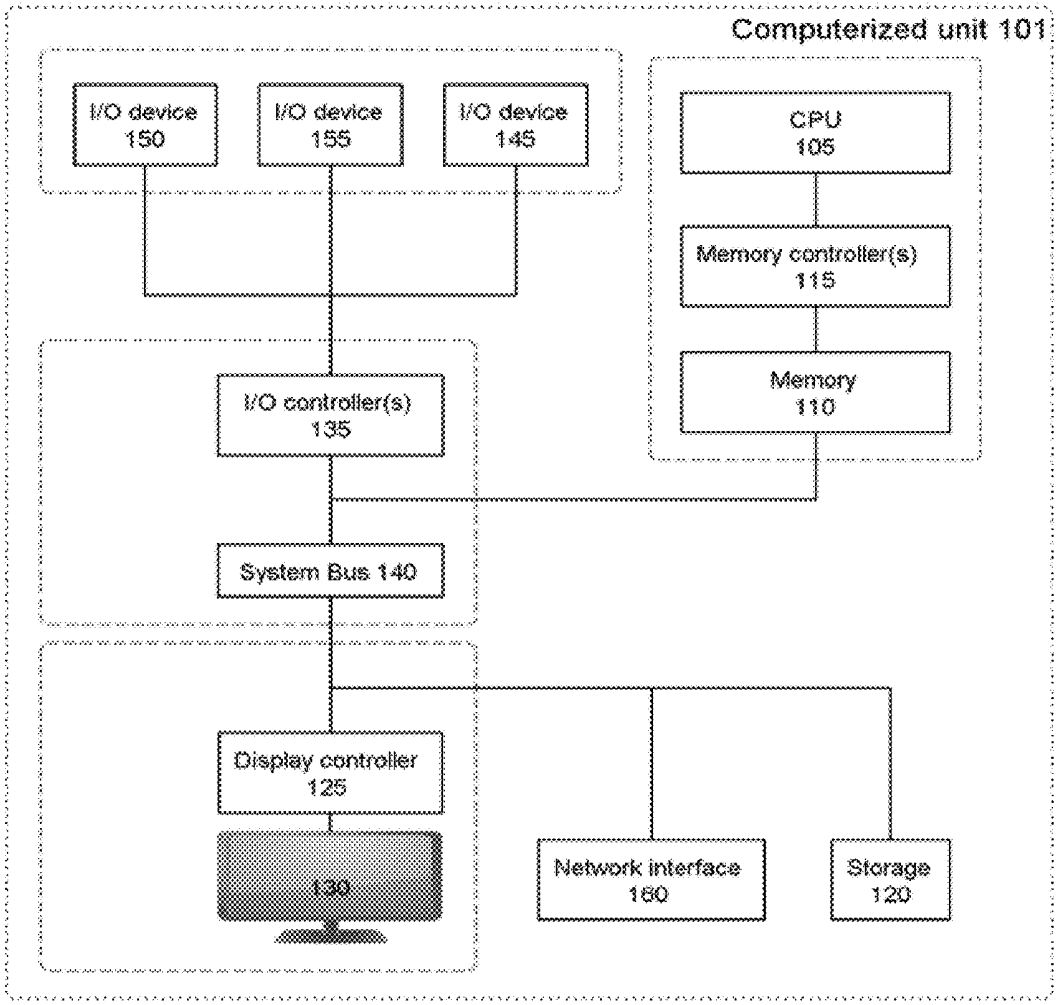

Computerized unit 101
I/O device 150
I/O device 155
I/O device 145
CPU 105
Memory controller(s) 115
Memory 110
I/O controller(s) 135
System Bus 140
Display controller 125
130
Network interface 160
Storage 120

FIG. 8

EFFICIENT COMPUTATION OF SPATIALLY VARYING ULTRASOUND ANALYTICAL POINT SPREAD FUNCTIONS

STATEMENT REGARDING PRIOR DISCLOSURES BY THE INVENTOR OR A JOINT INVENTOR

[0001] Aspects of the present invention have been disclosed by the inventors in the paper "On an Analytical, Spatially-Varying, Point-Spread-Function," published in the Proceedings of the 2017 IEEE International Ultrasonics Symposium (IUS), made available to the public on Sep. 6-9, 2017. The following disclosure is submitted under 35 U.S.C. § 102(b)(1)(A).

BACKGROUND

[0002] The invention relates in general to the field of computer-implemented methods for computing a spatially varying point spread function of an ultrasound apparatus from time signals obtained from transducers thereof, e.g., in order to subsequently compute tissue reflectivity functions, as well as to related ultrasound apparatuses.

[0003] Medical imaging is still a fast-developing research area, which is known to bring additional insights into diagnosis assistance. For instance, computed tomography methods exploiting X-ray and magnetic resonance imaging are known to provide high quality images of the body structure. However, such methods suffer from drawbacks, which notably include the cost of the acquisition system and a lack of portability. All the more, injection of active molecules in patient's body is required. Medical ultrasound may be regarded as a complementary imaging method, which is cheap, non-invasive, fast, and portable (to some extent). This makes ultrasound imaging an active research topic; efforts have been invested to overcome the main disadvantage of this technology, i.e., the low-contrasts obtained between the scanned body regions.

[0004] A usual medical ultrasound acquisition system comprises a probe, i.e., a linear-array of transducers, wired to a processing unit that computes and displays the scanned region. A transducer as used in such devices is typically a piezoelectric element converting electrical signals into a sound wave, and conversely, a sound wave into electrical signals. In medical applications, the probe usually generates waves within a frequency range of 1 to 20 MHz. The human body reflects such waves with an intensity that depends on the medium's reflectivity. The processing unit is configured to reconstruct intensity levels of the body's reflectivity based on time signals recorded at each transducer. High reflections usually arise when the waves pass through a density discontinuity of the internal body's surface. Now, the fact that the density structure lacks of regularity typically leads to loosely defined boundaries on the displayed image. Thus, post-processing methods are needed, to attempt to obtain sharper surface boundaries, e.g., in order to enable improved detection of tissue abnormalities such as tumors.

[0005] Some of the known methods to compute the tissue reflectivity function require an estimation of the so-called point spread function, or PSF, which function describes the response of the imaging system to a point source. In general, the estimation of the ultrasound PSF either assumes that the function is spatially invariant (i.e., it can be described by a spatially-invariant filter) or resorts to involved simulations, in order to calculate this function at various fixed points.

[0006] In more detail, the most common method for estimating the tissue reflectivity function (hereafter TRF) is the so-called Delay-And-Sum (DAS) method. This reconstruction technique can be regarded as a beamforming technique, whereby suitably delaying and summing the transducers signals allows to focus a signal coming from a particular point in space. Yet, in ultrasound imaging, the beamforming technique does actually not provide an estimate of the TRF. Rather, it leads to the so-called radio-frequency (RF) image, which can be thought of as a "blurred" version of the TRF image. RF images do not account for the device's physical limitation, which is instead characterized by the PSF of the device. The RF image can be conceptualized as a convolution between the PSF and the unknown TRF.

[0007] Post-processing techniques for image enhancement tackle the deconvolution problem, i.e., they attempt to reduce the effect of limited devices capabilities. The deconvolution problem can be mathematically expressed as the minimization of an objective function, whereby the distance between an estimated RF image and the PSF convolved with the unknown TRF need be minimized. This optimization problem is commonly subject to regularization. This brings prior information on the TRF structure, improving the ill-posedness or conditioning of the deconvolution problem. For instance, one may impose a penalization in the l_p-norm on the TRF ensuring inversion stability. This procedure is equivalent to inject prior knowledge on the TRF structure. For example, the l_1 norm can be used to promote sparsity.

