



- (51) **International Patent Classification:**
G01V 1/36 (2006.01) *G01V 1/38* (2006.01)
- (21) **International Application Number:**
PCT/IB2015/002485
- (22) **International Filing Date:**
16 December 2015 (16.12.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
62/102,654 13 January 2015 (13.01.2015) US
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- (81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

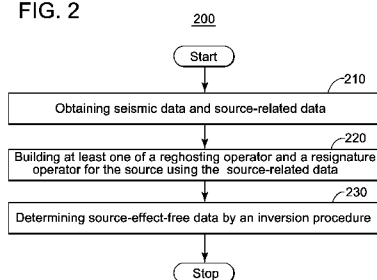
- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))

[Continued on next page]

(54) **Title:** SOURCE-SIDE DEGHOSTING AND DESIGNATURE METHOD FOR PROCESSING DATA ACQUIRED USING A MULTI-DIMENSIONAL SOURCE

(57) **Abstract:** A method for processing marine seismic data acquired with a multi-dimensional source performs deghosting and/or designature while taking into consideration the multi-dimensional geometry of the source. Source-effect-free data is determined by an inversion procedure, so that the seismic data to be substantially equal to the source- effects-free data to which a reghosting operator and/or a resignature operator built in view multi-dimensional geometry has/have been applied.

FIG. 2





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- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*
- *of inventorship (Rule 4.17(iv))*
- Published:**
- *with international search report (Art. 21(3))*

Source-side Deghosting and Designature Method for Processing Data Acquired Using a Multi-dimensional Source

CROSS REFERENCE TO RELATED APPLICATIONS

5 [0001] This application claims priority and benefit from U.S. Provisional Patent Application No.62/102,654, filed January 13, 2015, for "Joint 3D deghosting and designature for modern air-gun arrays," the content of which is incorporated in its entirety herein by reference.

10 **BACKGROUND**

TECHNICAL FIELD

[0002] Embodiments of the subject matter disclosed herein generally relate to seismic data processing or, more specifically, to an inversion method that performs deghosting and/or designature for marine seismic data acquired using a multi-
15 dimensional source (i.e., a source which is not properly approximated with a point-like source).

DISCUSSION OF THE BACKGROUND

[0003] Seismic surveys are used to acquire data, which are then processed to generate images of geophysical structures under the ground or the seafloor. These
20 images may be used to evaluate presence for oil and gas reservoirs.

[0004] In marine seismic surveys, a source that generates probing seismic excitations may include plural source element towed such as to maintain a predetermined arrangement. For example, a gun-array type of source may include 20
25 to 50 air-guns attached to air compressors on board a vessel via hoses. The air-guns are normally fired in a synchronized manner to output an excitation having generally an impulsive signature.

[0005] Figure 1 is a schematic illustration of source-side ghosts (i.e., reflections on the water surface) occurring in marine surveys. Two submerged individual marine sources, S1 and S2 (e.g., air-guns) are towed at different depths, emit energy at
30 substantially the same moment. The signals emitted by S1 and S2 travel through the water layer 105 between water surface 100 and seafloor 110, and then through rock

layers 115, 125, and possibly also an oil or gas reservoir 130. Reflections of the emitted signals are detected by receivers which may be carried by a towed streamer or placed on the seafloor.

[0006] The source-emitted energy may propagate isotropic or may be directed more toward one direction (e.g., seafloor 110). Portions of the energy emitted by S1 and by S2, respectively, travel directly toward the seafloor, for example, along paths 10, 20, 30 and 40. Other portions of the emitted energy propagate first to the water surface 100 (for example, along paths 11, 21, 31 and 41), where they are reflected toward seafloor 110. The water-surface reflected portions energy (e.g., propagating along paths 12, 22, 32 and 42) are known as “ghosts.” Far enough from the sources, the direct (or “primary”) signals and the ghost merge yielding excitation signals.

[0007] For example, the energy traveling along paths 10, 12, 30 and 32 merge to yield a first excitation signal 50 characterized by a first source signature. Similarly, the energy of traveling along paths 20, 22, 40 and 42 merge to yield a second signal 60 characterized by a second source signature. The first and second source signatures are different due to timing, phase and distance traveled by the direct energy and ghosts.

[0008] First signal 50 is partially reflected at the seafloor 110 yielding signal 52, at the interface 120 (between layers 115 and 125) yielding signal 54, at the top surface of reservoir 130 yielding signal 56, and at the bottom surface of reservoir 130 yielding signal 58. Reflections 52, 54, 56 and 58 are characterized by the same first signature as incident signal 50. Similarly, second signal 60 may be partially reflected at the seafloor 110 yielding signal 62, and at the interface 120 yielding signal 64, reflections 62 and 64 being characterized by the same second signature as second signal 60. Difference between the first signature and the second signature is larger if azimuth angle (in a horizontal plane between a towing/shot/reference direction and a line from the shot location to a detecting receiver) signal 50 is different from azimuth angle for signal 60. The detected signals (known as traces) carry information about the underground formation (e.g., thickness of layers 115 and 125, reservoir 130).

[0009] It has been established that the bandwidth of marine seismic data usable to extract information about the underground formation may be extended by removal of the receiver-side ghosts (not shown). To further maximize the bandwidth,

complementary efforts have been made to account for the source-side ghosts and signature-related effects. One conventional approach to remove the source-side ghost and/or signature has been to apply a single one-dimensional filter in a vertical take-off angle approximation (as described in articles “The signature of an air gun array: Computation from near-field measurements including interactions” by Ziolkowski et al., in *Geophysics* vol. 47, No. 10, pp. 1413-1421, and “Estimation of source array signatures” by Amundsen, in *Geophysics* vol. 58, No. 12, pp. 1865-1869).

[0010] Angle-dependent designation methods have been proposed since the 1980s (for example, in article “Angular-dependent signature deconvolution” by Van der Schans et al., published in *53rd SEG Annual International Meeting*, Expanded Abstracts, pp. 433-435, and article “Shot-to-shot directional designation using near-field hydrophone data” by Poole et al., published in *83rd SEG Annual International Meeting*, Expanded Abstracts, 4236-4240). Recently, receiver deghosting algorithms have been used to approximate source deghosting (as described in articles “Pressure wave-field deghosting for non-horizontal streamers” by Riyanti et al., published in *78th SEG Annual International Meeting*, Expanded Abstracts, pp. 2652-2656, “Premigration deghosting for marine streamer data using a bootstrap approach in $\tau - p$ domain” by Wang et al., published in *75th EAGE Conference & Exhibition*, Extended Abstracts, pp. 4221-4225, “3D joint deghost and crossline interpolation for marine single-component streamer data” by Wang et al., published in *84th SEG Annual International Meeting*, Expanded Abstracts, pp. 3594-3598, and the above-mentioned article by Poole et al.). These conventional methods often assume a single point source for source deghosting, which renders them less effective for increasingly complex air-gun array geometry, such as the multi-level air-gun array (described in “Synchronized multilevel source, a robust broadband marine solution” by Siliqi et al., published in *83rd SEG Annual International Meeting*, Expanded Abstracts).

