

DESCRIPTION

Method for measuring relief by means of an antenna with a known gain profile

5 Technical context

The invention that is the subject of the present document lies in the field of radar or sonar.

The receive antenna (or receiving array) may be a synthetic receive antenna, in which case reference is made to a synthetic aperture sonar or radar, but it may also be a real receive antenna or natural antenna (or real aperture sonar).

- 10 The transmit and receive antennas (or transmitting and receiving arrays) under consideration may be carried on the side by a vehicle moving at a distance from a surface, notably the surface of a seabed or seafloor in the case of a sonar carried by a marine or underwater vehicle, or else the land surface in the case of a radar carried by an aerial vehicle. In this case, they are therefore sideways-looking antennas (the central axis of the
15 antenna is typically inclined by around 15° downward with respect to the horizontal): reference is made to a side scan sonar.

The invention aims to provide a simple means for assisting the determination of the relative altitude of a point of the floor with respect to the antennas for a point imaged in the region close to the nadir (downward vertical direction) of the vehicle.

- 20 The imaged points are commonly localized by interferometry. The principle of interferometry is that of adding at least one receiver offset from the vertical plane with respect to the main antenna. While the antenna measures a first distance, the second receiver, by measuring a second distance, makes it possible to access a phase difference that is related to the location of the imaged point, give or take an integer number of
25 wavelengths. The integer number of wavelengths, which is initially unknown, is determined using what is known as the Vernier method. However, this method remains difficult to apply close to the nadir of the vehicle, and even in a wide cone around the nadir.

- The present invention therefore seeks to improve the determination of the relief of the floor in the area of the nadir, by using the fact that the antenna gain, counted for transmission
30 and reception, exhibits fluctuations that produce a fringe pattern in the received image, typically with an image that is "dark" where gain is low and "bright" where gain is high.

Generally speaking, it is sought to reduce these fluctuations in order to obtain a uniform gain image. This may be achieved in various ways, such as antenna lobe optimization or adaptive gain calculation.

5 It is nevertheless proposed to use these unwanted variations to find out the difference in relative altitude between the floor and the vehicle, noting that the location of the fringes depends on the direction of the local extrema of the antenna lobe and this relative altitude between the floor and the vehicle that it is sought to determine. Monitoring these fringes thus makes it possible to determine an estimate of the relief of the floor that is able to be used as such, or possibly be involved in a subsequent or complementary interferometry
10 process.

The invention may be used either upstream of synthetic image formation or downstream, in order to supplement the determination of bathymetry by interferometry in this case.

With regard to sonar, knowing the difference in relative altitude between the floor and the vehicle also helps to determine the relief of the floor, thereby making it possible to construct
15 a bathymetric map of the floor by taking into account the depth of the vehicle carrying the sonar, which is otherwise known, and tidal compensation.

The precise determination of the difference in relative altitude between the floor and the sonar is therefore an important function of a sonar imaging system, and it is important that it works satisfactorily.

20 Technical problem and solution provided thereto

In order to improve the existing solutions, and notably to improve the characterization of points in the vicinity of the nadir, what is proposed is a method for characterizing a reflective terrestrial or marine surface imaged by collecting echoes of waves transmitted toward said reflective surface, for example by a vehicle moving at a distance from said
25 reflective surface and, as it moves, collecting the echo of waves transmitted thereby toward said reflective surface from one of its sides. The waves are transmitted and received using a set of transmit and receive antennas, the set of antennas having a known angular gain profile in the vertical plane, which may for example have a main lobe and at least one sidelobe (and often numerous sidelobes), said main lobe and said at least one sidelobe
30 then being directed toward said reflective surface, and the intensities of the reflected signal as a function of the ranges between the set of antennas and the reflective surface being measured by the set of antennas in order to create an image of the surface.

The method comprises, in an original manner, searching the measured intensities for at least one local extremum (or even, in some cases, a global extremum) and, by identifying said at least one extremum at a (local or global) extremum of said known gain profile of the set of antennas (this extremum of the gain profile may be a zero of the antenna, or the apex of a lobe, but this is not necessary), localizing, with respect to the vehicle, or at least with respect to the set of antennas, a point of the image corresponding to said measured intensity extremum.

Optionally and advantageously, it is possible, where appropriate, to take into account a current value of the roll angle or a current value of the altitude of the vehicle (or at least of the set of antennas), or both of these values.

The invention is advantageous notably in that it provides a means for localizing points of the image in areas close to the nadir ($\gamma > 45^\circ$ typically; see figures 1 and 2), where interferometric methods are difficult to apply.

This method does not require any additional hardware equipment compared to the conventional assembly.

The method may then be used in addition to an interferometric method, in particular to help to initialize the reference phase difference of the signal. The corresponding point of the image may in any case be localized by providing an angle value, for example an elevation angle with respect to the set of antennas (or the vehicle), or a height value, such as the relief on the reflective surface.

According to some advantageous and optional features:

- the search may comprise searching for multiple gain extrema and creating a relief map of the reflective surface by interpolation between the corresponding points;
- the transmit antenna may have been chosen so that the lobes are present in a chosen number, a large number often being advantageous, said number possibly being arbitrary. It is possible to choose a high number of lobes and therefore fringes (notably a dozen or more), on the half of the transmit antenna on the side of the reflective surface;
- the search for extrema may be carried out on data (the measured intensities) before beamforming but after gain control, or on data (again the intensities) after beamforming, the beamforming having been carried out before or after gain control;
- the data (the intensities) may be subjected to prior low-pass filtering along the range

axis in order to eliminate dark areas due to relief and not due to the antenna gain pattern. This low-pass filter may be adaptive (that is to say with a different template depending on the position in the image) – the template may thus be variable or constant depending on the position in the image;

- 5 - the set of antennas may be carried by (fixed to) a moving vehicle, for example to the side thereof, successive acquisitions being carried out by the set of antennas, and optionally, but advantageously, low-pass filtering of the measured intensities is carried out along the axis of the acquisition numbers prior to the extremum search;
- 10 - the set of antennas may comprise a synthetic antenna or a natural antenna for reception;
- said localization may be used in a subsequent process of localizing the reflective surface by interferometry, as a reference or to resolve ambiguities;
- the waves may be sonar acoustic waves, the reflective surface comprising a seabed;
- 15 - the waves may be radar electromagnetic waves, the reflective surface comprising a land surface;
- the set of transmit and receive antennas has, in the elevation transmission pattern, a plurality of local minima and maxima with an amplitude large enough to enable said search, but small enough not to prevent the perception of objects located in
- 20 areas with a low gain level.