[0008] There are essentially two main active research directions in the field of deconvolution for ultrasound. The first axis focuses on the choice of the prior information to use with respect to tissue characterization. The second axis is concerned with the computation of the system's PSF, for which no closed-form formula exist. Thus, the PSF need, in general, be crudely approximated. Prior methods to obtain the PSF may be summarized as follows:

[0009] Simulation methods: the software "Field II" generates simulated ultrasound data. It is widely used and accepted in the community. For every fixed point in an empty medium and a particular probe/acquisition system, a new simulation must be run to obtain the PSF associated with this point, which is computationally intractable in practice. To circumvent this problem, it is normally assumed that the PSF is spatially invariant. However, such an approximation is particularly crude and limits the achievable quality enhancement. A similar approach can be conducted with a real acquisition system. However, it suffers from the same drawbacks.

[0010] Estimation methods: The PSF may be estimated from the data along with the deconvolution, which method is commonly referred to as blind deconvolution. Several methods exist, which allow this to be achieved, but they are rather computationally intensive. Machine learning approaches have further been developed to learn the PSF from experimental images. However, such methods involve complex optimization problems. Basically, a spatially invariant PSF must be assumed.

[0011] PSF computation methods: analytical and numerical approximations to the PSF have been explored. Yet, only the numerical approximations to the PSF account for its

spatially varying behavior in the near-field. Besides, such numerical approximations have not been extended to linear arrays of transducers.

SUMMARY

[0012] According to a first aspect, the present invention is embodied as a computer-implemented method for computing a tissue reflectivity function, or TRF. This method basically comprises accessing radio-frequency data, or RF data, and computing a point spread function, or PSF, to obtain the TRF. The RF data accessed are data obtained by beamforming time signals R_i from an array of transducers of an ultrasound device. The RF data are assumed to correspond to outputs of a radio-frequency function, or RF function, as evaluated at given points r of an imaging plane. The RF function is assumed to involve a convolution of the PSF with the TRF to be computed, where the PSF is here assumed to be defined at pairs of points of the imaging plane, so as to account for a spatial variance thereof.

[0013] Next, for each pair (r, s) of given pairs of points in the imaging plane, the PSF is computed as a sum of contributions from at least some of the transducers, to which respective time-of-flight functions can be associated. Each of said contributions is computed by evaluating a transducer's transfer function h, based on two outputs of the respective time-of-flight function τ. Such outputs are obtained by evaluating the time-of-flight function at a first point r and at a second point s of said each pair, respectively. Finally, the RF function can be deconvoluted, based on the computed PSF, so as to obtain the TRF.

[0014] The above method allows the PSF of an ultrasound apparatus to be efficiently computed, even though the PSF is defined so as to account for a spatial variance thereof. The underlying scheme relies on an analytical approximation to the PSF, which requires no simulation, such that a spatially varying PSF can easily be computed.

[0015] This, in turn, allow more efficient post-processing techniques, leading to sharper images with higher resolution and contrasts. In that respect, the present methods shall, preferably, further comprise displaying an image based on the computed TRF. In general, the present approach can be applied to ultrasound imaging techniques and related deconvolution methods. It can further be applied for probe setup purposes.

[0016] In embodiments, when computing the PSF, each of said contributions is computed by evaluating the transducer's transfer function h as a function of a difference between the two outputs of the time-of-flight function τ. The PSF may for instance be computed as a sum that can be written as $\Sigma_i h(\tau(r, p_i)-\tau(s, p_i))\times b_i$, where p_i denotes a position in space of an i^{th} transducer of the array, i=1, . . . N, and b, is a correction factor, which may possibly be assumed to be equal to 1. Introducing such a correction factor allows additional effects to be taken into account.

[0017] Preferably, the method further comprises accessing an explicit representation of the RF function that is constructed based on time signals R_i obtained from the transducers of said array. The TRF is subsequently obtained by deconvoluting the constructed RF function, based on the accessed representation of the RF function. This explicit representation of the RF function may for instance be obtained by interpolating the time signals R_i from the transducers.

[0018] The computation of the PSF may advantageously involve an interpolation of the transfer function h, which is based on a same interpolation scheme as used to interpolate the time signals R_i to construct the RF function. This way, the PSF is evaluated consistently with the RF function, such that no additional bias is introduced in the computation of the PSF.

[0019] To that aim, a representation of the transducer's transfer function h as an analytical function may need be accessed. More generally though, embodiments of the present methods may rely on an analytical representation of h, for its evaluation, without necessarily involving an interpolation thereof. The analytical function accessed can typically be written as a decaying function times an oscillating function. For example, it may be written as $h(t)=\beta e^{-\alpha t^2}\cos(2\pi f_0 t)$, where β is a constant.

[0020] Preferably, the array of transducers is configured to cause, in emission, a plane wave corresponding to a coherent summation of circular waves emitted by each of the transducers. In that case, the time-of-flight function rassociated with an i^{th} transducer of the array can be computed, for a given point r, as $\tau(r, p_i)=(r, e_y)/c+\|r-p_i\|/c$, where c is the speed of sound in the target medium, whose TRF is to be computed, and p_i corresponds to a position of the i^{th} transducer. The plane wave is assumed to be directed in the direction of the unit vector e_y.

[0021] In other cases, the array of transducers may be configured to cause a coherent divergent wave in emission. Assuming this wave has a virtual point source $r_n=(x_n, y_n)$, the time-of-flight function τ associated with the i^{th} transducer of the array can now be computed, for a given point r, based on the relation $\tau(r, p_i)=(\|r-r_n\|-(r_n, r)/c+\|r-p_i\|/c$, where c is the speed of sound in the target medium and pi corresponds to the position of the i^{th} transducer.

[0022] According to another aspect, the invention is embodied as an ultrasound apparatus. Basically, this apparatus comprises an array of transducers and a processing module.

[0023] The transducers are, each, configured to convert an electrical signal into a sound wave, in order to emit such a sound wave and, conversely, to convert a sound wave it receives into an electrical signal. Time signals can be obtained from the array of transducers, in operation, based on which the RF image can be computed in practice.

[0024] The processing module comprises: a beamforming module; a PSF module; and a deconvolution module. The beamforming module is configured to beamform time signals obtained from the array of transducers, so as to obtain RF data. Again, the RF data are assumed to correspond to outputs of a RF function, which involves a convolution of the PSF with the TRF, and the PSF is assumed to be defined at pairs of points in the imaging plane, so as to account for a spatial variance thereof.

[0025] The PSF module is configured to access RF data as obtained via the beamforming module. Consistently with the present methods, this module is further configured to compute the PSF for each pair (r, s) of points of interest, as a sum of contributions from at least some of the transducers, to which time-of-flight functions can respectively be associated. In operation, the PSF module computes each of said contributions by evaluating a transducer's transfer function h, based on outputs of the respective time-of-flight function τ, evaluated in r and s.

[0026] Finally, the deconvolution module is configured to deconvolve the RF function associated to RF data as accessed by the PSF module, to obtain the TRF, based on a PSF as computed by the PSF module, in operation.

[0027] Preferably, the processing module further comprises an interpolation module, which is configured in the processing module so as to be invoked by the beamforming module. The interpolation module is otherwise configured to interpolate time signals R_i obtained from the array of transducers, so as to provide interpolated time signals to the beamforming module, for the latter to construct the RF function, in operation.

[0028] In preferred embodiments, the interpolation module is further configured so as to be further invoked by the PSF module. This way, the interpolation module may interpolate the transfer function h, so as to provide to the PSF module a transfer function h interpolated based on a same interpolation scheme as used to interpolate the time signals to obtain the RF function, in operation.

[0029] According to another aspect, the invention is embodied as a computer program product for computing a tissue reflectivity function (TRF). The computer program product comprises a computer readable storage medium having program instructions embodied therewith, where the program instructions are executable by a processing unit to cause the latter to take steps according to embodiments of the present methods, i.e., to access RF data, compute the PSF, and deconvolve the RF function to obtain the TRF.

