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METHOD FOR PRODUCING A SONAR IMAGE

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The invention relates to a method for producing a sonar image of an underwater area, of the generic type defined in the precharacterizing clause of claim 1.

- 10 One known sonar system which operates on the basis of an ultrasound in order to produce an image of an underwater area (US 4 288 866) uses sound pulses with a high time/bandwidth product for good range resolution, and an image store which is organized as a three-
- 15 dimensional database of the object reflections. A sound transmitter transmits a pseudo-random pulse, and a sound receiver detects the sound pulses reflected from objects, as echo signals. A multi-beamformer or beamformer which is connected downstream from the sound
- 20 receiver and covers a number of beams or directivity characteristics, which spread out like a fan, in a reception sector of the underwater antenna emits a multiplicity of echoes for in each case one angle resolution cell, whose horizontal width is governed by
- 25 the horizontal beam angle, or the directivity characteristic. The echo signals are correlated in correlators with a stored pattern of the sound pulse, with time-compressed pulses being produced at the outputs of the correlators for angle resolution cells.
- 30 An image store receives the output pulses from the correlators and generates a three-dimensional database of the echoes in the form of a set of contour lines for each range cell. A standard computer graphics technique is used to form an optical image from the three-
- 35 dimensional database, assisting the operator in identifying an object.

It is known for this so-called broadband sonar transducer technology to be linked to signal processing for sound-reflection tomography for identification of underwater mines, in order to obtain high-resolution images of underwater mines from a safe separation distance of 100 m to 200 m (Brian G. Ferguson "Application of acoustic reflection tomography to sonar imaging", J. Acoust. Soc. Am. 117(5), May 2005, pages 2915 to 2928). For this purpose, the watercraft which is carrying the sonar has to move around the mine, which has been detected and classified in a conventional manner, for example by means of a mine hunting sonar, in order that the sonar can receive echo signals, reflected from the mine, from different aspect angles. Tomographic reconstruction algorithms are used to produce a two-dimensional image of the shape of the mine, from the received echo signals.

In one known method for producing a three-dimensional image, which represents the structure of an underwater environment, by means of a sonar (US 5 200 931), the underwater region is subdivided into a multiplicity of identical cubes which are arranged in rows and columns with respect to one another, with each cube being allocated one storage location in a separate store. A histogram of back-scattered or reflection data of the sonar is formed in the store for each instant at which a back-scattered signal, which originates from a volume associated with a cube, is detected. That cube which has the highest probability of being the location of the back-scattering in the underwater environment in each row and column is established, and the specific cubes are combined, using a standard image generation technique, to form a map of the underwater environment.

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One known multi-beam synthetic aperture sonar (WO 02/059645 A2) has a sonar projector which emits sonar signals, and a multi-beam sonar receiver which receives

reflected sonar signals which are created by reflection of the emitted sonar signals on objects in an underwater area which is "ensonified" by the sonar projector. The output signals from the multi-beam sonar receiver and the data in the transmission signal from the sonar projector are supplied to a synthetic aperture sonar processor. The processor processes these signals and data using synthetic aperture algorithms. The sonar system also has an interferometry processor, which processes the output data from the synthetic aperture sonar processor using interferometric algorithms, in order to achieve better vertical resolution.

In one known method for automatic target identification by means of a synthetic aperture radar (SAR) (US 6 897 802 B1), the radar echoes are processed to form pixels, and the stored pixels are preprocessed in order to extract a target. A first and a second identification algorithm are applied to the extracted target for a first and a second classification of that target, and the two classification results are fused with one another in order to identify the extracted target.

The invention is based on the object of specifying a method for producing a sonar image, by means of which a large underwater area can be scanned systematically with high position resolution and which is independent of the beam angle and/or the number of beams or directivity characteristics formed within the reception sector.

According to the invention, the object is achieved by the features of claim 1.

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The method according to the invention has the advantage that an underwater area of any desired size can be scanned with high resolution so that objects in the

underwater area and/or the surface of the bed of the underwater area can be recorded with high contour detail. It is sufficient for this purpose for the watercraft which is carrying the transmitting and receiving antenna to move effectively in a straight line over a specific path, which in turn is dependent on the extent of the underwater area to be covered in the direction of travel. In the known methods, the position resolution of the underwater area in the direction of travel is dependent on the beam angle and the number of directivity characteristics or beams, and deteriorates as the radial range increases. In contrast to this, in the case of the method according to the invention, the position resolution in the direction of travel is independent of the beam angle of the directivity characteristic, and is constant over range. It is dependent only on the magnitude of the aspect angle interval covered, that is to say on the sector angle φ_B of the reception sector of the receiving antenna, at which the same points in the underwater area are "considered" by the receiving antenna while the watercraft is traveling over that path. In general, the achievable position resolution in the direction of travel is $\frac{c \cdot \tau}{x} / \sin \frac{\varphi_B}{2}$, where c is the speed of sound in water, and τ is the pulse duration of the sound pulses. It is just as important to choose the number of measurement points and thus the aspect angle within the aspect angle interval to be sufficiently large.