List of the figures

Figure 1A shows principles of interferometry applied to the context of a sideways-looking antenna.

Figure 1B shows the principles of the invention.

- 25 Figures 2A and 2B show the geometry, used in the context of the invention, of the antenna lobes.

Figure 3 shows a sonar image, highlighting the areas visualized by the lobes, as opposed to the areas between the lobes, which are darker.

- 30 Figure 4 shows the gains of the imaging process, as a function of distance from the nadir, for two different depths.

Figure 5 shows a sequence of steps implemented in one embodiment of the invention.

Figures 6 and 7 show a transmit antenna geometry as discussed for optimization purposes.

These figures are simple illustrations, and will be commented upon in more detail here.

Detailed description

- 5 [Fig. 1A] Figure 1A, which is a vertical section along the trajectory of the sonar along a horizontal axis of coordinates x , shows a first antenna 1 located at the abscissa $y=0$ and at the altitude $z=H$ (above an arbitrarily adopted altitude reference, with an upwardly oriented altitude axis), along with a second antenna 2 located at the abscissa $y=B.\sin(\alpha)$ and $z=H+B.\cos(\alpha)$ and a target 3 placed on the ocean floor 4 and located at the abscissa $y=Y$ and at an altitude $z=h$.

The antennas 1 and 2, for the purposes of figure 1, are considered to be receive antennas.

For each receiver, in a given direction toward the ocean floor, there is a range r (r_1 or r_2 in the figure) to the ocean floor 4, which depends not only on the height of the receiver but also on variations in the relief of the ocean floor 4, which is not known in advance.

- 15 B refers to the base, or baseline, and is the gap between the two receivers. The angle α is the inclination of the antenna with respect to the vertical axis 5, and integrates the roll angle. This angle is known, for example through the use of an attitude measuring unit.

- The path difference measured between the two antennas 1 and 2 – that is to say the difference between the distance (or range) r_1 between the first antenna 1 and the target 3, on the one hand, and the distance r_2 (again the range, but for the second antenna) between the second antenna 2 and the target 3, on the other hand, is:

$$r_2 - r_1 = \sqrt{r_1^2 + B^2 + 2r_1B \cdot \cos(\gamma + \alpha)} - r_1$$

- where γ is the angle of the straight line connecting the target and the antenna 1 with respect to the horizontal direction (this angle would be the grazing angle - that is to say the angle between the tangent to the floor and the straight line connecting the target and the antenna 1, if the floor were horizontal, or if the tangent at the floor to the target were horizontal – it is defined at the center of the set of transmit and receive antennas, between the horizontal direction and the direction of the visualized point returning the reflected wave), which is the quantity to be determined because it makes it possible (knowing α , B , H , r_1 , r_2) to determine h :

$$h = H - r_1 \sin \gamma$$

However, the measurement is not directly $r_2 - r_1$, but a phase ϕ , proportional to $2\pi(r_2 - r_1)/\lambda$ modulo 2π , where λ is the wavelength of the sonar or radar carrier frequency:

$$\frac{2\pi}{\lambda}(r_2 - r_1) = \frac{2\pi}{\lambda} \left(\sqrt{r_1^2 + B^2 + 2r_1 B \cdot \cos(\gamma + \alpha)} - r_1 \right) = \phi + 2\pi N, N \in \mathbb{N}$$

5 ...with N unknown. Multiple angles γ are therefore solutions to the previous equation; specifically:

$$\gamma = \arccos \left(\frac{\left(r_1 + \frac{\lambda \phi}{2\pi} + N\lambda \right)^2 - r_1^2 - B^2}{2r_1 \cdot B} \right) - \alpha$$

A single value $N = N_0$ of the number of cycles is the correct one. The solution generally adopted to find this value N_0 of N is phase unwrapping (or phase unrolling). It will be
 10 assumed that a phase ϕ_1 is observed for a first point, and that the correct value of N_1 is known for this point. Then, if the phase ϕ_2 of a point close to the first is observed, such that it is known with confidence that the phase difference $\phi_2 - \phi_1$ is such that $-\pi < \phi_2 - \phi_1 < \pi$, then the value N_2 of the current point is able to be found immediately from that of the first point. It is then possible to propagate the value of the integer number of cycles step by
 15 step. In practice, work is done on an image, and therefore an observed point has up to eight neighbors, thereby making it possible to constrain the phase unwrapping with various approaches such as Markov fields or graph theory.

Moreover, it is possible to use multiple interferometric bases to determine the number of cycles. K receive antennas superimposed on one another are thus used, K being greater
 20 than the number 2 shown in figure 1. There are then $K-1$ phase measurements. The diversity of the measurements provides a system of equations that makes it possible to constrain the numbers of unknown cycles and to provide hypotheses that make it possible to eliminate outliers. The phase unwrapping process is essentially reproduced $K-1$ times, retaining solutions that are simultaneously correct for the $K-1$ equations thus obtained.

25 It is also possible to use frequency diversity. If it is possible, even for a base of $K=2$ receivers, as in figure 1, to have multiple different phase measurements (for L different wavelengths λ_1 to λ_L), L phase hypotheses are also obtained, making it possible to constrain the phase unwrapping. This phase diversity is achieved by rapidly transmitting a wideband signal. It is sought to adopt coprime values of λ_1 and λ_2 (one is not close to an

integer multiple of the other), so that the minimum distance at which the phases are identical is as great as possible – this is then the product $\lambda_1 \times \lambda_2$. The Vernier principle (Vernier phase unwrapping) is then reproduced.