[0030] Devices, methods and computer program products embodying the present invention will now be described, by way of non-limiting examples, and in reference to the accompanying drawings.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0031] These and other objects, features and advantages of the present invention will become apparent from the following detailed description of illustrative embodiments thereof, which is to be read in connection with the accompanying drawings. The various features of the drawings are not to scale as the illustrations are for clarity in facilitating one skilled in the art in understanding the invention in conjunction with the detailed description.

[0032] FIG. **1** schematically illustrates the operation of an ultrasound device, according to embodiments.

[0033] FIG. **2** is a block diagram that schematically depicts selected components of a processing module of an ultrasound device and how such components interact to compute a point spread function and a tissue reflectivity function, as involved in embodiments.

[0034] FIG. **3** is a flowchart illustrating high-level steps of a method for computing such a tissue reflectivity function, according to embodiments.

[0035] FIGS. **4**A and **4**B are plots representing a transfer function h as typically involved in embodiments. FIG. **4**A depicts a time domain representation of h(t), whereas FIG. **4**B shows a corresponding frequency domain representation.

[0036] FIGS. **5**A and **5**B are graphs representing point spread functions pertaining to a linear array of 128 transducers configured to generate a plane wave, as respectively obtained according to: (i) known simulation methods (not according to this invention, FIG. **5**A); and (ii) embodiments of this invention (FIG. **5**B).

[0037] FIGS. **6**A and **6**B are graphs representing point spread functions corresponding to a linear array of 64 transducers, configured to generate a divergent wave. FIG. **6**A is obtained using known simulation methods, whereas FIG. **6**B is obtained thanks to embodiments of this invention.

[0038] FIGS. **7**A and **7**B depict deconvolution results as respectively obtained with: (i) a spatially varying point spread function computed according to an embodiment (FIG. **7**A); and (ii) a spatially invariant point spread function (FIG. **7**B, not according to the invention). FIG. **7**C is an image of a test medium, consisting of point reflectors only and FIG. **7**D shows a corresponding radio frequency (RF) image as obtained by a mere delay-and-sum method. The graphs of FIGS. **7**A-**7**D otherwise assume a same setup as in FIGS. **6**A and **6**B.

[0039] FIG. **8** schematically represents a general purpose computerized system, suited for implementing one or more method steps as involved in embodiments of the invention.

[0040] The accompanying drawings show simplified representations of devices or parts thereof, as involved in embodiments. Similar or functionally similar elements in the figures have been allocated the same numeral references, unless otherwise indicated.

DETAILED DESCRIPTION

[0041] Detailed embodiments of the claimed structures and methods are disclosed herein; however, it can be understood that the disclosed embodiments are merely illustrative of the claimed structures and methods that may be embodied in various forms. This invention may, however, be embodied in many different forms and should not be construed as limited to the exemplary embodiments set forth herein. Rather, these exemplary embodiments are provided so that this disclosure will be thorough and complete and will fully convey the scope of this invention to those skilled in the art. In the description, details of well-known features and techniques may be omitted to avoid unnecessarily obscuring the presented embodiments.

[0042] The following description is structured as follows. First, general embodiments and high-level variants are described (sect. **1**). The next section addresses more specific embodiments and technical implementation details (sect. **2** and **3**).

1. General Embodiments and High-Level Variants

[0043] In reference to FIGS. **1**-**3**, an aspect of the invention is first described, which concerns computer-implemented methods for computing a tissue reflectivity function, or TRF. As reflected in FIGS. **2** and **3**, such methods involves three stages, where: (i) radio-frequency data are obtained; (ii) the point spread function (PSF) is computed; and (iii) the TRF is obtained based on the PSF.

[0044] First, such methods rely on radio-frequency data, or RF data, accessed at step **S14** (see the flowchart of FIG. **3**). The accessed RF data are assumed to have been obtained (step **S13**) by beamforming time signals R_i (i.e., time-series) collected **S12** by an array **20** of transducers **21**-**28** of an ultrasound device **1** (see FIG. **1**).

[0045] Beamforming, in this context, amount to delay and sum the transducers signals, which in turn makes it possible to focus on a particular point in space. In the context of ultrasound techniques, beamforming and delay-and-sum

(DAS) techniques are synonymous. The aim of the DAS process is to be able to evaluate the RF function from the time signals $R_i(t_1, t_2, \ldots)$, i.e., the signals recorded by the i^{th} transducer.

[0046] For the purpose of implementing the present methods, the RF data are assumed to correspond to outputs of a radio-frequency function (hereafter RF function), as evaluated at given points r of the imaging plane, i.e., the plane to which the RF data pertain and in which the TRF function may eventually be displayed. For reasons evoked earlier, this RF function can be devised as a convolution of the point spread function (PSF) with the TRF, i.e., the unknown function to be retrieved. Importantly, the PSF is here assumed to be defined at pairs of points of the imaging plane, so as to account for its spatial variance.

[0047] The PSF is estimated as follows. For each pair (r, s) of given pairs of points in the imaging plane, the PSF is computed S**18**-S**22** as a sum of contributions from at least some of the transducers **21**-**28**. Time-of-flight functions can be respectively associated to the transducers, as explained later in detail. Each of the contributions to the PSF is computed by evaluating S**20** the transducer's transfer function h (also called pulse function), where the latter takes as argument two outputs of the time-of-flight function τ associated to each contribution (i.e., respectively associated to each transducer considered for the computation of the PSF), where the function tis evaluated at each of the points of each pair (r, s) considered.

[0048] In other words, the outputs of the time-of-flight function rare obtained S**19** by evaluating the relevant time-of-flight function twice, a first time at point r and a second time at point s of the pair (r, s) and, this, for each of the contributions to be computed. I.e., each of said contributions involves two outputs of a respective time-of-flight function τ.

[0049] To fix ideas, the PSF may for instance be evaluated based on the equation:

$$PSF(r, s)=\Sigma_i h[\tau(r, p_i); \tau(s, p_i)], \quad (1)$$

where pi denotes a position in space of the i^{th} transducer, i=1, . . . N, and the sum is performed over each of the transducers taken into account. This amounts to sum outputs of the function h, which is a function of $\tau(r, p_i)$ and $\tau(s, p_i)$, i.e., the time-of-flight function associated to the i^{th} transducer by way of its dependence on p_i, and respectively evaluated in r and s.

[0050] Note that the italic notation "PSF" is used to denote a (specific) mathematical object, as in Eq. 1 above, contrary to the non-italic notation "PSF", which is a short notation for a (general) point spread function. The same distinction is later made between "RF function" and "RF".

[0051] In the present approach, contributions from some or all of the transducers **21**-**28** may be involved and, this, for each pair (r, s) of points considered in the imaging plane. All pairs of points (e.g., as defined on a grid, for a given resolution) are normally considered. Yet, some particular points (or pairs of points) might be skipped, should some approximation or simplification (e.g., symmetry) assumption be available. Also, instead of considering pairs of points, the PSF may for instance equivalently be computed based on intracular and extracular space coordinates R and σ, where R=r+s/2 and σ=r−s. More generally, any rotation of the coordinates (r, s) may be contemplated, e.g., r, r+s, etc. In addition, other coordinate systems might be considered. Yet, in all cases, the PSF as considered herein fundamentally remains a two-point function, which makes it possible to capture the spatial variability of the PSF.

[0052] That the PSF is spatially varying means that PSF $(r_1, r2)\gamma PSF(r_1-(r_2-r_3), r_3)$, whereas a spatially invariant PSF fulfils the condition $PSF_1(r_1, r_2)=PSF_I(r_1-(r_2-r_3), r_3)$, where r_1, r_2 and r_3 are 2D vectors pointing at points in the 2D imaging plane. The subscript I is used in the latter to distinguish the spatially invariant function PSF_I from a spatially varying function PSF(.,.) as computed herein. This is discussed later in detail.