The reception sector can be covered by beamforming with a plurality of beams or directivity characteristics which are adjacent to one another like a fan on the plane on which the watercraft is moving, as a result of which, the position resolution in the direction of travel is not changed despite it being possible to increase the distance between the measurement points, and therefore the speed of movement of the underwater

vehicle. The number of aspect angles from which an area element in the underwater area is considered is then equal to the number of beams or directivity characteristics in which the area element appears, and
 5 can be controlled by means of the distance between the measurement points. It is sensible to choose the distance A_y between the measurement points to be:

$$A_y \leq \frac{\tan \frac{\varphi_B}{2}}{\tan \left(\frac{\varphi_B}{2K} \right)} \cdot \frac{c \cdot \tau}{2 \cdot \sin \left(\frac{\varphi_B}{2} \right)} \quad (1)$$

10 where K is the number of beams or directivity characteristics which cover the reception sector with the horizontal sector angle φ_B .

By way of example, let us assume that the reception
 15 sector of the receiving antenna has a sector angle $\varphi_B = 90^\circ$, which is ensonified with sound pulses with a pulse duration of $\tau = 0.1$ ms, with the distance between the measurement points being A_y . The receiving antenna may have a set of beams which covers the reception sector
 20 and comprises 10 beams or directivity characteristics, each of which has a beam angle of 9° . Assuming the speed of sound to be $c = 1500$ m/s, this data results in a position resolution in the underwater area in the direction of travel within the reception sector of
 25 10.6 cm, irrespective of the range. The maximum distance A_y between the measurement points, which should not be exceeded, is about 1.35 m.

In the case of the methods that have normally been used
 30 until now, in which the angular resolution of the underwater area within the reception sector is governed by the beam angle φ of the beams or directivity characteristics the same position resolution in the direction of travel of 10.6 cm is achieved at a range

of 10 m, in contrast, using a receiving antenna with a set of beams comprising approximately 150 beams or directivity characteristics and each with a beam angle of $\phi = 0.6^\circ$. The same resolution at a range of 20 m would require twice the number of beams or directivity characteristics with a beam angle of $\phi = 0.3^\circ$. In order to halve the beam angle, the length of the receiving antenna would have to be doubled, for the same transmission frequency. This clearly shows that, with the watercraft traveling at a sufficiently high speed, the method according to the invention results in high, range-independent angular resolution with a receiving antenna whose length offers very much more freedom for fitting even to small underwater vehicles, for example autonomous or remotely controlled underwater vehicles. This position resolution in the direction of travel is constant and does not deteriorate as the range increases, in contrast to the situation with the known method. Conversely, very much better position resolution in the direction of travel is achieved by means of the method according to the invention with a receiving antenna of conventional length than in the case of the known methods, and which, furthermore, is still constant over a range.

Expedient embodiments of the method according to the invention as well as advantageous developments and refinements of the invention are specified in the further claims. A three-dimensional sonar image is advantageously reconstructed by means of an interferometric measurement, in which a second receiving antenna is used, preferably at a vertical distance from the first, which three-dimensional sonar image makes it possible to identify the seabed profile and objects on the seabed, and in the water volume of the underwater area.

The invention will be described in more detail in the following text with reference to exemplary embodiments which are illustrated in the drawing, in which:

- 5 Figure 1 illustrates, schematically, a rear view of a watercraft, which is moving in a sea region and has a sonar for detection of data from an underwater area,
- 10 Figure 2 shows a block diagram of the transmitter side of the sonar,
- 15 Figure 3 shows a block diagram of the receiver side of the sonar,
- 20 Figure 4 shows a schematic illustration of an instantaneous state during data recording, in the form of a plan view,
- Figure 5 shows an enlarged illustration of the detail V in Figure 4,
- Figures 6 each show an illustration in order to explain the association between an area element and the amplitude value of the filter signal, based on two method variants,
- 25 Figure 8 shows the same illustration as in Figure 4, with a modified path traveled by the watercraft,
- 30 Figure 9 shows a block diagram of the receiver side of this sonar according to a further exemplary embodiment,

Figure 10 shows an illustration in order to explain the interferometric measurement principle,

5 Figure 11 shows an example of a transfer function of a filter in the block diagram shown in Figure 3.

10 In the method described in the following text for producing a sonar image of an underwater area, a sonar is used which is carried by a watercraft and has a sound transmitter 12 (Figure 2) and a sound receiver 13 (Figure 3). The sound transmitter 12 has a transmission pulse generator 14 and a transmitting antenna 15, which
15 has a plurality of electroacoustic transducers 16 arranged on an antenna mount. The electrical transmission pulses which are generated by the transmission pulse generator 14 are emitted from the transmitting antenna 15 as sound pulses into a
20 transmission sector 17, whose spatial angle is at least as large as a reception sector 18, which is covered on the receiving side in the underwater area 10, with the sector angle lying on the plane of travel, referred to in the following text as the horizontal sector angle ϕ_h
25 (Figure 4), and the sector angle aligned at right angles to this, referred to in the following text as the vertical sector angle ϕ_v (Figure 1). The spatial angle of the transmission sector 17 ensonified by the transmitting antenna 15 is chosen to be larger than
30 that of the reception sector 18.