One limitation of the phase unwrapping method is that it is important to correctly initialize the method with a correct value. It is also necessary for the phase variations to be spatially slow enough, compared to the spatial sampling step, so that the phase unwrapping is able to be carried out correctly (the spatial sampling step must be smaller than the wavelength). Finally, the phase must not be too noisy.

These hypotheses are not necessarily achieved, in particular when the observation is close to the nadir, namely for $\gamma = 90^\circ$, and in a region where the angle γ is from approximately 45° to 90° . For these reasons, the determination of the angle γ is not robust in these regions.

[Fig. 1B] Figure 1B, the lower part of which constitutes a vertical section, shows elements in relation to a single antenna 1E carried by a vehicle V (seen from the back in the figure).

The antenna 1E is considered to be a transmit antenna, knowing that a receive antenna is placed, or multiple receive antennas are placed, in the immediate vicinity of the antenna 1E, for example on either side thereof – they are considered to be localized. The set of antennas transmits and receives with a wide angular aperture, but the angular gain pattern is not constant, which will be exploited. The ocean floor 4 reflects the transmitted waves and the trip times make it possible to determine the distances r . The sonar therefore has reflected signal intensity values as a function of distance values r .

The upper part of figure 1B depicts the curve showing the measured amplitude A of the reflected signal, received on a beam, as a function of distance r . The lower part of the figure shows alternating floor profiles 4A, 4B, 4C, 4D, in dashed lines, that have to be excluded in order to identify the true ocean floor 4, shown for its part as a solid line. The angle γ is estimated by counting the fringes in the image received by the sonar. It defines the direction of a minimum of the antenna pattern with respect to the horizontal, for example. In the curve in the upper part, the measured amplitude A has minima, corresponding to the dark fringes of the image (low intensity, at least before the image is processed), and to the minima of the antenna angular pattern, which will be exploited. By identifying, in this measured amplitude curve, a value A_0 that is a (local, or possibly global) minimum of A , which is observed for a range r_0 , this is used as a basis for deducing the distance between the sonar and the true ocean floor 4, and therefore the altitude (depth)

of the floor in the direction of the angle γ that corresponds to the local gain minimum in the angular gain pattern. Since the angle γ is thus determined, the depth is easily calculated by calculating the height difference $\Delta h = r_0 \cdot \sin \gamma$.

Conversely, the alternating floors 4A, 4B, 4C, 4D give range values r_A , r_B , r_C and r_D that are expressed, on the amplitude curve A, by high values corresponding to bright areas of the image. They are spaced apart.

[Fig. 2A] Figure 2A, which again is a vertical section, shows elements in relation to a single antenna 1E, which is considered to be a transmit antenna, knowing that a receive antenna is placed, or multiple receive antennas are placed, in the immediate vicinity of the antenna 1E, for example on either side thereof. The gain pattern shown in the figure corresponds to the sum (in dB) of the transmission and reception pattern. However, in one embodiment, it is the transmit antenna, by design, that creates a large number of lobes; the receive antenna creates fewer thereof.

To simplify matters, the figure shows a transmit antenna that is not curved in the vertical plane, that is to say is flat, with a transmission pattern typically in the shape of a cardinal sine. In one embodiment, the shape may be arbitrarily different in order to increase the number of lobes.

$G_e(\theta)$ denotes the gain of the transmit antenna (in decibels, dB) and $G_r(\theta')$ denotes the gain of the receive antenna (again in dB), with θ the elevation angle with respect to the main axis 6 of the antenna 1E and with θ' the elevation angle with respect to the main axis 6 of the receive antenna; considering that $\theta \approx \theta'$, the angle θ' is then omitted from figure 2A: to simplify matters, the total gain (in dB) may be considered as follows:

$$G(\theta) = G_e(\theta) + G_r(\theta)$$

The geometry of the transmit and receive antennas is such that the function $G(\theta)$ has a maximum at $\theta = 0$, in the main lobe 7 of the antenna with aperture $\Delta\theta$, and secondary maxima 8 generally distributed at progressively decreasing intervals on either side of the main lobe in sidelobes. The lobes are apex angles of the antenna 1E, in which gain increases steadily toward a maximum, and then globally decreases steadily (in fact, there are fluctuations) from this maximum, the graphical representation of the gain from the apex of the angle as a function of the angular position graphically forming a lobe.

Three lobes are visible in the figure, on either side of the main lobe, but there may be more, or even many more. Between the lobes, there are regions 9 where the gain tends toward

$-\infty$ (in dB) at $\pm \frac{k\Delta\theta}{2}$, $k \in \mathbb{N}$. The points 10 and 11 of the seabed shown in the figure are respectively in the direction $\theta + \frac{\Delta\theta}{2}$ (first inter-lobe toward the seabed) and $\theta + \frac{3\Delta\theta}{2}$ (second inter-lobe toward the seabed). They will be commented upon later. It is possible for the 3rd inter-lobe toward the seabed to be beyond the nadir but, depending on the angle α , which is the inclination of the antenna with respect to the vertical axis 5 or the horizontal axis (which is equal to the roll give or take an additive constant and is shown in two different arbitrary ways in figure 2), it may, like the following inter-lobes, but a limited number thereof, be before the nadir.

The sonar image is the function f that associates, with a measured distance r and with an abscissa x of the sonar along its trajectory, an acoustic intensity I in dB corresponding to all signals reflected by targets at a distance r from the sonar. The function f is therefore $\mathbb{R}^2 \mapsto \mathbb{R}$ - that is to say it associates a single real value with two real values.

Under a generally well-verified hypothesis that, for a given abscissa x and range r , there is only one target 3 that has an index - ratio expressed in decibels of returned energy to incident energy (target strength) - that is significant compared to the others, then it is possible to associate (x, y, r) with a single value of θ , the elevation angle of the target.

The measured intensity is then given in decibels by the sonar equation in the form:

$$I(x, r) = P + G(\theta) - 40 \log_{10} r + S(x, r, \theta) + K$$

with:

P the constant, known transmission power (however, the value is not necessary for the calculations explained here);

$G(\theta)$ the total (transmission and reception) gain, assumed to be known give or take an additive factor that does not depend on θ ;

$40 \log_{10} r$ the calculable term signifying dilution of power by distance, taking into account geometric losses on the outward path and return path of the wave under the hypothesis of constant speed in the medium, knowing r ;

$S(x, r, \theta)$ the index of the target (unknown);

K represents various gain terms (processing gains, etc.).