[0011] The drawback of the conventional methods is that the source geometry in general and the angle-dependence (both azimuth angle and opening angle) in particular have not been taken into consideration in source deghosting and designation. Angle dependence becomes more and more significant (resulting in larger and larger differences) as the source geometry has evolved to multiple source arrays and multi-

level (depths) sources. Accordingly, it is desirable to develop data processing methods that overcome the above-identified drawbacks of conventional methods.

SUMMARY

5 **[0012]** In the context of continuing efforts to extend the bandwidth of marine seismic data, in some embodiments, the source ghost and signature effects are removed using an inversion that performs angle-dependent source deghosting and designature jointly or separately. The various embodiments take into consideration the increasingly multi-dimensional source's geometry. Tests performed on synthetic ocean
10 bottom node data and on a field streamer dataset acquired with a multi-level source proved that this approach yields source-effect-free data of a wider bandwidth than the conventional methods.

[0013] According to an embodiment, there is a method for processing marine seismic data acquired with a multi-dimensional source. The method includes obtaining
15 seismic data and source-related data, and building at least one of a reghosting operator and a resignature operator for the source using the source-related data. The reghosting operator and/or the resignature operator depend on a multi-dimensional geometry of the multi-dimensional source. The method further includes determining source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the
20 source-effects-free data to which the reghosting operator and/or the resignature operator has/have been applied. The source-effect-free data is usable to generate an image of a formation under the seafloor.

[0014] According to another embodiment, there is a data processing system configured to process marine seismic data acquired with a multi-dimensional source.
25 The data processing system includes an input/output interface configured to obtain the marine seismic data and source-related data, and a processor. The processor is configured to build at least one of a reghosting operator and a resignature operator for the source using the source-related data, the reghosting operator and/or the resignature operator depending on a multi-dimensional geometry of the source, and to determine
30 source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator

and/or the resignature operator has/have been applied. The source-effect-free data is usable to generate an image of a formation under the seafloor.

[0015] According to yet another embodiment, there is a computer-readable recording medium storing executable codes which when executed by a processor make the computer perform a method for processing marine seismic data acquired with a multi-dimensional source. The method includes obtaining seismic data and source-related data, and building at least one of a reghosting operator and a resignature operator for the source using the source-related data. The reghosting operator and/or the resignature operator depend on a multi-dimensional geometry of the multi-dimensional source. The method further includes determining source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator and/or the resignature operator has/have been applied. The source-effect-free data is usable to generate an image of a formation under the seafloor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate one or more embodiments and, together with the description, explain these embodiments. In the drawings:

[0017] Figure 1 illustrates source related primaries and ghosts;

[0018] Figure 2 is a flowchart of a method according to an embodiment;

[0019] Figure 3 is a schematic two dimensional illustration of an air-gun source;

[0020] Figure 4 is an illustration of the data-acquisition geometry related to synthetic data;

[0021] Figure 5 illustrates notionals of the air-guns in Figure 2;

[0022] Figure 6 illustrates traces corresponding to different azimuth angles generated as synthetic data;

[0023] Figure 7 illustrates the traces in Figure 5 after applying a joint deghosting and designature method according to an embodiment;

[0024] Figures 8-11 are graphs illustrating the traces' frequency content at different azimuth angles, before and after applying the joint deghosting and designation method according to an embodiment;

[0025] Figures 12-16 are related to real data acquired with a source at 6 m and another source at 9 m generating the excitation incident to the explored underground structure, primaries and ghosts corresponding to each of the sources, respectively, obtained upon applying a joint deghosting and designation method according to an embodiment;

[0026] Figure 17 is a spectra illustrating the frequency content of the raw real data and of the primaries obtained upon applying the joint deghosting and designation method according to an embodiment; and

[0027] Figure 18 is a computing system configured to perform joint deghosting and/or designation methods, according to an embodiment.

DETAILED DESCRIPTION

[0028] The following description of the exemplary embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. The following embodiments are discussed, for simplicity, with regard to marine seismic data processing. However, similar embodiments and methods may be used for land data processing or for processing data acquired during a survey using electromagnetic waves as a probing tool.

[0029] Reference throughout the specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

[0030] Figure 2 is a flowchart of a method 200 for processing marine seismic data acquired with a multi-dimensional source. Method 200 includes obtaining seismic data and source-related data, at 210, and building at least one of a reghosting operator and a resigature operator for the multi-dimensional source using the source-related data at 220. The reghosting operator and/or the resigature operator depend on a multi-dimensional geometry of the source. The source-related data may include information indicating source elements' positions (relative to one another and/or to a reference point, so their location can be inferred for the activation time), activation times and amounts of emitted energy. An emission of a source element is characterized by a notional signature, and at least two among the source elements have distinct locations at an activation time (i.e., the two source elements cannot be considered operating as a single point source). For example, the two source elements may be located at different depths.

[0031] Method 200 further includes, at 230, determining source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator and/or the resigature operator has/have been applied. The source-effect-free data is then used to generate an image of a formation under the seafloor. As previously mentioned both or only one of the reghosting operator and the resigature operator may be built and used in the inversion procedure.

[0032] Article "3D joint deghost and crossline interpolation for marine single-component streamer data" by Wang et al. (complete reference already provided in this document) sets forth a sparse 3D $\tau - p$ inversion to obtain ghost-free data, U , which when reghosted and inverse $\tau - p$ transformed equals the input data, D :

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) R(f; z_0^i; p_x^j, p_y^j) U(f; p_x^j, p_y^j), \quad (1)$$

where L is the reverse $\tau - p$ transform operator, R is the reghosting operator, (x_0^i, y_0^i, z_0^i) is the average air-gun array location, and (p_x^j, p_y^j) is the slowness pair (i : trace index; j : slowness index). As already noted, most (if not all) conventional deghosting methods assume a single point source.