The sound receiver 13, as illustrated in the form of a block diagram in Figure 3, has an electroacoustic receiving antenna 19 comprising a multiplicity of
35 hydrophones 20, which are likewise arranged on an antenna mount. Hydrophones 20 which are located vertically one above the other are combined to form a so-called stave in order to achieve vertical

beamforming for the receiving antenna 19, that is to say the vertical sector angle ϕ_v . Each of the hydrophones 20 illustrated in Figure 3 is therefore part of a stave. All the hydrophones 20 and all the
5 staves are operated at the same time. Group signals are obtained from different reception directions, each with the maximum reception sensitivity, from the electrical output signals from the hydrophones 20 in a known manner by signal processing, so-called beamforming. The
10 maximum reception sensitivity of the receiving antenna 19 is also referred to as the directivity characteristic or beam. The beamforming is carried out in the beamformer 21, resulting in a fan of beams or directivity characteristics adjacent to one another.
15 The following text uses only the expression beams, in accordance with normal specialist use of the term.

The set of beams (Figure 4) which results from the multiplicity of beams 22 that are adjacent to one
20 another covers the reception sector 18 of the sound receiver 13. Each beam 22 has a beam angle on the plane of travel of the watercraft, referred to in the following text as the horizontal beam angle ϕ (Figure 4), and a beam angle aligned at right angles to this,
25 referred to in the following text as the vertical beam angle ϕ_v (Figure 1). In order to produce the group signals for the individual beams 22, the output signals from the hydrophones 20 or staves are amplified, are sampled at a sampling frequency $1/T$, and are processed
30 further in a complex form, with the individual sample values or samples being delayed with the correct timing, and being added in-phase to form complex group signals. Each of the complex group signals is mixed in complex form to baseband, and is low-pass filtered. The
35 magnitude of the low-pass filter output signal is then formed in the block 23. The waveforms of the magnitude obtained from the block 23 are referred to in the foreign text as received signals. However, in one

alternative embodiment of the method, it is also possible to form the squares of the magnitudes rather than the magnitudes themselves and to process their waveforms further as received signals. The complex group signals themselves can also be used, that is to say without the baseband mixing and magnitude or square of the magnitude formation process as described above, or their real part can be used as received signals.

10 The received signals are subject to at least one correction in the block 24, for example in order to compensate for the decrease in the amplitude of the output signals from the hydrophones 20 caused by geometric attenuation during the forward path and
15 return path of the sound pulse. The corrected received signals are filtered in the filter 25 in such a way that the low-frequency components of the magnitude signal are provided with lower weightings than high-frequency components. For this purpose, the filter 25
20 has a transfer function similar to a high-pass filter, with a rising, preferably linear profile over the frequency. One example of this filter 25, which is similar to a high-pass filter, is a so-called ramp filter. In the case of the described digital signal
25 processing, a linear system is used as the filter 25 whose periodic transfer function $H(e^{j\omega T})$ within the limits defined by the half-negative and half-positive sampling circular frequency $-\pi/2T$ and $+\pi/2T$, respectively, is proportional to the magnitude of the
30 circular frequency ω , falling in the range from $-\pi/2T$ to 0 and rising in the range from 0 to $+\pi/2T$. One such linear system is illustrated in Figure 11. The described filtering of the magnitude signal results in a filter signal with positive and negative amplitudes,
35 allowing reconstruction of the sonar image. Further low-pass filtering with a transfer function corresponding to an Si function or a window function, for example with a cosine, Hamming, Hanning or

Tschebyscheff window, leads to an improvement in the signal-to-noise ratio of the filter signal.

In order to produce a sonar image of an underwater area 10, as is illustrated schematically by way of example in Figure 4, a field comprising a multiplicity of area elements 26 arranged in rows and columns is defined in the underwater area 10. The area elements 26 are preferably square with an edge length which is dependent on the desired or maximum possible radial resolution. When continuous-wave pulses are emitted, the edge length is designed to be equal to or less than $c\tau/2$, where c is the speed of sound in water and τ is the pulse duration of the sound pulses emitted from the transmitting antenna 15. The edge length may be chosen to be greater than $c\tau/2$ when using the method, as illustrated in Figure 6, for association of amplitude values of the filter signal with the area elements 26.