[0053] Normally, all contributions from each transducer will be taken into account. However, the PSF may possibly be estimated based on contributions from a subset of the transducers **21**-**28** only, if necessary. For example, some of the transducers may be discarded, on purpose, e.g., because their locations is expected to introduce a bias or some of the transducers are not fully functional, etc.

[0054] Finally, the RF function can be deconvoluted S**24** based on the computed PSF, step S**21**, to obtain the TRF. Any suitable deconvolution scheme can be contemplated at this step. Examples are mentioned in sect. **2**.

[0055] If all pairs were not processed at step S**22**, then, at step S**23** the pair (r, s) may be incremented before returning to S**18**.

[0056] The present approach makes it possible to efficiently compute the PSF of the ultrasound device, even though the PSF is defined so as to account for a spatial variance thereof. Yet, and as present Inventors have realized, the PSF can be computed as a sum of contributions, each involving the transducer's transfer function h, suitably delayed thanks to outputs of the time-of-flight function τ. Exploiting this possibility, the present approach leverages an analytical approximation to the spatially varying PSF, such that the PSF can, eventually, easily be computed, without resorting to involved simulations or numerical approximations.

[0057] This, in turn, allow more efficient post-processing techniques, leading to sharper images with higher resolution and contrasts. I.e., the present methods are typically used to display S**25** an image of the target medium **30** (FIG. **1**) or internal surfaces thereof, based on the computed TRF, as they are particularly suited for real-time processing. In general, the present approach can be applied to ultrasound imaging techniques and related deconvolution methods. It may further be applied for probe setup purposes.

[0058] Preferred embodiments are now described. To start with, when computing the spatially varying PSF, each contribution from each transducer is preferably computed by evaluating S**20** the transducer's transfer function h as a function of a difference between said two outputs. I.e., the PSF may for example be evaluated as:

$$PSF(r, s)=\Sigma_i h[\xi(r, p_i)-\tau(s, p_i)]. \quad (2)$$

[0059] However, in variants, outputs from the time-of-flight functions may be provided in the form of ratios $\gamma(r, s, p_i)=\tau(r, p_i)/\tau(s, p_i)$ to the PSF computation algorithm, as per a design choice in the algorithm. In such cases, the transducer's transfer function may subsequently be evaluated as $h[\tau(s, p_i)\times(\gamma(r, s, p_i)-1)]$. Other variants may still lead to distinct implementations of the computation of h, such that, more generally, the PSF is said to be computed based on contributions involving, each, the transfer function h, which is evaluated based on distinct outputs $\tau(r, p_i)$ and $\tau(s, p_i)$ of

the time-of-flight function. Still, the PSF may equivalently be computed in the Fourier space, making use of the convolution theorem.

[0060] In more sophisticated embodiments, the PSF may be computed S**21** as a sum that can be written as $\Sigma_i h[\tau(r, p_i); \tau(s, p_i)]\times b_i$, where b_i is a correction factor. Again, p_i denotes the position in space of the i^{th} transducer of the array **20**, i=1, . . . N. The correction factor b_i may, in general, vary from one transducer to the other. It may further be non-constant, i.e., spatially varying. In the simplest cases, this correction factor is assumed to be equal to 1, as noted earlier. E.g.,

$$PSF(r, s)=\Sigma_i h[\tau(r, p_i); \tau(s, p_i)].$$

[0061] However, this factor may also be devised so as to take into account, e.g., an array pattern ($b_i=b(r)\forall_i$), accounting for a spatial selectivity. That is, the correction factor b varies in space but is identical for all transducers in that case. As another example, the correction factor may capture a decay law, to account for attenuation.

[0062] In other variants, an apodization strategy may be contemplated, whereby signals obtained from the transducers may be re-weighted. I.e., a re-weighting method is applied on the transducer channels in that case, in order to compute the RF-image.

[0063] In addition, distinct transducer's transfer functions h_i may be assumed for some of each of the transducers and, thus, for some or each of the contributions $h_i[\tau(r, p_i); \tau(s, p_i)]\times b_i$ to the PSF.

[0064] In preferred embodiments, the present methods rely on an explicit representation of the RF function, for deconvolution purposes. That is, an explicit representation of the RF function is accessed (after step S**15** and before step S**24** in FIG. **3**), which function is constructed, steps S**13**-S**15**, based on time signals R_i as obtained S**12** from the transducers **21**-**28** of the array **20**. Thus, the TRF can subsequently be obtained by deconvoluting S**24** the constructed RF function, based on the accessed representation thereof. To that aim, an interpolation scheme may be used, as discussed below. An explicit expression for the RF function makes it possible to compute the constructed function for all points r of interest in the imaging plane. In variants, other approximation techniques might be involved, e.g., where inferred analytical expressions are fitted onto given datasets. In other variants, numerical methods might be used, without it being necessary to resort to an explicit representation of the RF function.

[0065] Preferably though, the RF function is constructed S**13**-S**15** by interpolating S**15** the time signals R_i obtained S**12** from the transducers **21**-**28**. This way, an explicit representation of the RF function can easily be obtained.

[0066] In detail, the RF function can generally be written as $RF(r)=\Sigma_i R_i[\tau(r, p_i)]$, where $R_i(.)$ is the time-signal recorded by the i^{th} transducer. Now, we note that the RF function cannot be directly computed from the time signals $R_i(t_1, t_2, \ldots)$ as obtained from the transducers since values of R_i are only available for discrete time samples. Thus, an interpolation scheme may advantageously be introduced, in order to be able to more easily evaluate the R_i function, at any desired delay $\tau(r, p_i)$. Yet, in variants, an analytical expression of R_i may be devised and subsequently fitted onto the available datasets. However, an interpolation would likely be more accurate, while computationally not more intensive.

[0067] Interestingly, the computation of the PSF may further comprises interpolating S**17** the transfer function h, based on the same interpolation scheme as used to interpolate S**15** the time signals R_i when constructing the RF function. That is, the computation of the PSF is preferably conducted using the same context as otherwise used to compute the RF function, so that the PSF is evaluated consistently with the evaluation of the RF function. This way, no extra bias is introduced in the deconvolution scheme.

[0068] That a same interpolation scheme be used means that a same interpolation technique is involved, which uses a same or a common strategy. For example, same interpolation time points as used to compute the time signals R_i may be used and the functions h and R_i may be constrained to exactly match such points. In addition, the same type of functions (e.g., polynomials, splines) are preferably considered to interpolate the time signals and the transfer function, and, e.g., a same polynomial order may be used in each case, etc.

[0069] In variant, the transfer function h(t) may be analytically formulated and thus computed for any input values, without any interpolation being needed therefor. However, best is to rely on a same approximation technique for the computation of the functions h and R_i, to avoid or mitigate additional biases. Be it interpolated or not, the transfer function h is preferably provided as an analytical function. I.e., the present methods may access S**16** a representation of the transducer's transfer function h as an analytical function, prior to evaluating it at step S**20**. In variants, numerical approximations to h may be relied on, though such variants are believed to be less stable and computationally more intensive.

[0070] The analytical representation of h, as accessed at step S**16**, may for instance be simply written as a decaying function (e.g., any exponentially decaying function) times an oscillating function (e.g., polynomial or a trigonometric function), which would suffice to describe most cases of interest, as illustrated in sect. **2**. For example, the analytical function h may be written as $h(t)=\beta e^{-\alpha t^2}\cos(2\pi f_0 t)$, where β is a constant, which can typically be set equal to 1.