[0033] In order to take into consideration the complex geometry of the sources, operator R in equation (1) is replaced with operator G :

$$G(f; x_0^i, y_0^i, z_0^i; p_x^j, p_y^j) = \sum_k A_k R_k^{ij}(f; z_k^i; p_x^j, p_y^j) S_k^{ij}(f; x_k^i, y_k^i, z_k^i; p_x^j, p_y^j) \quad (2)$$

where A_k is amplitude of the k^{th} source element's notional, which is used to calculate the source's signature, R_k^{ij} is a reghosting operator, S_k^{ij} is a resigature operator, and (x_k^i, y_k^i, z_k^i) represents the location of the k^{th} source element. The notional of a source element is a representation of the source element's contribution to the source emitted signal. A multi-element source's (far-field) signature is a superposition of the notionals of the source elements. In other words, the notional is a tool for representing the contribution of individual source elements to the source's signature, such that an individual source element's contribution is decoupled from contributions of other source elements of the source.

[0034] The reghosting operator, R_k^{ij} , and resigature operator, S_k^{ij} , may be expressed as

$$R_k^{ij} = e^{-i2\pi f z_k^i \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2}} - e^{i2\pi f z_k^i \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2}} \quad (3)$$

$$S_k^{ij} = S_k^0(f) e^{-i2\pi f \left[t_k^0 + (x_k^i - x_0^i) p_x + (y_k^i - y_0^i) p_y + (z_k^i - z_0^i) \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2} \right]} \quad (4)$$

where v is the wave propagation velocity in water (also known as "water velocity"), S_k^0 is the notional for the k^{th} source element (which can be obtained from near-field hydrophone measurements as described in the articles by Ziolkowski et al. and Poole et al. mentioned above), and t_k^0 is the delay-time used to synchronize individual notionals (as described in article by Siliqi et al., which has also been previously mentioned).

[0035] In one embodiment, ghost and signature-free data, U , is obtained by solving the following equation

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) (\sum_k A_k R_k^{ij} S_k^{ij}) U(f; p_x^j, p_y^j). \quad (5)$$

Equation 5 has been obtained by replacing R in equation 1 with G . In various embodiments, reghosting operator R_k^{ij} and/or resigature operator S_k^{ij} are replaced in equation 5 using formula 3 and 4.

[0036] Some embodiments perform only source deghosting (i.e., the resigature operator in equation 5 is the identity operator) to obtain ghost-free data by solving the following equation

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) (\sum_k A_k R_k^{ij}) U(f; p_x^j, p_y^j). \quad (6)$$

5 **[0037]** Some other embodiments perform only source designation (i.e., the deghosting operator in equation 5 is the identity operator) to obtain signature-free data by solving the following equation

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) (\sum_k A_k S_k^{ij}) U(f; p_x^j, p_y^j). \quad (7)$$

[0038] The above-described joint source deghosting and designation methods
10 have been tested on a synthetic ocean bottom node (OBN) data set. Figure 3 illustrates an air-gun source 300 used to generate this data set, source 300 including 32 individual air-guns (301-332) arranged along lines 340, 350 and 360. Air-gun source 300 may cover an area of about 15 x 16 m. Each air-gun contribution (notional) to the source's signature has been calculated based on near-field hydrophone measurements acquired
15 during a real survey.

[0039] Considering now Figure 4, the OBN nodes such as 410 are at 500 m depth, and the synthetic data corresponds to a surface distance between the source (placed around circle 400 pointing parallel to the reference direction) and OBN node 410 of 1000 m. Some azimuth angle values are marked in Figure 4, the source
20 signatures and source ghosts being directional (i.e., depending on the azimuth angle defined relative to the reference direction as illustrated in Figure 4.

[0040] Figure 5 illustrates the notional 501 to 532 (amplitude as a function of time, represented along the vertical axis) for the air-guns 301-332 in Figure 3.

[0041] Figure 6 illustrates traces for source activation locations on circle 400 in
25 Figure 4, before applying joint deghosting and designation. The activation locations are at 10° azimuth angle difference from a trace to the next, between 0° to 360° azimuth. In Figure 6, wavelets (the largest bumps along traces, which correspond to a reflector) are sharper at 0°/180° azimuth than that at 90°/270° azimuth. Looking now at the frequency content of detected signals, there is more high-frequency amplitude loss at 90°/270° azimuth than at 0°/180° azimuth. This directional wavelet variation has been observed
30 also in real-world OBN data sets.

[0042] Figure 7 illustrates the same traces as in Figure 6, but after applying a joint deghosting and designation method according to an embodiment. The ghost and signature effects are now effectively removed, and the azimuthal wavelet variation has been normalized.

5 **[0043]** Figures 8-11 are spectra (i.e., amplitude versus frequency graphs) illustrating the frequency content of the traces before (the continuous lines) and after (the dashed lines) applying the joint source deghosting and designation, for azimuth angles of 0°, 90°, 180°, and 270°, respectively. The frequency depletion at the low-frequency end of the spectra before applying the joint source deghosting and
10 designation is caused by source ghosts, and the lower levels of high-frequency in the raw spectra are due to the air-gun array directivity.

[0044] After applying the joint source deghosting and designation (dashed lines in Figure 8-11), the low-frequency depletion and the high-frequency level drops are compensated at all azimuth angles. This type of frequency level uniformity facilitates
15 4D time-lapsed processing (i.e., simultaneous processing of data acquired during different surveys).

[0045] The deghosting and designation method has also been tested on multi-level source streamer data (i.e., data acquired with variable-depth streamers towed at depths from 8 m to 50 m) and an air-gun source with 21 source elements positioned at
20 different depths of 6 m and 9 m. The 9 m sources fired 2 ms after the 6 m sources, so that the source-side down-going wavefield (primary) of the deeper sources was synchronized with the source-side down-going wavefield of the shallower sources (by zero-angle approximation). Meanwhile, the source-side up-going wavefield (source ghost) did not coincide with one another. Figures 12-17 are related to this real data
25 set.

[0046] Figure 12 illustrates the input data as acquired, which is schematically suggested in the left upper corner. Input data includes direct signals 1210 (i.e., known as “primaries”), and source-side ghosts 1220 and 1230, respectively. The primaries are source-effect-free data which may be obtained using a joint deghosting and designation
30 method according to an embodiment.

[0047] The amplitudes of the primaries (1310 and 1410 that are illustrated for the 9 m depth source and for the 6 m depth source in Figures 13 and 14, respectively) are higher than the amplitudes of the ghosts (1220 and 1230 that are illustrated for the 9 m depth source and for the 6 m depth source in Figures 15 and 16, respectively).

5 **[0048]** Considering now the frequency content of the input data 1710 (continuous line in Figure 17) and that of the primaries 1720 (the dashed line in Figure 17), the same improvement in the uniformity of the frequency content is noted for real data as when applying a joint deghosting and designature method to the synthetic data.