[Fig. 2B] Figure 2B shows a transmit antenna pattern $G_e(\theta)$, which is a gain curve (logarithmic scale, as a function of elevation angle θ , typical for a curved antenna

(described later in figures 6 and 7). For $\theta = 0^\circ$, the gain is zero, and is therefore equal to 0 dB, whereas, for positive or negative angles θ , the gain becomes negative, and experiences fluctuations. There are amplitude fluctuations of 3 to 5 dB, as shown in figure 2B for example, for an area with positive elevation angles, in which the gain passes through a local minimum and then through a local maximum higher than said local minimum by a gain denoted Δ , of the order of 3 to 5 dB. In the example shown, the gain then decreases while the elevation angle increases, but then experiences larger fluctuations, which may be from 10 to 15 dB. The pattern shown is given purely by way of illustration, and other patterns are possible. One effect of the curvature of the transmit antenna is specifically that of creating fluctuations that are as small as a few decibels. These fluctuations, although small, are exploited in some embodiments by the invention, since they are visible in the image over numerous consecutive transmissions, and it is therefore possible to identify them and exploit them through a time integration effect. Local minima of the gain pattern are therefore used. These local minima may be compensated for in a posteriori processing for imaging purposes but, before such compensation, they are used to carry out bathymetry calculations according to the invention.

[Fig. 3] With reference to figure 3, a discussion is given of an image formed by the sonar during its trajectory, considered to be rectilinear, along the x-axis, with r being the range on the abscissa and x being the trajectory on the ordinate in the figure. The grayscale level of the image at a point is, as indicated above, the acoustic intensity I in dB corresponding to the signals reflected by targets at a distance r from the sonar, light grays being associated with high intensities, and dark grays being associated with low intensities. In the left-hand part of the figure, for small ranges, less than the shortest distance between the antenna system and the reflective surface, the intensity is low, in the absence of any reflective surface for the range values in question. Then, moving toward higher range values, a specular reflection is observed, corresponding to the surface of the underwater floor at the nadir. For range values increasing from this first value, the observed floor consists of the areas crossed by a movement from the floor to the nadir, in a direction perpendicular to the axis of movement of the vehicle or at least in the viewing direction of the antenna system, which is generally perpendicular to the movement.

Under one of the following two hypotheses: i) that the amplitude of the variations in the total gain $G(\theta)$ with θ is large compared to that of the index of the observed elements $S(x, r, \theta)$, or ii) that the spatial extent of large variations in index $S(x, r, \theta)$ is small compared to that of the variations in $G(\theta)$, it may be considered that the measured intensity is written:

$$I(x, r) \approx G(\theta) + K'(r), \text{ with } K' \text{ a term almost solely dependent on } r.$$

This approximation is particularly true in the vicinity of the nadir (on the left in the figure). Its implication is that the sonar image has dark fringes 20, 21 (and so on, even though it is possible that only two inter-lobes are present before the nadir, in which case there are only two dark fringes), where $G(\theta)$ is low, and that these dark fringes alternate with bright fringes 23 and so on, where $G(\theta)$ is high. In the example in figures 2 and 3, the points 10 and 11 are, as mentioned above, in the direction $\theta + \frac{\Delta\theta}{2}$ (first inter-lobe) and $\theta + \frac{3\Delta\theta}{2}$ (second inter-lobe), respectively, and their sonar images 100 and 110 are black, this thus expressing a very low received power. Conversely, the point 3 is close to the direction of the main lobe, and its image 30 therefore appears in a well-illuminated region.

There is a link between the angle θ , the angle γ and the height difference between the antenna 1E and the target 3. Specifically, since the roll angle α is measured by an attitude measuring unit, it is equivalent to determine the elevation angle θ and to determine the angle γ , because $\gamma = \alpha + \theta$ (this may be seen clearly in figure 2). Also:

$$\sin(\gamma) = \frac{H - h}{r} = \frac{\Delta z}{r}$$

If r , θ and α are known, then the relationship $\Delta z = H - h = r \cdot \cos(\alpha - \theta)$ expresses the height difference between the antenna 1E and the target 3.

If it is known, for a given range r , what the elevation angle θ is, this is used as a basis for deducing the height difference $H - h$. However, spatially, the alternations of dark fringes 20, 21 and so on and bright fringes 23 and so on are highly visible and may be sought by varying x , therefore by scanning the sonar image. It is possible to ascertain the dark fringe 20, 21 and so on to which an angle θ corresponding to a region 9 where the antenna gain is low corresponds. It is therefore possible to deduce the altitude difference $H - h$.

[Fig. 4] With reference to figure 4, which shows the trend of the gain function (in dB) (the range r in meters on the abscissa, from 0 to 150 m in the figure, and the gain from -150 dB to -60 dB on the ordinate) for two different heights $H = 15$ m and $H = 20$ m (therefore offset by 5 m from one another), the invention begins with detecting, in the image, dark fringes 20, 21 and so on corresponding to the inter-lobe spaces 90 (the zeros of the antenna, or antenna nulls), or to a local minimum of the antenna pattern. It should be noted that the antenna may have a rectangular aperture or be a curved antenna. The figure shows the case of a flat, non-curved antenna with a transmission pattern typically in the shape of a cardinal sine.

This detection may be carried out at various stages of the sonar data processing, for example by using the gain calculated in the automatic gain control stage, or else in the beamforming image, or else a combination of both. This step makes it possible to provide, for each given position x of the sonar along its trajectory, corresponding to a transmission number (ping number) n , a collection of p ranges $r_{n,k}$, $1 \leq k \leq p$ where p is the number of dark fringes detected – figure 4 shows a case with $p = 5$ fringes.