[0071] Different expression of the function $\tau(r, p_i)$ may be relied on, depending on the context at issue and the corresponding physics. For example, where the array **20** of transducers **21**-**28** is configured to generate a plane wave (in emission S**11**), i.e., a wave corresponding to a coherent summation of circular waves emitted by each of the transducers, then the time-of-flight function may be computed S**19**, for a given point r, as $\tau(r, p_i)=(r, e_y)/c+\|r-p_i\|/c$. Here, the plane wave is assumed to be directed in the direction of the unit vector e_y, c is the speed of sound in the target medium **30** (whose TRF is to be computed), and p_i corresponds to the position of the i^{th} transducer.

[0072] In variants where the transducers **21**-**28** are configured to generate S**11** a coherent divergent wave, the function τ associated with the i^{th} transducer would instead be computed S**19**, for a given point r, as $\tau(r, p_i)=(\|r-r_n\|-(r_n, r)/c+\|r-p_i\|/c$. The point $r_n=(x_n, y_n)$ corresponds to the virtual point source (also called focal point), which is a virtual emission point, i.e., the virtual origin of the diverging wave. This point is typically located behind the array of transducers, i.e., opposite to the medium **30** with respect to the array **20** of transducers. All this is illustrated in sect. **2**.

[0073] Additional insights can be gained by examining the mathematical background for the present approach. Assume that the time-of-flight law $\tau(r, p)$, the transfer function $h(t)$ and the probe geometry $p_1, \ldots, p_N$ are known. As mentioned earlier, the RF image computed by a standard delay-and-sum technique may be expressed (at a continuous level) by:

$$RF(r)=\Sigma_{i=1}^{N} R_i[\tau(r, p_i)], \quad (3)$$

where $R_i(\cdot)$ is the time-signal recorded by the i^{th} transducer, for $t\in[0, T]$. Under the widely accepted linear system approximation, the data-model for the time signal writes as:

$$R_i(t)=\int_\Omega h(t-\tau(s, p_i))\chi(s)ds, \quad (4)$$

where $\chi(\cdot)$ is the unknown TRF. At the continuous limit (assuming infinitely many samples are available), it may be realized that the RF function can be successively expressed as:

$$RF(r) = \sum_{i=1}^{N} R_i[\tau(r, p_i)] \quad (5)$$

$$= \sum_{i=1}^{N} \int_0^T R_i(t)\delta(t - \tau(r, p_i))dt \quad (6)$$

$$= \sum_{i=1}^{N} \int_\Omega \int_0^T h(t - \tau(s, p_i))\delta(t - \tau(r, p_i))dt\chi(s)ds \quad (7)$$

$$= \sum_{i=1}^{N} \int_\Omega \int_0^T h(\tau(r, p_i) - \tau(s, p_i)\chi(s)ds \quad (8)$$

$$= \int_\Omega PSF(r, s)\chi(s)ds, \quad (9)$$

[0074] where use is made of the properties of the Dirac delta function $\delta(\cdot)$ and T is assumed to be large enough to ensure that $\tau(r, p_i)\in[0, T]\forall r\in\Omega/\backslash\forall i\in[1, \ldots, N]$, and where the integration domain Ω corresponds to the 2D imaging plane. The PSF as eventually obtained corresponds to the PSF as defined in Eq. 2.

[0075] Now, it should be reminded that the above formula result from approximations and have limitations. First, the RF image cannot be directly computed as defined in Eq. 5, since only a finite number of time samples are available. Thus, an approximation is needed, as discussed earlier. For example, an interpolation scheme may be introduced to evaluate $R_i(t)$ at the desired delay, i.e., corresponding to an output of the time-of-flight function $\tau(r, p)$, evaluated for $p=p_i$. Yet, any computation of the PSF based on Eq. 1 or 2 may be performed using a same interpolation scheme. That is, a discrete version of the pulse $h(t)$ can be interpolated using that same interpolation scheme, to cope with this practical limitation and avoid introduction of biases. Second, the derivation of Eqs. 4-9 relies on approximations: they are derived at the continuous limit, and under the assumption of the linear system approximation. In addition, the array pattern and attenuation were ignored, though they could easily be inserted, thanks to added correction factors b_i, as noted earlier.

[0076] As a further comment, note that if the function $x(s)$ is substituted with a Dirac delta function in Eq. 9, i.e., $RF(r)=\int_\Omega PSF(r, s)\delta(s-r_0)$ cls, the resulting RF function is equal to $RF(r)=PSF(r, r_0)$. Thus, the PSF function can be regarded as the RF image obtained for a single point reflector located in r_0. On this basis, a bivariate PSF function $PSF(r_1, r_2)$ is often depicted by fixing its second argument (here r_2), by convention. The resulting image can thus be displayed in the plane (x, y) in which ri is varied, as latter discussed in detail in reference to FIGS. **5-7**.

[0077] As noted earlier, a spatially varying PSF is one for which $PSF(r_1, r_2)\gamma PSF(r_1-(r_2-r_3), r_3)$, whereas, for a spatially invariant PSF, the condition $PSF_I(r_1, r_2)=PSF_I(r_1-(r_2-r_3), r_3)$ holds. Thus, saying that a PSF is spatially invariant means that the depiction of $PSF_I(r_1, r_3)$, where r_3 is fixed and r_1 is varied in the plane (x, y), yields a same image as $PSF_I(r_1, r_2)$, except that $PSF_I(r_1, r_3)$ is shifted so as to be centered on r_3 instead of r_2. On the contrary, $PSF(r_1, r_3)$ differs from $PSF(r_1, r_2)$ wherever $r_2\gamma r_3$.

[0078] The present methods may be applied to any ultrasound imaging technique, probe setup, or deconvolution methods. Accounting for the spatially varying behavior of the PSF dramatically impacts the accuracy of the reconstruction of the TRF, as illustrated in the next section. Yet, simple computational schemes are proposed herein, which leverage analytical formulations of the PSF. As a result, the TRF can be efficiently, yet accurately evaluated.

[0079] At present, referring more particularly to FIGS. **1**, **2** and **8**, another aspect of the invention is described, which concerns an ultrasound apparatus **1**. The latter basically comprises an array **20** of transducers **21-28** (see FIG. **1**) and a processing module **107** (see FIG. **2**). The module **107** may be implemented in hardware or in software, the latter run, e.g., at a computerized unit **101** of a computerized device **10** connected to the array **20**, so as to receive data from the transducers, as assumed in FIG. **1**.

[0080] The transducers **21-28** may for instance be piezoelectric elements; they are each configured to convert an electrical signal into a sound wave, in order to emit S**11** such a sound wave and, conversely, to convert a sound wave it receives S**12** into an electrical signal. Thus, time signals can be obtained from the array of transducers, in operation.

[0081] For the sake of description, the processing module **107** can be regarded a set of distinct modules, the latter comprising a beamforming module **1071**, a PSF computation module **1073**, and a deconvolution module **1074**.

[0082] The beamforming module **1071** is generally configured to beamform S**13** time signals obtained S**12** from the array of transducers. This way, RF data can be obtained S**13**, which data are assumed to correspond to outputs of a RF function, just as described earlier in reference to the present methods. That is, the RF function is again assumed to involve a convolution of the PSF function with the TRF and the PSF is assumed to be defined at pairs of points in the imaging plane, so as to account for a spatial variance thereof.

[0083] The PSF module **1073** is configured to compute the PSF, consistently with the methods disclosed herein. I.e., the module **1073** may access RF data as obtained via the beamforming module **1071** and compute S**18**-S**22** the PSF, for each pair (r, s), as a sum of contributions from transducers **21-28**, to which respective time-of-flight functions can be associated. As explained earlier, each contribution is computed by evaluating S**20** the transfer function h, based on distinct outputs of a respective function τ, evaluated at r and s.

[0084] Finally, the deconvolution module **1074** is configured to deconvolve the RF function associated to RF data as accessed by the PSF module **1073**, so as to obtain the TRF and, this, based on a PSF as computed by the PSF module **1073**, in operation.