Figure 5 illustrates an enlarged detail of the area element field. Each area element 26 is allocated a storage location in a storage medium 27, referred to in the following text for short as the store 27 (Figure 3). The watercraft 11 now travels over an essentially straight path 28, running along the y coordinate in Figure 4. The receiving antenna 19 is aligned such that its reception sector 18 points to starboard in the exemplary embodiment. In this case, the angle which the center axis 181 or angle bisector of the reception sector 18 includes with the longitudinal axis of the watercraft 11 is chosen to be 90° in the exemplary embodiment. However, it may also be other than 90° . When traveling over the path 28, the reception sector 18 has a multiplicity of beams 22 within it covering the underwater area 10 over a width $x_{\max} - x_{\min}$ (Figures 1 and 4). The transmitting antenna 15 emits a sound pulse with the pulse duration τ at each of the successive, preferably equidistant, measurement points

29 along the path 28. The receiving antenna 19 receives the echo signals which have been scattered back from the underwater area 10 and are emitted from the beamformer 21 as complex received signals associated with the beams 22.

The group signals are subjected to signal processing in the manner described above, so that a discrete-time filter signal (Figures 6 and 7) is produced from each beam 22, as described. The filter signals of all the beams 22 are used to successively reconstruct the sonar image from one measurement point 29 to another measurement point 29, thus resulting in a complete sonar image of the underwater area 10 at the end of the path 28. For this purpose, strips 30 (Figure 5) which are curved in a circular shape and are adjacent to one another in the radial direction and with a radial width of $c\tau/2$ are defined at each measurement point 29 in the region of the area element field constrained by the beam angle ϕ of the beam 22, extending as far as the field region boundaries, that is to say as far as the boundary edges 222 of the beams 22.

The mean radii of curvature of the strips 30 are calculated taking account of the speed of sound c from the discrete time values of the filter signals. The mean radius of curvature of a strip 30 in this case corresponds to the distance between the centre line 301 of the strips 30 from the location of the receiving antenna 19. The latter is located at the center point of the reception sector 18. This is illustrated in Figures 5 and 6. By way of example, a front strip 30 is defined by the discrete time value nT of the filter signal and a rear strip 30, adjacent to it, of the same radial width by means of the time value $(n+1)T$ of the filter signal. As is illustrated in Figure 6, each area strip 30 is allocated the amplitude value of the discrete-time filter signal associated with the time

value nT or $(n+1)T$, respectively. In the example in Figure 6, the front strip 30 is allocated the amplitude value $a(n)$ on the basis of the time value nT , and the rear strip 30 is allocated the amplitude value $a(n+1)$ on the basis of the time value $(n+1)T$. As can be seen from Figure 5, each strip 30 entirely or partially covers a plurality of area elements 26. For all the area elements 26 which are located entirely or partially within the front strip 30, the amplitude value $a(n)$ is written to those storage locations in the store 27 which are associated with those area elements 26 which are located entirely or partially in the front strip 30. For all area elements 26 which are located entirely or partially within the rear strip 30, the amplitude value $a(n+1)$ is written to those storage locations in the store 27 which are associated with those area elements 26 which are located entirely or partially in the rear strip 30, with the amplitude value in each storage location being added to a store value which is already located in this storage location and is obtained from other beams 22 or from measurements carried out at previous measurement points 29. This is done for all the strips 30 which are adjacent to one another in the radial direction and are defined by the discrete time values $(n+2)T$ etc., and to which the amplitude values $a(n+2)$ etc. are then assigned.

However, the amplitude values are not associated 1:1 with all the area elements 26 within the same strip 30 but only in a manner which takes account of their position within the strip 30, for which purpose the amplitude values are weighted before they are written to the store 27. The weighting process is in this case carried out in two ways. Firstly, the area component of each area element 26 which is covered by the strip 30 and secondly the reception sensitivity of the beam 22 are taken into account, with the latter decreasing from

the centre axis 221 of the beam 22 towards the beam edges 221. The described process of reconstruction of the sonar image is carried out in the circuit arrangement shown in Figure 3 in the block 31 for each beam 22, with the area weighting being carried out in the sub-block 311 by multiplication of the amplitude value by an area weighting factor, and with the reception sensitivity weighting being carried out in the sub-block 312 by multiplication of the amplitude value by a weighting factor which is derived from the reception sensitivity in the beam 22 over its beam angle ϕ , the so-called beam width.

In a method variant, as illustrated in Figure 7, for the association of amplitude values from the discrete-time filter signals with the individual area elements 26, the distance between the center 261 and the area element 26 and the center point of the reception sector 18 is determined for each area element 26 which is located within the area covered by the beam 22, that is to say within the area of the area element field which is bounded by the beam angle ϕ of the beam 22, and a time value t_0 is calculated from this distance, using the speed of sound c . An associated amplitude value $a(t_0)$ is taken from the discrete-time filter signal relating to the time value t_0 . In the example illustrated in Figure 7, the time value t_0 is located between the discrete time values nT and $(n+1)T$. In this case, the amplitude value $a(t_0)$ for the time value t_0 is determined by interpolation between the amplitude values $a(n)$ and $a(n+1)$. The amplitude value $a(t_0)$ obtained by interpolation is associated with the area element 26. This amplitude value $a(t_0)$ is weighted corresponding to the position of the area element in the beam 22, to be precise by being multiplied by a weighting factor which takes account of the reception sensitivity of the beam 22 at the location of the area element 26. This is done for all the area elements 26