This determination of ranges is followed by a labeling process using the angles of the inter-lobe spaces or local minima. For this purpose, for example, the process starts by identifying the position of the main lobe in the image, identifying the associated maximum 50 in the gain pattern, and then assigning the angle $\theta_{n,1} = \theta_0 + \frac{\Delta\theta}{2}$ to the minimum 200 closest to the maximum 50, the angle $\theta_{n,2} = \theta_0 + \frac{2\Delta\theta}{2}$ to the second minimum 210 closest to the maximum 50, and so on, so that the k th inter-lobe space starting from the main lobe and going toward the low ranges is assigned to the angle $\theta_{n,k} = \theta_0 + \frac{k\Delta\theta}{2}$.

The algorithm for determining the local minima followed by the assignment of the angles therefore provides an estimate of p range-elevation pairs, for example $(r_{n,k}, \theta_{n,k} = \theta_0 + \frac{k\Delta\theta}{2})$, $1 \leq k \leq p$. Since, for $r > H_n$ where H_n is the flight altitude of the sonar (height from the seabed to the nadir) as measured by a sounder at the transmission date of the transmission n , it is possible to link the distances r_k to the abscissas y_k of the point on the ground using the relationship:

$$y_{n,k} = \sqrt{r_{n,k}^2 - H_n^2}$$

there are therefore also abscissa-elevation angle pairs $(y_{n,k}, \theta_{n,k} = \theta_0 + \frac{k\Delta\theta}{2})$. Since, using the relationship already seen above, it is possible to find out a height difference:

$$\Delta z_{n,k} = r_{n,k} \cdot \sin(\alpha_n - \theta_{n,k})$$

where α_n gives the inclination of the sonar at the transmission n , there are therefore abscissa-height difference pairs $(y_{n,k}, \Delta z_{n,k})$.

Local maxima 51 and so on may also be identified for the sidelobes, and they are associated with the ranges $r'_{n,1}$ $r'_{n,2}$ and so on.

These pairs $(y_{n,k}, \Delta z_{n,k})$ may be filtered in order to incorporate an *a priori* provided by the

dynamics of the vehicle (values of H_n , α_n) or an *a priori* on the profile of the floor coming from another sensor, another implementation of the method presented to another data processing stage, *etc.*, in order to eliminate outliers.

This filtering step may employ existing conventional techniques such as optimal filtering, Kalman filtering, set membership filtering, or other techniques.

The process may finish by generating a height profile by interpolation (linear, spline or the like) of the measurement points thus obtained, for $0 \leq y \leq y_{n,1}$:

$$\Delta z(n, y) = \text{interpolation}(y, \{(0, H_n); (y_{n,p}, \Delta z_{n,p}), (y_{n,p-1}, \Delta z_{n,p-1}); \dots; (y_{n,1}, \Delta z_{n,1})\})$$

It is likewise possible to obtain a map of the angles γ , this constituting a central element of the objectives of the invention:

$$\gamma(n, y) = \arccos \frac{\Delta z(n, y)}{\sqrt{H_n^2 + y^2}}$$

As an alternative, it is possible to provide the raw points $\{(0, H_n); (y_{n,p}, \Delta z_{n,p}), (y_{n,p-1}, \Delta z_{n,p-1}); \dots; (y_{n,1}, \Delta z_{n,1})\}$ as references able to be used to initialize a conventional phase unwrapping algorithm, which, unlike interpolation, supplements the missing data with real measurements.

As an alternative and ideally, it is possible to hybridize these two approaches: interpolation and phase unwrapping constrained by measurements on the fringes.

[Fig. 5] Figure 5, which shows a typical block diagram of two approaches for determining the profile $\Delta z(n, y)$, is now used as a reference for presenting multiple approaches that may be implemented autonomously or complementarily, and that are described below. In a successful implementation, these approaches are implemented sequentially in order to increase the performance of the method, but it is possible to use one without the other.

A first approach, or a first stage, consists in working on data derived from automatic gain control on the raw sensor signals, after remote pulse compression but before natural or synthetic antenna beamforming. This automatic gain control equalizes the received intensities in order to incorporate them into the dynamics of the data storage file and also facilitates the visualization of the data by the operator. Automatic gain control aims to completely eliminate local variations in intensity in the image due to the effects of antenna gain and distance attenuation.

One typical but non-limiting conventional implementation of gain control is as follows, and

is shown in figure 5. The implementation details are not essential. Let N_c be the number of sensors of the receive antenna and $I(i, n, r)$ be the intensity received at transmission n for the distance r for the i th sensor of the antenna ($1 \leq i \leq N_c$). Let $\bar{I}$ be the average intensity – the signal 410 – received at the distance r for all sensors:

$$\bar{I}(n, r) = \frac{\sum_{1 \leq i \leq N_c} \alpha_i I(i, n, r)}{\sum_{1 \leq i \leq N_c} \alpha_i}$$

with α_i a parameter (a real value close to 1) used to correct any inter-sensor calibration faults in terms of intensity. It is then possible to estimate a function $f(n, r)$ obtained by convolution on the distance axis of $\bar{I}(n, r)$ with a typically rectangular impulse response function $B(r, H_n)$ the typical length $l(r)$ of which on the distance axis may (or may not) vary as a function of r according to the constraints specific to the field of application of the sonar (in particular the flight altitude H_n of the sonar at the n –th transmission), in order to carry out low-pass filtering 420 (low-pass filtering on the distance axis r), the result of this filtering 420 being $f(n, r)$:

$$f(n, r) = \bar{I}(n, r) \star B(r, H)$$

The exact implementation of this filter $B(r, H)$ is not essential, but it is desirable for the spatial medium of this filter to smooth variations in typical spatial length, which are small compared to those of the fringes (the inter-lobe width, estimated approximately) of the transmit-receive antenna lobes. From $f(n, r)$, it is also possible to estimate a second function $g(n, r)$ – after the filtering 420, this is second filtering 430, namely low-pass filtering $g(n, r)$ carried out on the axis of the transmission numbers, at transmission n ; one non-limiting approach is for example based on recursive first-order filtering of the type:

$$g(1, r) = f(1, r)$$

$$g(n, r) = (1 - \beta)g(n - 1, r) + \beta f(n, r)$$

with β a parameter between 0 and 1. The multiplicative gain applied to the data from the sensor i is then $\alpha_i/g(n, r)$ for the values $r > H$ (and 1, for the values $r \leq H$), bringing (on average) the observed values to around 1 for sonar distances greater than the altitude, and therefore where the ocean floor is imaged. Regardless of the low-pass filter used, its design criterion is that the impulse response of the filter must have the longest possible medium, while being small compared to the minimum spatial period L of variation of the position of the fringes (20, 21) on the axis of movement x of the vehicle. The value of L is taken empirically as a hypothesis. The digital implementation of the filter therefore involves

the instantaneous speed of the vehicle, measured elsewhere, and also Δt the pulse repetition period. In the particular case of a recursive first-order low-pass filter-based implementation, $\beta = \exp(-V\Delta t/L)$.