[0049] Moreover, the deghosted output obtained by applying the deghosting and
10 designature method to this real data set may be re-datumed from different gun depths (i.e., 6 and 9 m) to the water surface and then summed together to synchronize the primaries for all propagation angles. In contrast, the conventional methods achieve a valid synchronization only for zero angles.

[0050] Some of the methods require the input data in the common-receiver
15 domain, which is inherently natural for OB nodes, which are stationary. For streamer data, common-receiver gathers can only be approximated due to non-stationary receivers and they are usually not dense enough due to coarse shot sampling perpendicular to the shooting direction. A practical solution is to use shot gathers as input. The underlying assumption is that surface incidence angles in the source side
20 are the same as (or close to) those in the receiver side. This approach is effective and performs deghosting/designature better than the conventional one-dimensional filter (which assumes zero surface incidence angles), although it can introduce inaccuracies for complex subsurface geology.

[0051] According to yet another embodiment, Figure 18 is a schematic diagram
25 of a computing system 1800 configured to perform methods performing deghosting and/or designature of data acquired with a multi-dimensional source. System 1800 may include a server 1801 that has at least one processor 1802 coupled to a random access memory (RAM) 1804 and to a read-only memory (ROM) 1806. ROM 1806 may also be other types of storage media to store programs, such as programmable ROM (PROM),
30 erasable PROM (EPROM), or Flash. Processor 1802 may communicate with other internal and external components through input/output (I/O) circuitry 1808 and bussing

1810, to provide control signals and the like. The processor 1802 may carry out a variety of functions as are known in the art, as dictated by software or firmware instructions.

[0052] The server 1801 may also include one or more data storage devices, including a disk drive 1812 (e.g., a hard drive), CD-ROM drives 1814, and other hardware capable of reading or storing information such as DVD, etc. In one embodiment, software for carrying out the above-discussed methods may be stored as executable codes and distributed on a CD- or DVD-ROM 1816, removable memory device 1818 or other tangible, non-transitory computer-readable storage medium capable of portably storing information. These storage media may be inserted into, and read by, devices such as CD-ROM drive 1814 or disk drive 1812. The server 1801 may be coupled to a display 1820, which may be any type of known display or presentation screen, such as LCD, LED displays, plasma displays, cathode ray tubes (CRT), etc. A user input interface 1822 can be provided, including one or more user interface mechanisms such as a mouse, keyboard, microphone, touchpad, touch screen, voice-recognition system, etc.

[0053] The server 1801 may also be coupled to other computing devices or systems, such as landline or wireless terminals, via a network. The server may be part of a larger network configuration as in a global area network such as the Internet 1828, which permits connection to various landline or mobile client devices. The network may include a satellite telephone link or shortwave radio link. The computing system 1800 may be placed on a vessel that performs a marine seismic survey.

[0054] Various interfaces may feed seismic data to the processor 1802 from internal or external memories. The processor 1802 is configured to build the reghosting operator and/or the resignature operator for the source using the source-related data, taking into consideration the multi-dimensional geometry of the multi-dimensional source. The processor 1802 is also configured to determine source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator and/or the resignature operator has/have been applied.

[0055] The disclosed exemplary embodiments provide methods, apparatuses and a computer readable medium storing executable codes, for source-side deghosting and/or designation during processing of marine seismic data acquired using a complex-geometry source. It should be understood that this description is not intended to limit the invention. On the contrary, the exemplary embodiments are intended to cover alternatives, modifications and equivalents, which are included in the spirit and scope of the invention as defined by the appended claims. Further, in the detailed description of the exemplary embodiments, numerous specific details are set forth in order to provide a comprehensive understanding of the claimed invention. However, one skilled in the art would understand that various embodiments may be practiced without such specific details.

[0056] Although the features and elements of the present exemplary embodiments are described in the embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the embodiments or in various combinations with or without other features and elements disclosed herein.

[0057] This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

WHAT IS CLAIMED IS:

1. A method (200) for processing marine seismic data acquired with a multi-dimensional source, the method comprising:

obtaining (210) the marine seismic data and source-related data;

5 building (220) at least one of a reghosting operator and a resignature operator for the source using the source-related data, the reghosting operator and/or the resignature operator depending on a multi-dimensional geometry of the multi-dimensional source; and

determining (230) source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator and/or the resignature operator has/have been applied,

wherein the source-effect-free data is usable to generate an image of a formation under the seafloor.

15 2. The method of claim 1, wherein both the reghosting operator and the resignature operator are built and used in the inversion procedure.

3. The method of claim 1, wherein the source includes source elements, and the source-related data includes information indicating source elements' positions, activation times and amounts of emitted energy, an emission of any of the source elements being characterized by a notional signature, and at least two among the source elements having distinct locations.

25 4. The method of claim 3, wherein at least two among the source elements are located at different depths.

5. The method of claim 1, wherein the inversion is performed in $\tau - p$ space, the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free data U according to following formula:

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k R_k^{ij} S_k^{ij} \right) U(f; p_x^j, p_y^j)$$

where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, R_k^{ij} is a reghosting operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , S_k^{ij} is a ressignature operator, (x_k^i, y_k^i, z_k^i) represents location of the source element k .

6. The method of claim 5, wherein the reghosting operator, R_k^{ij} is calculated using the formula:

$$R_k^{ij} = e^{-i2\pi f z_k^i \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2}} - e^{i2\pi f z_k^i \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2}}.$$

7. The method of claim 5, wherein the ressignature operator, S_k^{ij} is calculated using the formula:

$$S_k^{ij} = S_k^0(f) e^{-i2\pi f \left[t_k^0 + (x_k^i - x_0^i) p_x + (y_k^i - y_0^i) p_y + (z_k^i - z_0^i) \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2} \right]}.$$

8. The method of claim 1, wherein the inversion is performed in $\tau - p$ space, the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free data U according to following formula:

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k S_k^{ij} \right) U(f; p_x^j, p_y^j)$$

where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, S_k^{ij} is a ressignature operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , and (x_k^i, y_k^i, z_k^i) represents location of the source element k .

9. The method of claim 1, wherein the inversion is performed in $\tau - p$ space,

the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free U data according to following formula:

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k R_k^{ij} \right) U(f; p_x^j, p_y^j)$$

where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, R_k^{ij} is a reghosting operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , and (x_k^i, y_k^i, z_k^i) represents location of the source element k .