which are located within the area of the area element field which is bounded by the beam angle φ of the beam 22. The process is then continued in the same manner as that described, that is to say by writing the weighted
 5 amplitude values to the associated storage locations, and by adding them to the stored values already present there. One precondition for this method step is that the edge length of the square area element 26 is designed to be less than or equal to the radial
 10 resolution, which is illustrated in Figure 7 by a front and a rear boundary line, and is $c \cdot \tau / 2$ in the exemplary embodiment. In the method variant shown in Figure 6, it is not permissible for the area elements 26 to have an edge length of more than $c \cdot \tau / 2$.

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When the watercraft 11 is moving without interruption, preferably continuously, the described reconstruction is carried out at all the measurement points 29 along the path 28, in each case in all the beams 22, with the
 20 measurement points 29 being at a distance A_y from one another (Figure 4). The maximum distance A_y which should not be exceeded for correct data recording is dependent on the number of beams 22 which cover the reception sector 18, and can be estimated roughly to
 25 be:

$$A_y \leq \frac{\tan \frac{\varphi_B}{2}}{\tan \left(\frac{\varphi_B}{2K} \right)} \cdot \frac{c \cdot \tau}{2 \cdot \sin \left(\frac{\varphi_B}{2} \right)} \quad (1)$$

where K is the number of beams 22 which cover the reception sector 18 with the sector angle φ_B .

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At the end of the path 28 traveled by the watercraft 10, the storage content of the store 27 is normalized in the block 32. The normalization process is carried out in such a way that each of the stored values

contained in the storage locations in the store 27 is divided by the sum of the squares of the weighting factors included in the respective stored value. In this case, the weighting factor in the first-described method variant is the product of the reception sensitivity weighting factor and the area weighting factor, and in the second-described method variant, it is solely the reception sensitivity weighting factor. The normalized storage content is stored in a storage medium 33 (store 33 in Figure 3), which therefore contains the entire sonar image, which can be displayed visually on a display, using computer-graphics techniques.

Figure 8 shows, schematically, a path on which the underwater area 10 is "considered" from aspect angle intervals or sector angles ϕ_B pointing at right angles to one another. The path traveled by the watercraft 11 is in this case subdivided into two path sections 281 and 282, which are aligned at right angles to one another. Each path section 281, 282 is designed to be of such a size that each area element 26 in the area element field is covered by each path section 281, 282 at least once by the two time boundary edges 182 of the reception sector 18 with the sector angle ϕ_B . As has been described with reference to Figure 4, the reception sector 18 may once again be covered by a multiplicity of beams 22 in order to obtain a distance A_y between the measurement points 29 which allows the watercraft to travel at a sufficiently high speed. The underwater area 10 to be surveyed is scanned once along the path section 281 in the x direction and once along the path section 282 in the y direction while traveling along the path, so that the underwater area 10 will have been recorded completely at the end of the path. The described way of traveling over the path 28 is particularly advantageous when the sector angle ϕ_B of the receiving antenna 19 has only small values, for

example 10°, by virtue of its design. A plurality of paths are arranged one behind the other, as illustrated in Figure 4 or Figure 8, in order to produce sonar images of extended underwater areas.

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For cartographic surveying of the seabed profile of an underwater area 10 and/or in order to display three-dimensional objects on the seabed and/or in the water volume, the method as described above is linked to
10 interferometric measurement methods by means of which the vertical component can be determined for each scatter point in the underwater area 10. For this purpose, a further receiving antenna 19' is arranged at a vertical distance from the first receiving antenna 19
15 (Figure 10). As before, the transmitting antenna 15 is positioned close to the first receiving antenna 19, although it can just as well be arranged close to the second receiving antenna 19'. The second receiving antenna 19' is preferably identical to the first
20 receiving antenna 19.

The circuit arrangement for producing a three-dimensional sonar image is illustrated in Figure 9. For the sake of completeness, Figure 10 illustrates the
25 method known per se for interferometric surveying of the vertical component of a scatter point P. The vertical component z of the scatter point P with respect to a reference plane 36 is calculated from the time difference Δt of reception of the echo signal
30 scattered back from the point P in the two receiving antennas 19 and 19' and the distance r to the point P, using:

$$z = \frac{c \cdot \Delta t}{d} \cdot r \quad (4),$$

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where d is the distance between the two receiving antennas 19, 19'. The horizontal reference plane 36

passes through the receiving antenna location. The range r is calculated from half the measured delay time of the sound pulse from its emission to reception of the echo signal that results from it.