It has been seen above that, under one of the following two hypotheses: i) that the amplitude of the variations in the total gain $G(\theta)$ with θ is large compared to that of the index of the observed elements $S(x, r, \theta)$, or ii) that the spatial extent of large variations in index $S(x, r, \theta)$ is small compared to that of the variations in $G(\theta)$, it may be considered that:

$$\bar{I}(n, r) \approx G(\theta) + K'(r)$$

By design, the function $g(n, r)$ has the following properties: it eliminates (through the low-pass effect) large variations in $S(x, r, \theta)$ of small size compared to the spatial extent of $G(\theta)$ and it carries out local integration of the image on the cross-range axis; in other words, it increases the signal-to-noise ratio of the image of $G(\theta)$ with respect to that of $S(x, r, \theta)$. Although hypotheses i) and ii) are not always true for $\bar{I}(n, r)$, they are on the other hand much more often true for $g(n, r)$:

$$g(n, r) \approx G(\theta) + K'(r)$$

This image $g(n, r)$ is then a good approximation of $G(\theta) + K'(r)$, and takes the form of a function whose logarithmic representation has numerous notches 90 (visible in figure 4) where the gain tends toward $-\infty$ in ranges falling in the inter-lobe areas 9 where the antenna gain is very low. The trend of this function is illustrated in figure 4 by taking arbitrary values $\alpha = 15^\circ$ (typical but non-limiting value of the sum of roll, generally almost zero, and of the antenna tilt angle toward the seabed) and $\Delta\theta = 10^\circ$ (typical non-limiting values of the aperture of the main lobe). The figure also illustrates the fact that the distance r at which the minima 200, 210 are located depends on the topography of the floor: specifically, in the case illustrated here, the floor is assumed to be perfectly flat, at 15 and 20 meters from the sonar, respectively, and the notches 90 are offset toward small ranges if the floor is closer.

Using a determination algorithm 440 to determine local maxima and minima (determination of the range of local minima and maxima of $g(n, r)$), it is possible to determine, at transmission n , the range $r_{n,k}$ of the minima 200, 210 corresponding to the points 100, 110 located at the centers of the inter-lobe spaces, and also the range $r'_{n,k}$ of the maxima 220, 230 corresponding to the points located at the changes of sign of the derivative of the intensities, lobe by lobe. This determination algorithm 440 constitutes a search in the

measured ranges (r) for at least one gain extremum.

This determination of the ranges $r_{n,k}$ is followed by a labeling process 450 using the angles corresponding to the local minima and maxima of the radiation pattern, in particular labeling of the ranges $r_{n,k}$ using the angles of the inter-lobe spaces $\theta_{n,k}$. This involves
 5 identifying or associating measured intensity local extrema (for example A_0 in figure 1B) with local extrema of the angular gain profile.

For this purpose, the main lobe, corresponding to the maximum 50 of the gain function $g(n, r)$, is first identified. Assuming for example that the inter-lobe spaces are equidistant by a value $\Delta\theta$, the angle $\theta_{n,1} = \theta_0 + \frac{\Delta\theta}{2}$ is assigned to the minimum 200 closest to the
 10 maximum 50, the angle $\theta_{n,2} = \theta_0 + \frac{3\Delta\theta}{2}$ is assigned to the second minimum 210 closest to the maximum 50, and so on, such that the k th inter-lobe space starting from the main lobe and going toward the low ranges is assigned to the angle $\theta_{n,k} = \theta_0 + \left(k - \frac{1}{2}\right)\Delta\theta$. The same is done with the local maxima, by assigning the angle $\theta'_{n,0} = \theta_0$ to the first maximum 50, the angle $\theta_{n,1} = \theta_0 + \Delta\theta$ to the second maximum 51, and so on, such that the k th inter-lobe space starting from the main lobe and going toward the low ranges is assigned to the
 15 angle $\theta_{n,k}' = \theta_0 + k\Delta\theta$. If the inter-lobe spaces are not equidistant or approximately equidistant by a value $\Delta\theta$, the calculation is carried out by taking the known exact values tabulated beforehand.

For a less regular profile, such as the one shown in figure 2B, it is easy to recognize the
 20 local minima and maxima by proceeding in order and searching for them one after another.

The process of determining the local minima and maxima followed by the assignment of the angles, which constitutes steps 440 and 450 in figure 5, therefore provides an estimate of $2p$ range-elevation angle pairs, for example $(r_{n,k}, \theta_{n,k} = \theta_0 + \left(k + \frac{1}{2}\right)\Delta\theta)$, $1 \leq k \leq p$ and $(r_{n,k}, \theta_{n,k}' = \theta_0 + k\Delta\theta)$, $0 \leq k \leq p - 1$. Since, for $r > H_n$ where H_n is the flight altitude
 25 (reference 452 in figure 5, also visible in figure 2) of the sonar (height to the nadir) provided as datum to the algorithm, measured either by a sounder or by the sonar itself at the transmission date of transmission n , it is possible to link the distances r_k to the abscissas y_k of the point on the ground using the relationship:

$$y_{n,k} = \sqrt{r_{n,k}^2 - H_n^2}$$

there are therefore also the abscissa-elevation angle pairs, for example $(y_{n,k}, \theta_{n,k} = \theta_0 + \frac{k\Delta\theta}{2})$. Since, using the relationship already seen above, it is possible to find out a height difference using the roll information α_n (reference 451 in figure 5, the roll angle being an element of the attitude of the vehicle and the inclination angle α of the receiver being also visible in figure 2), according to the expression

$$\Delta z_{n,k} = r_{n,k} \cdot \sin(\alpha_n - \theta_{n,k})$$

where α_n gives the inclination of the sonar at transmission n , it is ultimately possible to carry out a calculation 460 of the abscissa-height difference pairs, or elevation abscissa $(y_{n,k}, \Delta z_{n,k})$. This involves a localization, with respect to the vehicle, of the points of the image corresponding to the local intensity extrema (such as A_0).