[0085] Consistently with preferred embodiments of the present methods, the apparatus **1** may further comprise an interpolation module **1072**. The latter shall typically be configured in the processing module **107** so as to be invoked by the beamforming module **1071**. This way, the interpolation module **1072** may, upon request by the module **1071**, interpolate time signals R_i obtained from the transducers, so as to return corresponding interpolants to the beamforming module, for the latter to construct the RF function, in operation.

[0086] Preferably, the interpolation module **1072** is further configured in the processing module **107** so as to be invoked by the PSF module **1073** too. This way, the interpolation module **1072** may, upon request by the module **1073**, interpolate the transfer function h, and return a corresponding interpolant to the PSF module **1073**. More preferably, the transfer function h is interpolated based on a same interpolation scheme as used to interpolate the time signals, in order to obtain the RF function, as described earlier.

[0087] For completeness, and according to a final aspect, the invention can also be embodied as a computer program product for computing a tissue reflectivity function. This program may for instance be run on a computerized unit **101** of a device **10**. This program shall typically implement functions of the module **107** depicted in FIG. **2**. In all cases, the computer program product comprises a computer readable storage medium having program instructions embodied therewith, which program instructions are executable by a processing unit (e.g., such as unit **105** in FIG. **8**), to cause the latter to take steps according to the present methods. Aspects of the present computer programs are discussed in detail in sect. **3.1** and **3.2**.

[0088] The above embodiments have been succinctly described in reference to the accompanying drawings and may accommodate a number of variants. Several combinations of the above features may be contemplated. Examples are given in the next sections.

2. Specific Embodiments and Example of Applications

[0089] The specific embodiments described in this section assume the following inputs:

[0090] A given emitted-wave strategy, i.e., reflected by a time-of-flight law $\tau(r, p)$, which represents a wave's travel time from a position p of a given transducer on the array **20** to a point

[0091] r on the imaging plane and back to p;

[0092] An array geometry expressed as transducer positions $p_1, \ldots, p_N$; and

[0093] A transducer's transfer function h(t), which determines the shape of the wave along the propagation direction.

[0094] An output of the PSF computation module **1073** (see sect. **1**, FIG. **2**) is then, for each pair (r, s) of points considered, an estimate of the PSF, e.g., computed according to Eq. 2. One assumes that Eq. 10 holds at the continuous limit (i.e., considering infinitely many time samples).

[0095] Any deconvolution method (e.g., formulated on a grid over the spatial domain Ω) may be contemplated for the computation of the PSF according to Eq. 2.

[0096] The following assumes a linear array of transducers, arranged along the x-direction, located at y=0. The transfer function h is further assumed to follow a Gaussian pulse model, i.e.,

$$h(t)=e^{\alpha t^2}\cos(2\pi f_0 t),$$

where α is a function increasing with the transducer bandwidth (BW), and f_0 denotes a central operating frequency of this transducer, see FIGS. **4**A and **4**B. The graphs depicted in FIGS. **4**A and **4**B assume a frequency f_0=10 MHz and a bandwidth BW=0.8f_0. The resulting transfer function is depicted in the time domain in FIG. **4**A and in the frequency domain in FIG. **4**B.

2.1 Plane Wave Configuration

[0097] For emission, assuming that electrical excitation signals are simultaneous created across the array **20**, a plane wave results by coherent summation of circular waves emitted by each transducer. The planar wave front may be scattered back to the array with a circular wave, when encountering a particular point, interface, inhomogeneity, etc., of the target medium **30**. Assuming the plane wave is directed in the y-direction, the time-of-flight is then given by:

$$\tau(r, p_i)=(r, e_y)/c+\|r-p_i\|/c,$$

where c the speed of sound in the target medium **30**.

[0098] Contrary to the naíve depiction of FIG. **1**, a typical transducer array may involve numerous transducers, e.g., 64 or 128 transducers, as assumed in this section. For instance, FIG. **5**B depicts an "analytical" PSF as computed according to Eq. 2, for a plane wave and assuming a linear array of 128 transducers, with f_0=5 Mhz and BW=0.4 f_0.

[0099] Note that, as per the convention evoked in sect. **1**, each of these PSFs is displayed by fixing its second argument r_2 and varying its first argument ri in the plane (x, y). Now, what is actually displayed in FIGS. **5** and **6** is a sum of PSFs, as obtained for a collection of M fixed points, the sum being performed over each of these fixed points. That is, the function depicted, call it $\Sigma(r_1)$, is defined by: $\Sigma(r_1)=\Sigma_{k=1}^{M}\mathrm{PSF}(r_1, r_k)$. In FIGS. **5**A and **5**B, the points r_k are uniformly distributed along the axis y (for x=0) and each contribution to $\Sigma(r_1)$ gives rise to a respective pattern formed by a dark spot, surrounded by a pattern of lighter spots. Comparing FIGS. **5**A and **5**B, we observe a great similarity between the present PSF and the PSF as simulated with the software Field II. In particular, the present approach captures well the spatially varying nature of the PSF implied by the delay law and probe geometry.

2.2 Divergent Wave

[0100] It is now assumed that electrical excitation signals are delayed in order to form a coherent divergent wave, having a virtual point source $r_n=(x_n, y_n)$. The diverging front wave is scattered back with circular waves when encountering, e.g., inhomogeneities in the medium, whereby the time-of-flight is now given by $\tau(r, p_i)=(\|r-r_n\|-(r_n, r)/c+\|r-p_i/c$.

[0101] FIG. **6**B depicts the PSF as computed according to Eq. 2, for a divergent wave, and assuming a linear array of 64 transducers, with f_0=2.5 Mhz and BW=0.4 f_0. Again, what is actually displayed in FIGS. **6**A and **6**B is a sum of PSFs obtained for a collection of fixed points. However, this time, the points r_k are uniformly distributed on a grid, which is identical to that depicted in FIG. **7**C. The obtained patterns are, accordingly, somewhat more involved. In particular, the PSFs now strongly vary over the imaging plane and, in particular, exhibit a rotated pattern far from the center. Yet,

the PSF as computed according to embodiments (FIG. **6**B) compares again favorably with that of FIG. **6**A, simulated with Field II.

2.3 Impact on Sparse Deconvolution

[0102] As seen in FIGS. **6**A, **6**B, a spatially invariant approximation of the PSF may be markedly insufficient in some cases and may thus have severe consequences on the subsequent deconvolution. The present subsection illustrates the weakness of such an approximation, when using an l_1 deconvolution algorithm.

[0103] Deconvolution results are shown in FIGS. **7**A, **7**B, which both depict TRFs as estimated by deconvoluting a RF function (FIG. **7**D), which was obtained from the test medium of FIG. **7**C (i.e., consisting of point reflectors only), using a mere DAS technique. Data were generated using Field II, assuming a divergent wave on the same setup as in FIGS. **6**A, **6**B. FIG. **7**A show deconvolution results, using a spatially varying PSF, computed according to embodiments (and based on Eq. 2), whereas FIG. **7**B was obtained using a spatially invariant PSF. In both cases, an l_1 promoting regularization was relied on.

[0104] As seen in FIGS. **7**A-**7**D, a deconvolution that assumes a spatially invariant PSF allows an acceptable recovery of the point scatters only near the center, where the approximation remains acceptable. However further apart from point (0, 5) cm, a reasonable recovery is only possible when the spatial variation of the PSF is taken into account.