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The method as described above for scanning the underwater area 10 to the start of the process of writing the weighted amplitude values associated with the area elements 26 from the discrete-time filter signals remains unchanged and is represented by the block 35 for each beam 22 in the circuit arrangement as shown in Figure 9 (see also the same block 35 in Figure 3). In addition, the vertical component related to the horizontal reference plane 36 (Figure 10) is determined for each area element 26 by means of interferometric measurement, and this is referred to in the following text as the depth value z . For this purpose, for interferometry, the block 37 is supplied with the received signals of each beam 22 from the two receiving antennas 19, 19'. For example, the time difference of signal reception is determined by correlation of the received signals from the two receiving antennas 19, 19' in the block 37, and the depth value z is calculated using equation (4). An associated depth value z is produced at the output of the block 37 for each of the area elements 26 located within a beam 22. In a modified form of the more far-reaching method as described above, the weighted amplitude value associated with each area element 26 and taken from the discrete-time filter signal is now written to a storage location such as this in a three-dimensionally addressed storage medium 38, referred to as the store 38 for short, whose vertical address corresponds to the depth value z of the area element 26. In other words: all the weighted amplitude values which are associated with the area elements 26 located on a horizontal plane are written to x/y -addressed storage locations which all have the same vertical address z . This is done for

each beam 22 and is repeated at each measurement point 29, with the weighted amplitude values once again being added to the stored values when they are written to the store, with the stored values being those which are already stored in the storage locations in the three-dimensional store 38. The number of x/y-address storage locations which are located one above the other in the z direction and form a store column in the store 38 is defined on the basis of the vertical beam angle ϕ_v of the beam 22 (Figure 1) and the measurement accuracy of the interferometric depth measurement.

At the end of the path 28 traveled by the watercraft 10, the stored values which are contained in the store columns formed by the storage locations located vertically one above the other of the store 38 are normalized (block 43), with the normalization process being carried out in the manner described above by dividing the stored value contained in each storage location by the sum of the squares of the weighting factors included in the respective stored value. The stored values that have been normalized in this way are stored in a three-dimensional storage medium 39 (store 39 in Figure 9). All the stored values which are located within one store column, that is to say those which have the same x/y address, are accumulated to form an intensity value, for example by adding them (block 40). In addition, statistical methods are used to calculate a depth value z for the intensity value of the store column from the normalized stored values (block 41). For example, the centroid or the median of the normalized stored values from the store column is calculated as the depth value z, and is associated as a depth value with the intensity value. Intensity values and depth values are stored in x/y-addressed storage locations in a two-dimensional storage medium 42 (store 42 in Figure 9), which therefore contains a sonar image of a 2D surface of the seabed of the underwater area 10

and of objects in the water volume. The storage content of the store 39 can once again be displayed on a display, for example three-dimensionally, using computer-graphics techniques.

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The method described above for scanning the underwater area including the interferometric measurement method can be modified such that a three-dimensional region is defined (rather than a field of area elements) in the underwater area, composed of volume elements which are located adjacent to one another and one above the other and have a base area, top area and a vertical height corresponding to the dimensions of the area elements 26, with the height being in the order of magnitude of $c\tau/2$. Instead of forming the strips 30 in the beam 22, spherically curved cuboids with the radial width $c\tau/2$ are defined, extending over the cross section of the beam 22. The mean radii of curvature of the spherical cuboids are - in the same way as the radii of curvature of the strips 30 - calculated from the discrete time values of the filter signals taking into account the speed of sound, and the amplitudes of the discrete time values are assigned in the same way to the volume elements, rather than to the area elements 26, subject to a restriction to those volume elements which are located on the layer plane whose depth is defined by the depth value measured at that time. Before the amplitude values are stored in the storage locations associated with the volume elements by addition to already existing stored values, the weighting process as described above is likewise carried out. At the end of the measurement run, the stored values are processed, that is to say normalized, as described above, the intensity value is accumulated, and a depth value for the intensity value is calculated using statistical methods. This method variant has the advantage that, during the reconstruction process, the curvature of the sound waves as they propagate in a

spherical shape from the transmitting antenna is taken into account, thus obtaining more accurate data, particularly at short range, for image production.

5 As a modification of the described method, the reception sector 18 can also be covered on the port side or by two receiving antennas on the starboard side and port side of the watercraft 11. In the latter case, underwater areas on both sides of the direction of
10 travel are scanned at the same time. It may also be advantageous for the watercraft 11 to travel on a meandering path. It is, of course, possible to dispense with the digitizing of the output signals from the hydrophones, and to carry out the method on the basis
15 of analog received signals.

The method described above can also be modified such that just one beam is generated rather than a beam fan, whose horizontal beam angle ϕ is equal to the
20 horizontal sector angle ϕ_B . In this case, the distance A_y between the measurement points 29 must be very much shorter, thus resulting in a reduction in the maximum possible speed of travel of the watercraft 11. However, in this case as well, the horizontal beam angle ϕ_B of
25 the reception sector 18 of the receiving antenna 19 is made as large as the installation conditions on the watercraft allow.

The method described above can also be modified by
30 using a diving appliance, rather than a watercraft 11, as the sonar mount, moving on a vertical path. In this case, the same method will be carried out with the reception sector rotated through 90° , and with a beam fan rotated through 90° in a corresponding manner.