A linear, spline or other type of interpolation 470 is carried out on the measurement points 460 thus obtained:

$$\Delta z(n, y) = \text{interpolation} \left(y, \{(0, H_n); (y_{n,p}, \Delta z_{n,p}), (y_{n,p-1}, \Delta z_{n,p-1}); \dots; (y_{n,1}, \Delta z_{n,1})\} \right)$$

This involves an interpolation of the profile $\Delta z(y)$ from the points $y_{n,k}, \Delta z_{n,k}$. It is possible to finish by generating a height profile 480 $\Delta z(n, y)$. This output may be sufficient, depending on the applications, or be reused downstream.

This first approach involved working on raw data before beamforming or in the absence of beamforming.

In a second approach, a beamforming image (the image obtained after the beamforming process) is used. Depending on whether this beamforming image is calculated before or after applying gain control, the method is slightly different.

If the beamforming image is calculated before gain control, gain control is applied in accordance with a procedure similar to that described above in relation to the first approach, considering that $\bar{I}(n, r)$ here denotes the intensity observed at the range r for the n th beam formed. The generation of the height profile $\Delta z(n, y)$ follows the same procedure as described above in the first approach. This solution has the advantage that the spatial resolution on the movement axis x is greater than in the transmission-by-transmission work of the first approach, by a factor of typically up to 50 beams per transmission, or even more. Moreover, the raw data from the sensors have an effect of averaging the intensities received on the movement axis x , thereby making detection of the notches 90 robust.

If, on the other hand, the beamforming image is calculated after gain control, the determination of the position of the alternating dark and bright fringes in the image takes into account the fact that the gain control might have been parameterized so as to eliminate them in order to provide a good visual quality of the image and exploit small remaining residual intensity variations, with an amplitude of the order of ± 1 dB. It is possible to determine the position of the fringes in the image via various image processing techniques. Here, $\bar{I}(n, r)$ denotes the intensity measured on the beam n for the range r . These image processing methods are, for example and without limitation, the following approaches:

The application of a second automatic gain control stage similar to that described in the first approach, but parameterized so as to isolate dark and bright fringes well;

Or it is possible to use hidden Markov chain segmentation methods, considering that the intensity $\bar{I}(n, r)$ may be of two classes "pixel of a dark fringe" and "pixel of a bright fringe" the intensity distribution of which is known a priori, and the conditional probability of a pixel of a beam n being of a given class, given the class of pixels of the beam $n - 1$.

Once the local minima and maxima have been detected, the generation of the height profile $\Delta z(y)$ follows the same procedure as described above in the first approach.

The process may thus successively include the following processing of the received acoustic signal averaged for each transmission (ping) on all sensors or, if beamforming has taken place, for the signal of each beam of the sonar image after beamforming:

- i) low-pass filtering on the distance axis, configured to smooth variations smaller than the spatial spacing between the fringes;
- ii) the result of the previous low-pass filtering, passing through low-pass filtering on the ping axis recursively using the result of the same step, for the previous ping;
- iii) the result of the above two filtering operations, used as an approximate measure of the intersection of the radiation pattern with the ground, being subjected to the algorithm for determining the range of the local maxima and minima of said pattern;
- iv) the ranges estimated in the previous step, along with the a priori knowledge of the angles where the maxima and minima are located, making it possible to label a collection of pairs (range, elevation angles with respect to the main transmission axis);
- v) this collection of pairs (range, elevation angles with respect to the main transmission axis), associated with the measurement of the attitude of the vehicle at the current ping, in particular the roll, along with the altitude of the vehicle at the transmission

date of the current ping, making it possible to localize the points of the image, for example by finding a collection of pairs (reference ground abscissa, reference ground-vehicle height difference), where the ground abscissa is along the transverse axis of the vehicle, parallel to the ground;

- 5 vi) this collection of pairs (reference ground abscissa, reference ground-vehicle height difference) then serving as a support for an interpolation, for example of a "ground-vehicle height difference as a function of the ground abscissa" function.

It is also possible to combine the antenna lobe estimate explained here with interferometric measurements known elsewhere.

- 10 The profiles 480 of the first approach or of the second approach are used to initialize and constrain a phase unwrapping algorithm using interferometric measurements. For example, the algorithm may unwrap the phase by choosing, in the event of phase ambiguity, the altitude best corresponding to the one estimated in the profile 480. The estimate of the local elevation of the ground relative to the sonar or radar antenna obtained
15 based, as taught above, on the knowledge of the angular pattern of the antenna array may thus be used as a reference for an algorithm for estimating the local elevation of the ground by interferometry using phase unwrapping (Vernier method or its derivatives), by resolving phase ambiguities through the choice of the phase giving the elevation closest to that estimated by the method proposed here.

- 20 [Fig. 6] With reference to figure 6, which is a three-quarter view, and also to figure 7, which is a cross-sectional view, an optimized mechanical design of the transmit antenna makes it possible to forge the transmission pattern, and therefore the position of the antenna lobes may also be used.

- 25 [Fig. 7] The shape of the transmit antenna may influence the shape of the antenna lobes and the alternation of bright and dark fringes in the image.

It is possible to couple the use of the method for determining the position of fringes in the image with a deliberate design of the antenna in order to maximize the presence and visibility of these fringes.

- 30 If the antenna 300 is considered to be a three-dimensional shape resulting from extrusion, over a length L in the longitudinal axis, of a part 301, the surface of the part 301 must be optimized, in particular the side 302 of this surface, which, after extrusion, forms the transmission face 305.