3. Technical Implementation Details

3.1 Computerized Systems and Devices

[0105] Computerized systems and devices can be suitably designed for implementing embodiments of the present invention as described herein. In that respect, it can be appreciated that the methods described herein are largely non-interactive and automated. In exemplary embodiments, the methods described herein can be implemented either in an interactive, partly-interactive or non-interactive system. The methods described herein can be implemented in software, hardware, or a combination thereof. In exemplary embodiments, the methods described herein are implemented in software, as an executable program, the latter executed by suitable digital processing devices. More generally, embodiments of the present invention can be implemented wherein general-purpose digital computers, such as personal computers, workstations, etc., are used.

[0106] For instance, the system depicted in FIG. **8** schematically represents a computerized unit **101**, e.g., a general- or specific-purpose computer, which may be used in place or as part of the computerized device **10** of FIG. **1**. As such, the unit **101** may interact with the array **20** of transducers **21-28**, e.g., via suitable converters and I/O units **145-155**.

[0107] In exemplary embodiments, in terms of hardware architecture, as shown in FIG. **8**, the unit **101** includes a processor **105**, and a memory **110** coupled to a memory controller **115**. One or more input and/or output (I/O) devices **145**, **150**, **155** (or peripherals) are communicatively coupled via a local input/output controller **135**. The input/output controller **135** can be coupled to or include one or more buses and a system bus **140**, as known in the art. The input/output controller **135** may have additional elements, which are omitted for simplicity, such as controllers, buffers (caches), drivers, repeaters, and receivers, to enable communications. Further, the local interface may include address, control, and/or data connections to enable appropriate communications among the aforementioned components.

[0108] The processor **105** is a hardware device for executing software, particularly that stored in memory **110**. The processor **105** can be any custom made or commercially available processor, a central processing unit (CPU), an auxiliary processor among several processors associated with the computer **101**, a semiconductor based microprocessor (in the form of a microchip or chip set), or generally any device for executing software instructions.

[0109] The memory **110** can include any one or combination of volatile memory elements (e.g., random access memory) and nonvolatile memory elements. Moreover, the memory **110** may incorporate electronic, magnetic, optical, and/or other types of storage media. Note that the memory **110** can have a distributed architecture, where various components are situated remote from one another, but can be accessed by the processor **105**.

[0110] The software in memory **110** may include one or more separate programs, each of which comprises an ordered listing of executable instructions for implementing logical functions. In the example of FIG. **8**, the software in the memory **110** includes methods described herein in accordance with exemplary embodiments and, in particular, a suitable operating system (OS) **111**. The OS **111** essentially controls the execution of other computer programs and provides scheduling, input-output control, file and data management, memory management, and communication control and related services.

[0111] The methods described herein may be in the form of a source program, executable program (object code), script, or any other entity comprising a set of instructions to be performed. When in a source program form, then the program needs to be translated via a compiler, assembler, interpreter, or the like, as known per se, which may or may not be included within the memory **110**, so as to operate properly in connection with the OS **111**. Furthermore, the methods can be written as an object oriented programming language, which has classes of data and methods, or a procedure programming language, which has routines, subroutines, and/or functions.

[0112] Possibly, a conventional keyboard and mouse can be coupled to the input/output controller **135**. Other I/O devices **140-155** may include or be connected to other hardware devices **10**, as noted earlier.

[0113] In addition, the I/O devices **140-155** may further include or be connected to devices **410**, **510**, **610** that communicate outputs, e.g., time series. The computerized unit **101** can further include a display controller **125** coupled to a display **130**. In exemplary embodiments, the computerized unit **101** can further include a network interface or transceiver **160** for coupling to a network, to enable, in turn, data communication to/from other, external components.

[0114] The network transmits and receives data between the unit **101** and external devices, e.g., transducers **21-28**. The network is possibly implemented in a wireless fashion, e.g., using wireless protocols and technologies, such as Wifi, WiMax, etc. The network may be a fixed wireless network, a wireless local area network (LAN), a wireless wide area network (WAN) a personal area network (PAN), a virtual

private network (VPN), intranet or other suitable network system and includes equipment for receiving and transmitting signals.

[0115] The network can also be an IP-based network for communication between the unit **101** and any external server, client and the like via a broadband connection. In exemplary embodiments, network can be a managed IP network administered by a service provider. Besides, the network can be a packet-switched network such as a LAN, WAN, Internet network, an Internet of things network, etc.

[0116] If the unit **101** is a PC, workstation, intelligent device or the like, the software in the memory **110** may further include a basic input output system (BIOS). The BIOS is stored in ROM so that the BIOS can be executed when the computer **101** is activated. When the unit **101** is in operation, the processor **105** is configured to execute software stored within the memory **110**, to communicate data to and from the memory **110**, and to generally control operations of the computer **101** pursuant to the software.

[0117] The methods described herein and the OS **111**, in whole or in part are read by the processor **105**, typically buffered within the processor **105**, and then executed. When the methods described herein are implemented in software, the methods can be stored on any computer readable medium, such as storage **120**, for use by or in connection with any computer related system or method.

3.2 Computer Program Products

[0118] The present invention may be an apparatus, a method, and/or a computer program product. The computer program product may include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the present invention.

[0119] The computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium may be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium includes the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a static random access memory (SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, a mechanically encoded device such as punch-cards or raised structures in a groove having instructions recorded thereon, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

[0120] Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network may comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

[0121] Computer readable program instructions for carrying out operations of the present invention may be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, or either source code or object code written in any combination of one or more programming languages, including an object oriented programming language such as Smalltalk, C++ or the like, and conventional procedural programming languages, such as the C programming language or similar programming languages. The computer readable program instructions may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider). In some embodiments, electronic circuitry including, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) may execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of the present invention.

[0122] Aspects of the present invention are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

[0123] These computer readable program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions may also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture including instructions which implement aspects of the function/act specified in the flowchart and/or block diagram block or blocks.

[0124] The computer readable program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0125] The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments of the present invention. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

[0126] While the present invention has been described with reference to a limited number of embodiments, variants and the accompanying drawings, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the scope of the present invention. In particular, a feature (device-like or method-like) recited in a given embodiment, variant or shown in a drawing may be combined with or replace another feature in another embodiment, variant or drawing, without departing from the scope of the present invention. Various combinations of the features described in respect of any of the above embodiments or variants may accordingly be contemplated, that remain within the scope of the appended claims. In addition, many minor modifications may be made to adapt a particular situation or material to the teachings of the present invention without departing from its scope. Therefore, it is intended that the present invention not be limited to the particular embodiments disclosed, but that the present invention will include all embodiments falling within the scope of the appended claims. In addition, many other variants than explicitly touched above can be contemplated. For example, any suitable number of transducers may be contemplated, other than N=8, 64 or 128 as assumed in examples described herein.

What is claimed is:

1. A computer-implemented method for computing a tissue reflectivity function (TRF), comprising:

accessing radio-frequency (RF) data obtained by beamforming time signals R_i from an array of transducers of an ultrasound device, wherein the RF data are assumed to correspond to outputs of a radio-frequency function, or RF function, evaluated at given points r of an imaging plane, which RF function involves a convolution of a point spread function (PSF) with the TRF to be computed, the PSF assumed to be defined at pairs of points of the imaging plane, so as to account for a spatial variance thereof;

for each pair of given pairs of points in the imaging plane, computing the PSF as a sum of contributions from at least some of the transducers, to which respective time-of-flight functions can be associated, wherein each of said contributions is computed by evaluating a transducer's transfer function h, based on two outputs of a respective time-of-flight function τ, said two outputs obtained by evaluating the time-of-flight function at a first point r and at a second point s of said each pair, respectively; and

based on the computed PSF, deconvoluting the RF function to obtain the TRF.

2. The method according to claim **1**, wherein at computing the PSF, each of said contributions is computed by evaluating the transducer's transfer function h as a function of a difference between said two outputs.

3. The method according to claim **2**, wherein the PSF is computed as a sum that can be written as $\Sigma_i h(\tau(r, p_i)-\tau(s, p_i))\times b_i$, where p_i denotes a position in space of an i^{th} transducer of the array, i=1, . . . N, and b_i is a correction factor.