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1. A method for producing a sonar image of an
5 underwater area (10) using a sonar which is carried by
a watercraft, has a transmitting antenna (15) for
emission of sound pulses and a receiving antenna (19),
which covers a reception sector (18) with a sector
angle (ϕ_B), for receiving sound waves scattered back
10 from the underwater area (10), which underwater area
(10) is covered by at least one directivity
characteristic with a predeterminable beam angle (ϕ),
in which the following method steps are carried out:
- a field comprising a multiplicity of area elements
15 (26) arranged in rows and columns is defined in
the underwater area (10),
 - each area element (26) is allocated a storage
location in a storage medium (27),
 - the watercraft (11) is moved over a preferably
20 linear path (28) with the reception sector (18)
pointing to starboard and/or to port,
 - one sound pulse is in each case emitted at
successive, preferably equidistant, measurement
points (29) along the path (28) and, after being
25 scattered back from the underwater area (10), is
detected and filtered via the directivity
characteristic as a received signal,
 - an amplitude value is determined on the basis of
the position of the area element (26) in the field
30 region at each measurement point (29) from the
filter signal obtained by the filtering (25) for
each area element (26) which is located within the
region of the area-element field bounded by the
beam angle (ϕ) of the directivity characteristic,
35 in that strips (30) which are curved in a circular
shape, are adjacent to one another in the radial
direction and extend to the field region
boundaries in the field region are formed with a

- predeterminable radial width, whose mean radii of curvature are defined by time values which are taken from the filter signal and are multiplied by the speed of sound, and the filter signal amplitude value associated with each time value that is obtained is associated with each area element (26) which is located entirely or partially within the strip (30) defined by the time value,
- 5
- 10 - the amplitude value determined for each area element (26) is weighted as a function of the specific position of the respective area element (26) in the field region, and
- the weighted amplitude values are written to the storage locations allocated to the area elements (26) and, in the process, are added to a stored value which is already in that storage location.
- 15

2. The method as claimed in claim 1, in which the position-specific weighting of the amplitude values of the area element (26) is carried out in such a way that each amplitude value that is associated with one area element (26) is multiplied by an area weighting factor, which takes account of that component of the area of the area element (26) which is located within the strip (30), and/or by a reception sensitivity weighting factor, which takes account of the reception sensitivity of the directivity characteristic at the location of the area element (26).
- 20
- 25
- 30

3. The method as claimed in claim 1 or 2, in which the area elements (26) are square with an edge length which is in the range of a desired radial resolution, preferably equal to the radial resolution, and the radial width of the strips (30) is designed to be equal to the desired radial resolution.
- 35

4. A method for producing a sonar image of an

underwater area (10) using a sonar which is carried by a watercraft, has a transmitting antenna (15) for emission of sound pulses and a receiving antenna (19), which covers a reception sector (18) with a sector angle (ϕ_B), for receiving sound waves scattered back from the underwater area (10), which underwater area (10) is covered by at least one directivity characteristic with a predeterminable beam angle (ϕ), in which the following method steps are carried out:

- 10 - a field comprising a multiplicity of area elements (26) arranged in rows and columns is defined in the underwater area (10),
- each area (26) is allocated a storage location in a storage medium (27),
- 15 - the watercraft (11) is moved over a preferably linear path (28) with the reception sector (18) pointing to starboard and/or to port,
- one sound pulse is in each case emitted at successive, preferably equidistant, measurement points (29) along the path (28) and, after being
- 20 scattered back from the underwater area (10), is detected and filtered via the directivity characteristic as a received signal,
- an amplitude value is determined on the basis of
- 25 the position of the area element (26) in the field region at each measurement point (29) from the filter signal obtained by the filtering (25) for each area element (26) which is located within the region of the area-element field bounded by the
- 30 beam angle (ϕ) of the directivity characteristic, the distance between the center (261) of each area element (26) within the field region from the center point of the reception sector (18) is determined for each area element (26) within that
- 35 field region, a time value is calculated from this using the speed of sound, and the amplitude value which is associated with that time value is taken

from the filter signal for each time value, and is assigned to that area element (26),

- the amplitude value determined for each area element (26) is weighted as a function of the specific position of the respective area element (26) in the field region, and
- the weighted amplitude values are written to the storage locations allocated to this area elements (26) and, in the process, are added to a stored value which is already in that storage location.

5. The method as claimed in claim 4, in which the position-specific weighting of the amplitude values of the area element (26) is carried out in such a way that each amplitude value that is associated with one area element (26) is multiplied by a reception sensitivity weighting factor which takes account of the reception sensitivity of the directivity characteristic at the location of that area element (26).

6. The method as claimed in claim 4 or 5, in which the area elements (26) are square, with an edge length which is less than or equal to the desired radial resolution.

7. The method as claimed in one of claims 1 to 6, in which complex group signals obtained by beamforming are used as received signals.