10. A data processing system (1800) configured to process marine seismic data acquired with a multi-dimensional source, the system comprising:

an input/output interface (1812, 1814) configured to obtain the marine seismic data and source-related data; and

a processor (1802) configured

to build at least one of a reghosting operator and a resignature operator for the source using the source-related data, the reghosting operator and/or the resignature operator depending on a multi-dimensional geometry of the source; and

to determine source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator and/or the resignature operator has/have been applied, wherein the source-effect-free data is usable to generate an image of a formation under the seafloor.

11. The data processing system of claim 10, wherein the processor builds both the reghosting operator and the resignature operator, and uses both the reghosting operator and the resignature operator in the inversion procedure.

12. The data processing system of claim 10, wherein the source includes source elements, and the source-related data includes information indicating source elements' positions, activation times and amounts of emitted energy, an emission of any of the source elements being characterized by a notional signature, and at least two
5 among the source elements having distinct locations.

13. The data processing system of claim 12, wherein at least two among the source elements are located at different depths.

10 14. The data processing system of claim 10, wherein the processor is configured to perform the inversion in $\tau - p$ space, the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free data U according to following formula:

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k R_k^{ij} S_k^{ij} \right) U(f; p_x^j, p_y^j)$$

15 where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, R_k^{ij} is a reghosting operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , S_k^{ij} is a resignature operator, (x_k^i, y_k^i, z_k^i) represents location of the source element k .

20 15. The data processing system of claim 14, wherein the processor calculates the reghosting operator, R_k^{ij} using the formula:

$$R_k^{ij} = e^{-i2\pi f z_k^i \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2}} - e^{i2\pi f z_k^i \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2}}.$$

25 16. The data processing system of claim 14, wherein the processor calculates the resignature operator, S_k^{ij} using the formula:

$$S_k^{ij} = S_k^0(f) e^{-i2\pi f \left[t_k^0 + (x_k^i - x_0^i) p_x + (y_k^i - y_0^i) p_y + (z_k^i - z_0^i) \sqrt{v^{-2} - (p_x^j)^2 - (p_y^j)^2} \right]}.$$

17. The data processing system of claim 10, wherein the processor is configured to perform the inversion in $\tau - p$ space, the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free data U according to following formula:

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k S_k^{ij} \right) U(f; p_x^j, p_y^j)$$

where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, S_k^{ij} is a ressignature operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , and (x_k^i, y_k^i, z_k^i) represents location of the source element k .

18. The data processing system of claim 10, wherein the inversion is performed in $\tau - p$ space, the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free U data according to following formula:

$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k R_k^{ij} \right) U(f; p_x^j, p_y^j)$$

where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, R_k^{ij} is a reghosting operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , and (x_k^i, y_k^i, z_k^i) represents location of the source element k .

19. A non-transitory computer-readable recording medium (1804) storing executable codes which when executed by a processor make the computer perform a method (200) for processing marine seismic data acquired with a multi-dimensional source, the method comprising:

obtaining (210) seismic data and source-related data;

building (220) at least one of a reghosting operator and a resigature operator for the source using the source-related data, the reghosting operator and/or the resigature operator depending on a multi-dimensional geometry of the multi-dimensional source; and

5 determining (230) source-effect-free data by an inversion procedure, so that the seismic data to be substantially equal to the source-effects-free data to which the reghosting operator and/or the resigature operator has/have been applied,

wherein the source-effect-free data is usable to generate an image of a formation under the seafloor.

10

20. The non-transitory computer-readable recording medium of claim 19, wherein the inversion is performed in $\tau - p$ space, the seismic data for a trace i associated with coordinates x_0^i, y_0^i in the seismic data, and a frequency f , being substantially equal to the source-effect-free data U according to following formula:

15
$$D(f; x_0^i, y_0^i) = \sum_j L(f; x_0^i, y_0^i; p_x^j, p_y^j) \left(\sum_k A_k R_k^{ij} S_k^{ij} \right) U(f; p_x^j, p_y^j)$$

where L is a reverse $\tau - p$ transform operator, A_k is an amplitude associated to each source element k used to calculate a signature of the source, R_k^{ij} is a reghosting operator related to trace i for the source element k and path j characterized by slowness pair (p_x^j, p_y^j) , S_k^{ij} is a resigature operator, (x_k^i, y_k^i, z_k^i) represents location of the source element k .