4. The method according to claim **3**, wherein at computing the PSF, each b_i is equal to 1.

5. The method according to claim **1**, wherein the method further comprises: accessing an explicit representation of the RF function that is constructed based on time signals R_i obtained from the transducers of said array, and wherein

the TRF is subsequently obtained by deconvoluting the constructed RF function, based on the accessed representation of the RF function.

6. The method according to claim **5**, wherein the RF function is constructed by interpolating the time signals R obtained from the transducers to obtain said explicit representation of the RF function.

7. The method according to claim **6**, wherein computing the PSF further comprises:

interpolating the transfer function h, based on a same interpolation scheme as used to interpolate the time signals R_i to construct the RF function.

8. The method according to claim **1**, wherein the method further comprises:

accessing a representation of the transducer's transfer function h as an analytical function, prior to evaluating the transducer's transfer function.

9. The method according to claim **8**, wherein the analytical function accessed can be written as a decaying function times an oscillating function.

10. The method according to claim **9**, wherein the analytical function h accessed can be written as $h(t)=\beta e^{-\alpha t^2}\cos(2\pi f_0 t)$, where β is a constant.

11. The method according to claim **1**, wherein:

the array of transducers is configured to cause, in emission, a plane wave corresponding to a coherent summation of circular waves emitted by each of the transducers; and

the time-of-flight function τ associated with an i^{th} transducer of the array is computed, for a given point r, as $\tau(r, p_i)=(r, e_y)/c+\|r-p_i\|/c$, wherein:

said plane wave is assumed to be directed in a direction of a unit vector e_y;

c is the speed of sound in a given target medium, whose tissue reflectivity function is to be computed; and

p_i corresponds to a position of said i^{th} transducer.

12. The method according to claim **1**, wherein:

the array of transducers is configured to cause, in emission, a coherent divergent wave having a virtual point source $r_n=(x_n, y_n)$; and

the time-of-flight function τ associated with an i^{th} transducer of the array is computed, for a given point r, as $\tau(r, p_i)=(\|r-r_n\|-(r_n, r)/c+\|r-p_i\|/c$, wherein:

c is the speed of sound in a given target medium, whose tissue reflectivity function is to be computed; and

p_i corresponds to a position of said i^{th} transducer.

13. The method according to claim **1**, further comprising:

displaying an image based on the computed tissue reflectivity function.

14. An ultrasound apparatus, comprising:

an array of transducers, each configured to convert an electrical signal into a sound wave, in order to emit such a sound wave and, conversely, to convert a sound wave it receives into an electrical signal, whereby time signals can be obtained from the array of transducers, in operation; and

a processing module, comprising: a beamforming module; a point spread function (PSF) computation module; and a deconvolution module, wherein:

the beamforming module is configured to beamform time signals obtained from the array of transducers, so as to obtain radio-frequency (RF) data, wherein the RF data are assumed to correspond to outputs of a radio-frequency function, or RF function, evaluated at given points r of an imaging plane, which RF function involves a convolution of a point spread function, or PSF, with a tissue reflectivity function (TRF) the PSF assumed to be defined at pairs of given pairs of points in the imaging plane, so as to account for a spatial variance thereof;

the PSF module is configured to access RF data as obtained via the beamforming module and, for each pair (r, s) of given pairs of points in the imaging plane, to compute the PSF as a sum of contributions from at least some of the transducers, to which respective time-of-flight functions can be associated, wherein, in operation, each of said contributions is computed by evaluating a transducer's transfer function h, based on two outputs of a respective time-of-flight function τ, said two outputs obtained by evaluating the time-of-flight function at a first point r and at a second point s of said each pair, respectively, and

the deconvolution module is configured to deconvolve a RF function associated to RF data as accessed by the PSF module, to obtain the TRF, based on a PSF as computed by the PSF module, in operation.

15. The ultrasound apparatus according to claim **14**, wherein:

the processing module further comprises an interpolation module, configured in the processing module so as to be invoked by the beamforming module, and wherein the interpolation module is further configured to interpolate time signals R_i obtained from the array of transducers, so as to provide interpolated time signals to the beamforming module, for the latter to construct the RF function, in operation.

16. The ultrasound apparatus according to claim **15**, wherein:

the interpolation module is further configured in the processing module so as to be invoked by the PSF module, and wherein the interpolation module is further configured to interpolate the transfer function h, so as to provide to the PSF module a transfer function h interpolated based on a same interpolation scheme as used to interpolate the time signals to obtain the RF function, in operation.

17. A computer program product for computing a tissue reflectivity function (TRF), the computer program product comprising a computer readable storage medium having program instructions embodied therewith, the program instructions being executable by a processing unit to cause the latter to:

access radio-frequency (RF) data as obtained by beamforming time signals from an array of transducers of an ultrasound device, wherein the RF data are assumed to correspond to outputs of a radio-frequency function, or RF function, evaluated at given points r of an imaging plane, which RF function involves a convolution of a point spread function (PSF) with a tissue reflectivity function (TRF) to be computed, the PSF assumed to be defined at pairs of points of the imaging plane, so as to account for a spatial variance thereof;

compute the PSF, for each pair of given pairs of points in said imaging plane, as a sum of contributions from at least some of the transducers, to which time-of-flight functions can respectively be associated, wherein each of said contributions is computed by evaluating a transducer's transfer function h, based on two outputs of a respective time-of-flight function τ, said two outputs obtained by evaluating the time-of-flight function at a first point r and at a second point s of said each pair, respectively; and

based on the computed PSF, deconvolve the RF function corresponding to said RF data to obtain the TRF.

18. The computer program product according to claim **17**, wherein at computing the PSF, each of said contributions is computed by evaluating the transducer's transfer function h as a function of a difference between said two outputs.

19. The computer program product according to claim **18**, wherein the PSF is computed as a sum that can be written as $\Sigma_i h(\tau(r, p_i)-\tau(s, p_i))\times b_i$, where p_i denotes a position in space of an i^{th} transducer of the array, i=1, . . . N, and b_i is a correction factor.

20. The computer program product according to claim **19**, wherein:

at computing the PSF, each b_i is equal to 1.

* * * * *

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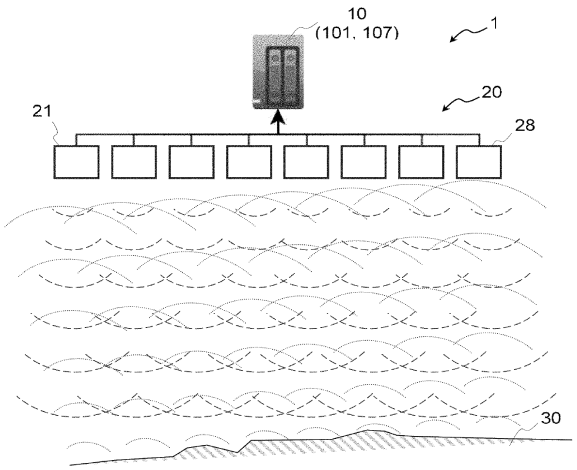
本发明涉及一种用于计算组织反射率函数（TRF）的计算机实现的方法。该方法包括访问射频（RF）数据和计算点扩散函数（PSF），以获得TRF。所访问的RF数据是通过从超声设备的换能器阵列波束形成时间信号R i而获得的数据。接下来，对于成像平面中给定点对的每对（r，s），PSF被计算为来自至少一些换能器的贡献之和。基于相应的飞行时间函数τ的两个输出，通过评估换能器的传递函数h来计算每个所述贡献。这样的输出是通过评估第一点r处的飞行时间函数而获得的。在所述每对的第二点s处。最后，可以基于计算的PSF对RF函数进行解卷积，以便获得TRF。