8. The method as claimed in one of claims 1 to 6, in which the time profile of the magnitude or of the square of the magnitude of complex group signals which have been obtained by beamforming is used as received signals.

9. The method as claimed in one of claims 1 to 6, in which the real parts of group signals that have been obtained by beamforming are used as received signals.

10. The method as claimed in claim 8, in which the magnitude signal is sampled at a sampling frequency of $1/T$, and the discrete-time magnitude signal is filtered by means of a linear system whose periodic transfer function $H(e^{j\omega T})$ within the limits defined by half the negative and half the positive sampling circular frequency ($-\pi/2T$ and $+\pi/2T$, respectively) is proportional to the magnitude of the circular frequency ω , falls from the lower limit to zero, and rises from zero to the upper limit.

11. The method as claimed in one of claims 1 to 3 and claim 10, in which discrete time values are searched for in the filter signal, and the mean radii of curvature of the strips (30) which can be associated with those time values are calculated by means of the speed of sound.

12. The method as claimed in one of claims 4 to 6 and claim 10, in which amplitude values which are associated with the time values calculated for the area elements (26) in the filter signal are obtained by interpolation.

13. The method as claimed in one of claims 1 to 12, in which the storage content of the storage medium (33) is normalized at the end of the path (28) traveled by the watercraft (11).

14. The method as claimed in claim 13, in which the normalization is carried out in such a way that each of the stored values contained in the storage locations is divided by the sum of the squares of the weighting factors included in the respective stored value.

15. The method as claimed in one of claims 1 to 14, in which the radial resolution is $c\tau/2$, where c is the speed of sound in water and τ is the pulse duration of

the sound pulses emitted from the transmitting antenna (12).

16. The method as claimed in one of claims 1 to 15, in which a vertical depth value (z) is determined at each measurement point (29) by interferometric measurement for each area element (26) at right angles to a horizontal reference plane (36), such that the amplitude values which are associated with the area elements (26) and are obtained from the filter signal are written to those storage locations in a three-dimensional storage medium (38) whose vertical address corresponds to the depth value (z), and such that, at the end of the path (28) traveled by the watercraft (11), the stored values which are contained in store columns which are formed by storage locations located vertically one above the other in the storage medium (38) are normalized and are accumulated to form an intensity value, and the depth value (z) associated with that intensity value is determined using statistical methods from the normalized stored values in each store column.

17. The method as claimed in claim 16, in which the centroid or median of the stored values contained in a store column is determined as a depth value.

18. The method as claimed in claim 16 or 17, in which the reference plane (36) is defined such that the sound reception location of the interferometric measurement is located on the reference plane (36).

19. The method as claimed in one of claims 16 to 18, in which the number of the storage locations in a store column is defined on the basis of the vertical beam angle (ϕ_v) of the directivity characteristic of the receiving antenna (19) and the measurement accuracy of the interferometric depth measurement.

20. The method as claimed in one of claims 16 to 19, in which a second receiving antenna (19') is provided for interferometric measurement and is arranged at a vertical distance from the first receiving antenna (19), and the depth values (z) are determined by measurement and evaluation of delay-time differences between the signals received by the two receiving antennas (19, 19').

21. The method as claimed in claim 20, in which the delay-time differences are determined by correlation of the signals received by the two receiving antennas (19, 19') in a time window which in each case covers the same time values for the two received signals.

22. The method as claimed in one of claims 17 to 21, in which the receiving antennas (19, 19') are identical.

23. The method as claimed in one of claims 1 to 22, in which the sector angle (φ_B) of the reception sector is designed to be as large as the installation allows, and the beam angle (φ) of the directivity characteristic of the receiving antenna (19) is chosen to be equal to the sector angle (φ_B).

24. The method as claimed in one of claims 1 to 22, in which the receiving antenna (19) covers a multiplicity of directivity characteristics, which are arranged in rows in the form of fans, preferably with the same beam angle (φ), whose added beam angle (φ) is designed to be equal to the sector angle (φ_B) of the reception sector (18), and the sector angle (φ_B) is preferably designed to be as large as the installation allows.

25. The method as claimed in claim 23 or 24, in which the path (28) traveled by the watercraft (11) is designed to be at least sufficiently long that each

area element (26) in the area element field is covered at least once by each side boundary edge (182) of the reception sector (18).

5 26. The method as claimed in claim 25, in which the path (28) is subdivided into two path sections (281, 282) which are aligned at right angles to one another, and each path section (281, 282) is designed to be
10 sufficiently long that each area element (26) in the area element field is covered at least once, from each path section (281, 282), by two side boundary edges (182) of the reception sector (18).

15 27. The method as claimed in claim 25 or 26, in which a plurality of paths (28) traveled by the watercraft (11) are arranged in rows one behind the other in order to cover a relatively large sea area.

20 28. The method as claimed in one of claims 1 to 27, in which the center axis (181) of the reception sector (18) pointing in the starboard and/or port direction is aligned at an angle of 90° to the longitudinal axis of the watercraft (11).