20

FIG. 1

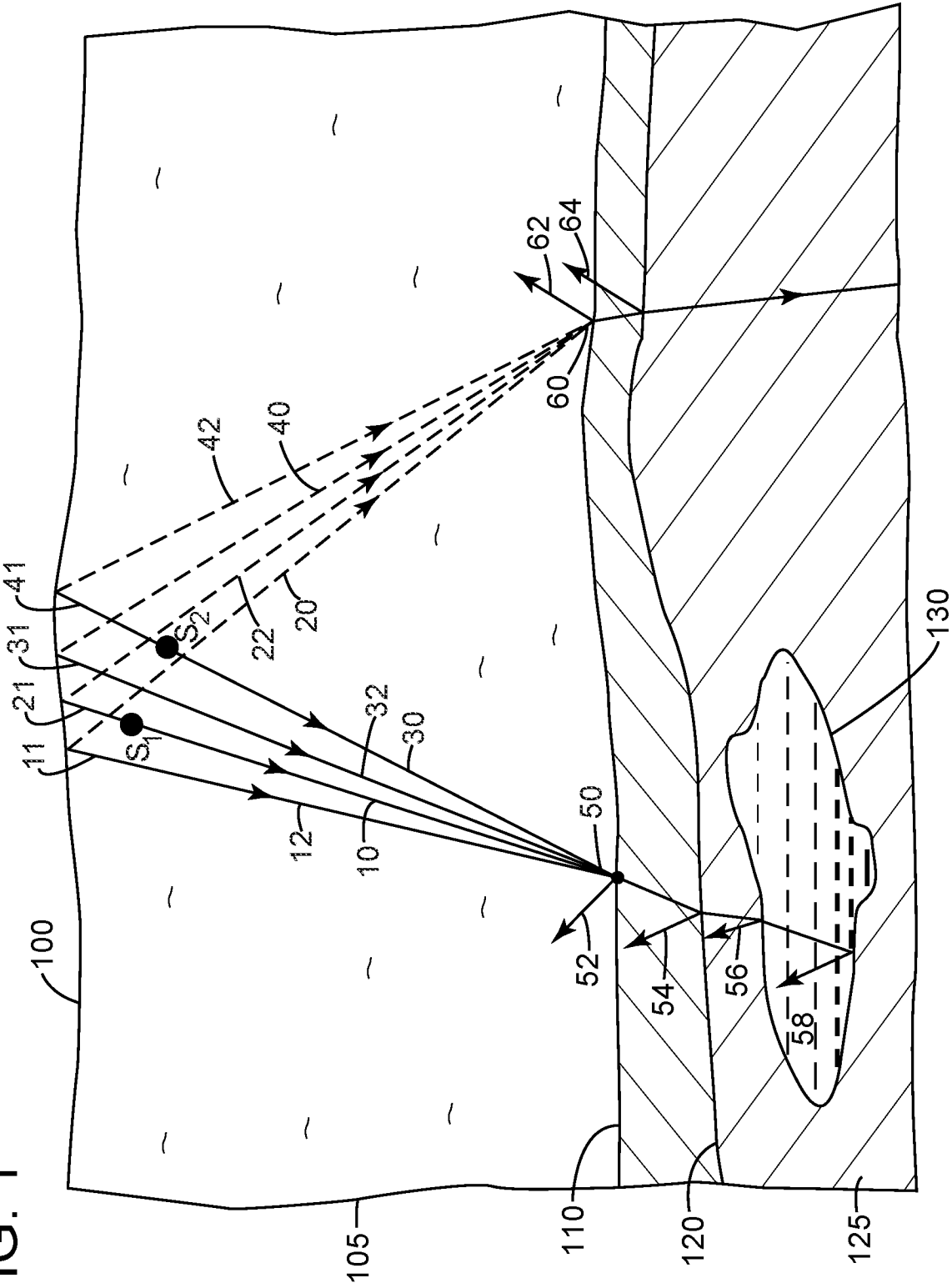
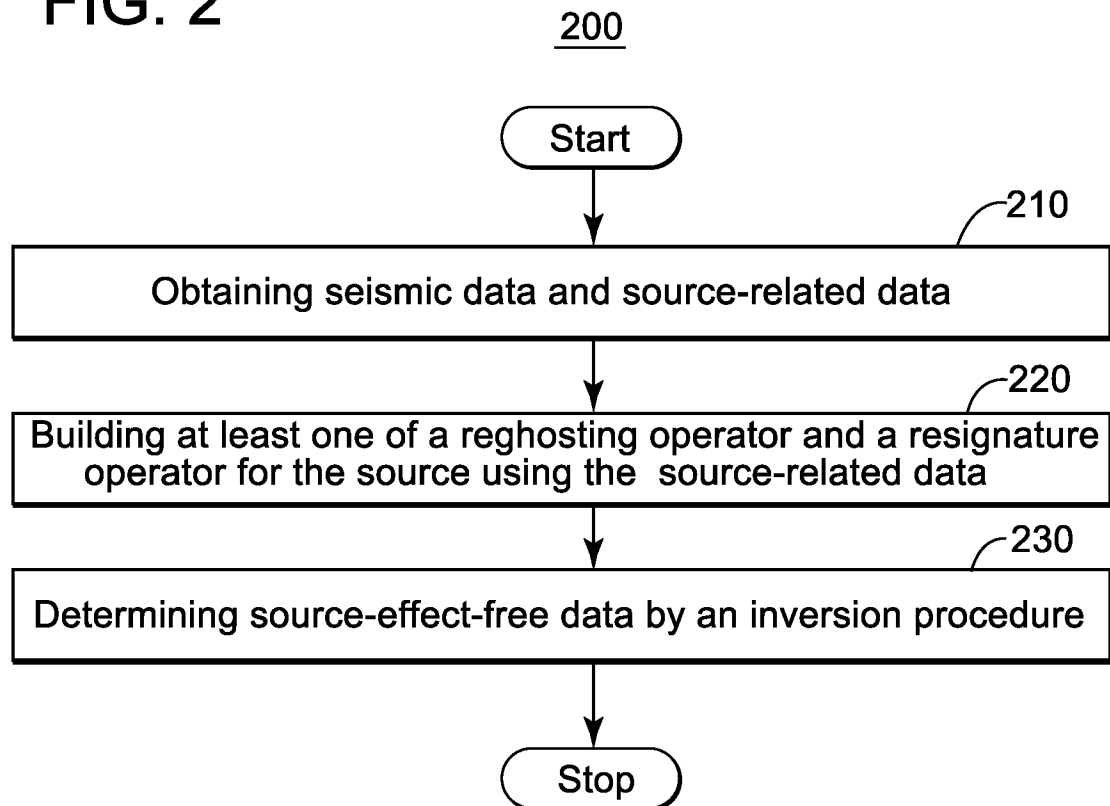