The local radius of curvature 304 at a point 303 on the side 302 immediately influences the elevation angle transmission pattern of the antenna.

The antenna is then designed based on multi-criteria optimization in order to optimize the following factors:

- 5 - The position, width and amplitude of the main lobes and sidelobes
- The angular position of the inter-lobe local minima
- The local radii of curvature 304, which cannot drop below a minimum value depending on the antenna manufacturing process.

10 The shape of the transmit antenna is therefore, in these embodiments, subject to a multi-criteria optimization method in order to optimize its shape, essentially on the transverse plane, in order to optimize the position of the local minima and maxima on the basis of the following criteria: multiplicity of said minima and maxima, relative amplitude of the minima and maxima, radius of curvature of the transmission face of the antenna in the transverse plane.

15 In this embodiment, the main lobe is optimized so as to be as wide as possible in terms of elevation, with an overall uniform gain, but having slight variations of the order of a few decibels. These slight variations, denoted Δ in figure 2B, are artefacts of the antenna design during the multi-criteria optimization method, said artefacts advantageously being used for the invention. Specifically, these slight variations are too small to affect the link

20 budget in very harmful fashion (it is still possible to image a region on the ground with an energy budget sufficient to discern the scene therein), but these local variations in gain cause, in the image, the appearance of dark fringes that, compared to the invention, have the same effect as the alternation of the gain minima caused by sharp inter-lobe spaces (elements 90 in figure 4) where the gain tends toward minus infinity, as would be observed

25 with a flat antenna, where the elevation gain pattern is typically in the shape of a squared cardinal sine. Although the variation in gain is smaller (a few decibels rather than a few tens, which may be assimilated to an infinite variation), this variation is, crucially for the invention, sufficient to be detectable by one, the other or both image filtering approaches (blocks 420, 430 and 440 in figure 5), notably through the integration effect caused by low-

30 pass filtering on the ping axis (block 430).

The receive antenna may also be designed so as to optimize the shape of the antenna lobes for operation thereof within the scope of the invention but, in one advantageous embodiment, it is only the transmit antenna that is curved and that therefore causes the

most fluctuations in the transmission lobe. The receive antenna has a smoother gain in the working area and its effect is felt little but, in one variant, the receive antenna is also sized differently in order to amplify the effects.

5 The invention is applied to improving the robustness of the altimetry and bathymetry function of an underwater drone, for rapid environment assessment (REA) functions or for an application dedicated to bathymetry and mapping. It is also applied to the possibility of designing a lateral micro-antenna that gives, through a specific design of the transmit antenna, a low-cost function of determining local relief (without interferometry, or with low-resolution interferometry with small antennas), this function making it possible for example
10 to readjust the vehicle with respect to an altimetric map previously acquired and recorded in the vehicle (using a TERCOM method, TERCOM standing for *Terrain Contour Matching*). The use of unsophisticated sensors is beneficial for small mass-produced vehicles such as swarms of drones or else small vehicles expected to be lost, such as single-use drones or smart munitions.

15 The invention has been presented with a side scan sonar or a sideways-looking antenna on a moving vehicle, but it also applies to the case of a stationary antenna, with for example azimuthal beamforming.

The invention is then used by representing the sonar image at the fixed point as a B-scan representation: the horizontal axis is the distance axis and the vertical axis is the azimuthal
20 axis: $X=r$, $y=\text{azimuth}$. The y-axis is then called the azimuthal axis. The representation of the geometry of the side scan sonar is found.

In a B-scan representation, the operations remain the same, and the bathymetry of the floor is then determined by adapting the reprojection equations.

CLAIMS

1. A method for characterizing a reflective terrestrial or marine surface (4) imaged by collecting echoes of waves transmitted toward said reflective surface (4), the waves being transmitted and received using a set of transmit and receive antennas (1E and 1, 2), the set of antennas having a known angular gain profile in the vertical plane, intensities (410) as a function of ranges (r) between the set of antennas (1E, 1, 2) and the reflective surface (4) being measured by the set of antennas (1E, 1, 2) in order to create an image of the surface, the method being **characterized in that** it comprises searching (440) the measured intensities (410) for at least one local extremum (A_0) and, by identifying (450) said at least one local extremum (A_0) at a local extremum of said angular gain profile, localizing (460), with respect to the set of antennas, at least one point of the image corresponding to said measured intensity local extremum (A_0), said corresponding point of the image being localized by providing an elevation angle value or a height value.
2. The method for characterizing a reflective surface (4) as claimed in claim 1, characterized in that the set of antennas (1E) is carried on the side thereof by a moving vehicle (V), successive acquisitions being carried out by the set of antennas.
3. The method for characterizing a reflective surface (4) as claimed in either of the preceding claims, characterized in that the search (440) comprises searching for multiple intensity extrema, and the method comprises identifying them at multiple local extrema of the angular gain profile and creating (470) a relief map (480) of the reflective surface (4) by interpolation.
4. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that the search (440) for at least one extremum is carried out on intensities measured before beamforming but after gain control or on intensities measured after beamforming, the beamforming having been carried out before or after gain control.
5. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that the measured intensities are subjected to low-pass filtering (420), prior to said search (440), along the axis of said ranges, with a template that is variable or constant depending on the position in the image.
6. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that the set of antennas (1E, 1, 2) comprises, for reception, a synthetic antenna or a natural antenna.

7. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that said localization is used in a subsequent process of localizing the reflective surface (4) by interferometry, as a reference or to resolve ambiguities.

5 8. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that the waves are sonar acoustic waves, the reflective surface (4) comprising a seabed, or the waves are radar electromagnetic waves, the reflective surface (4) comprising a land surface.

10 9. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that the localization is carried out taking into account a current value (451) of the roll angle of the set of antennas, or a current value (452) of the altitude of the set of antennas, or both.

15 10. The method for characterizing a reflective surface (4) as claimed in one of the preceding claims, characterized in that the set of transmit and receive antennas (1E and 1, 2) has, in the elevation transmission pattern, a plurality of local minima and maxima with an amplitude large enough to enable said search (440), but small enough not to prevent the perception of objects (10) located in areas with a low gain level (20).