FIG. 2



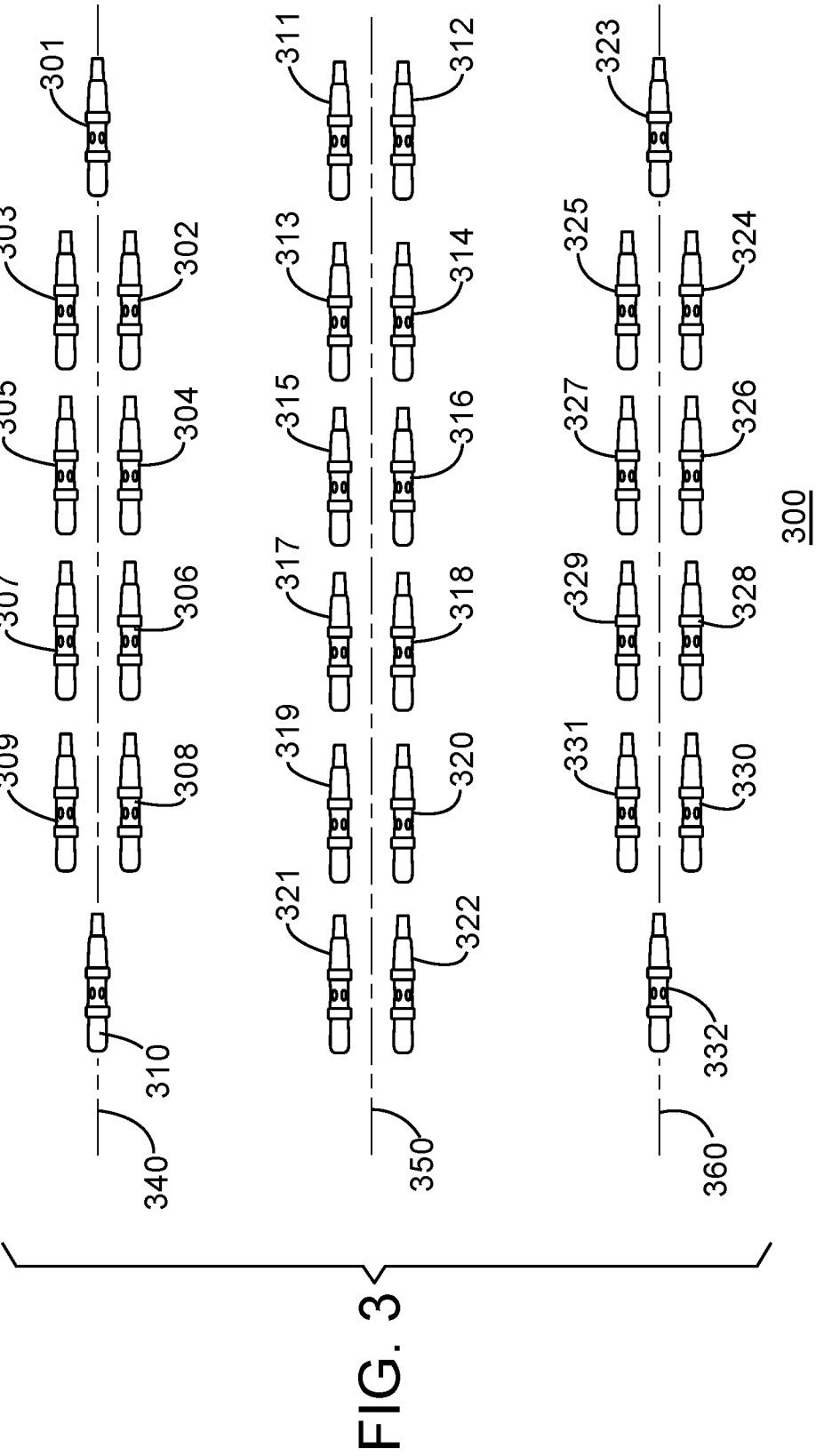


FIG. 4

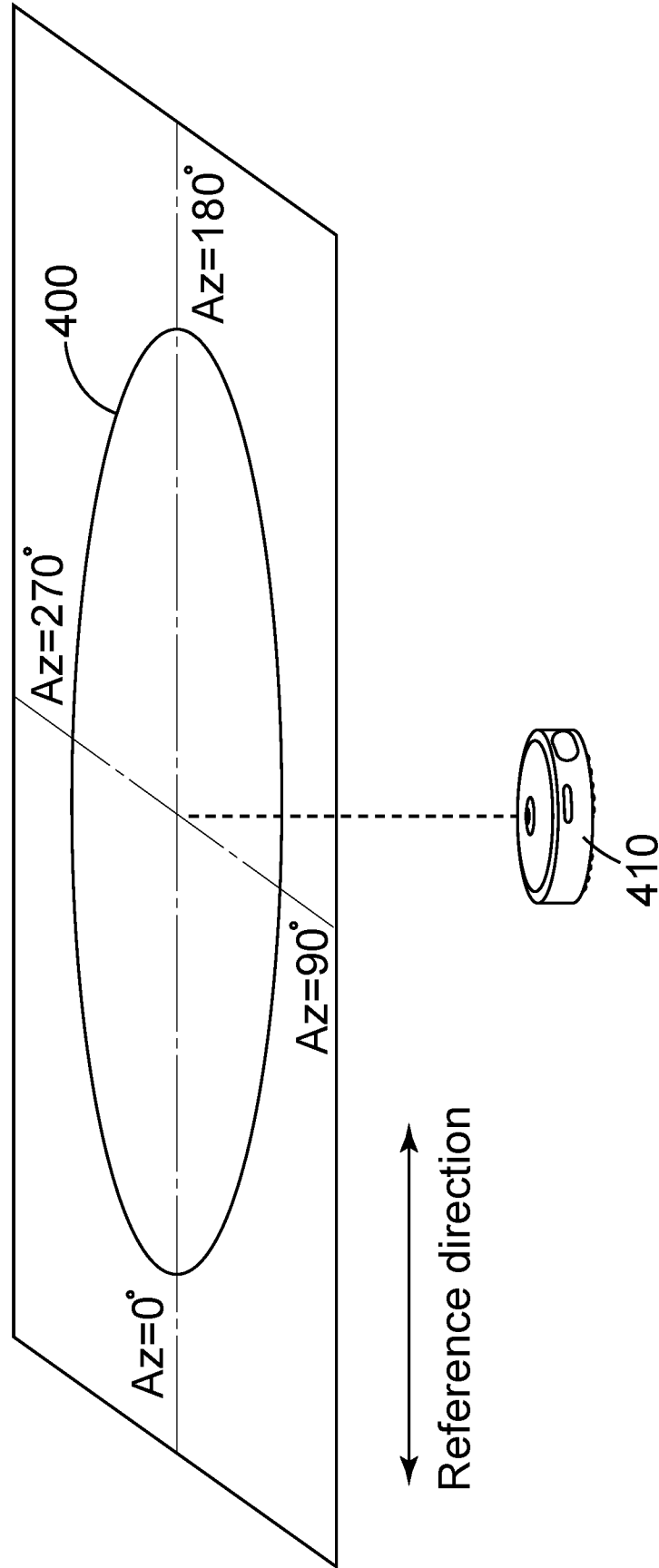


FIG. 5

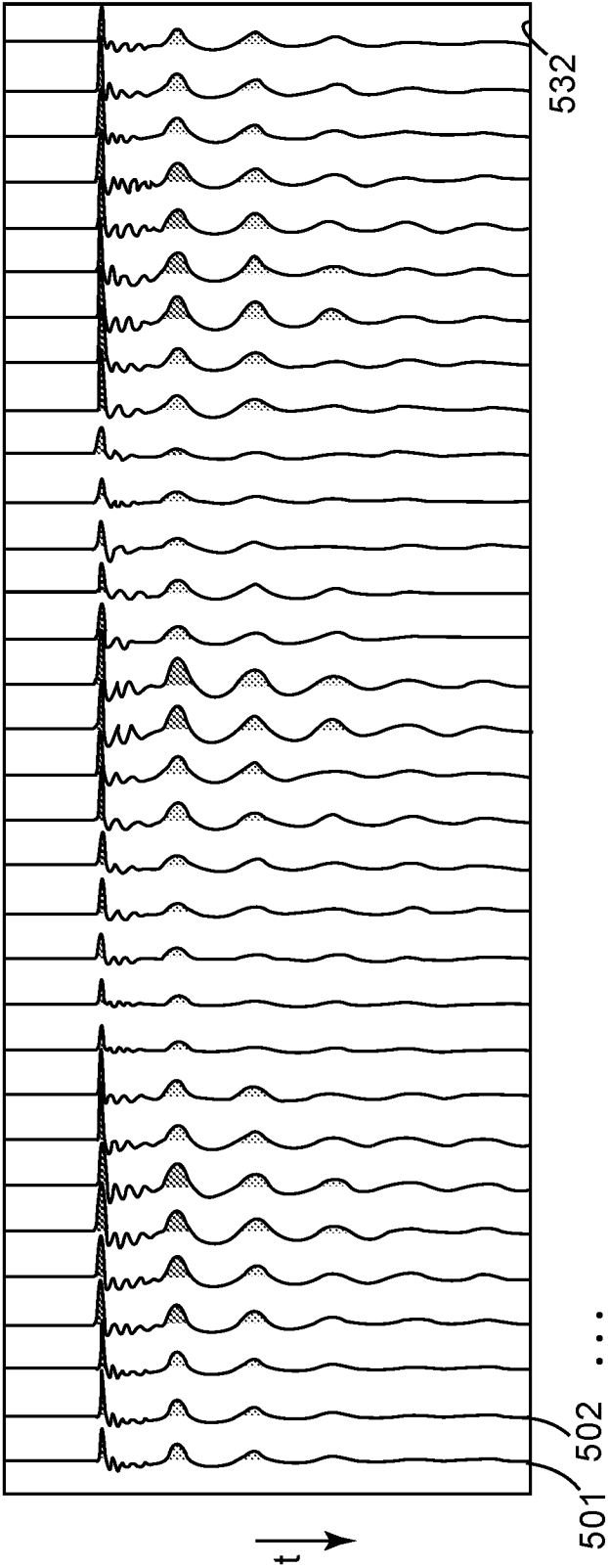


FIG. 6

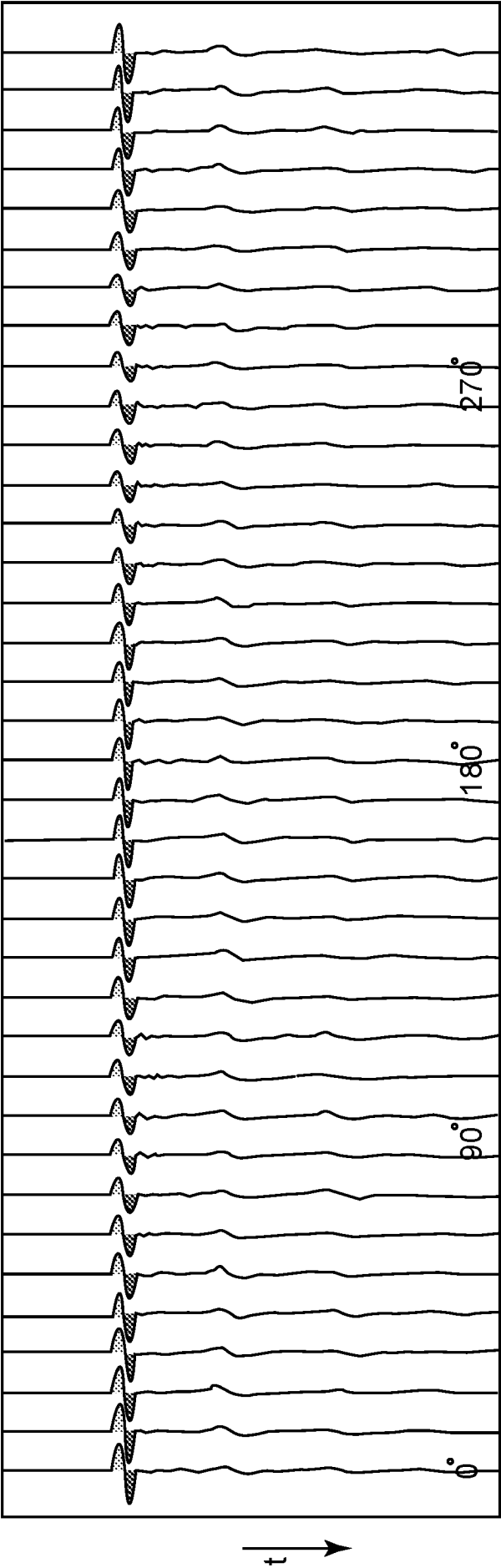


FIG. 7

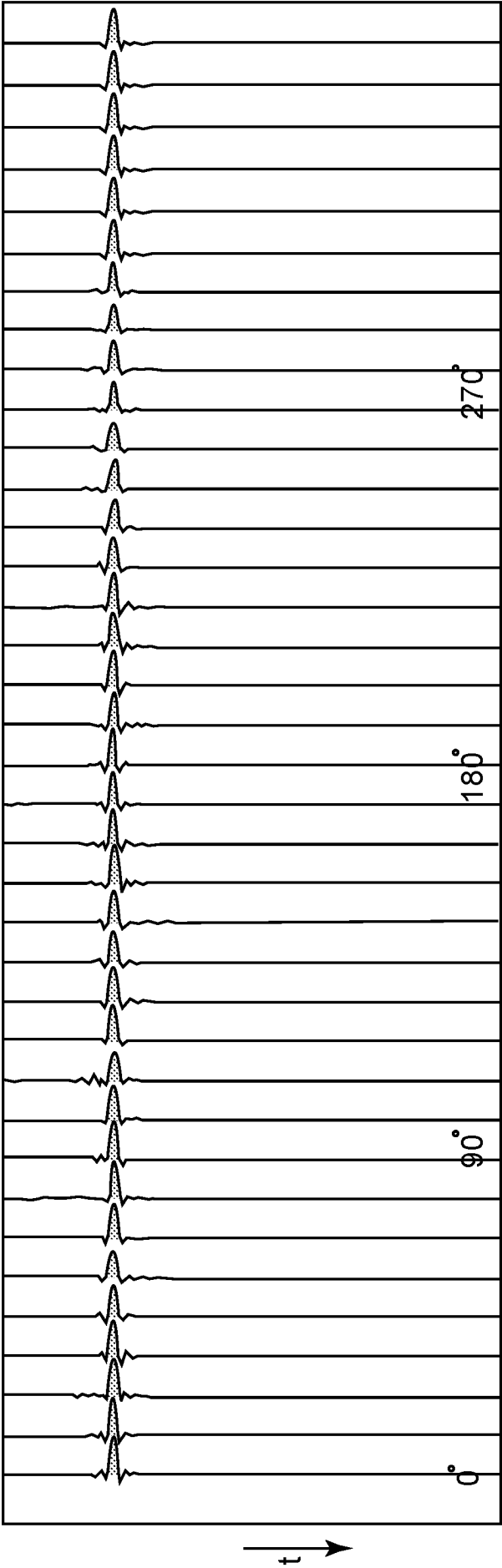


FIG. 8

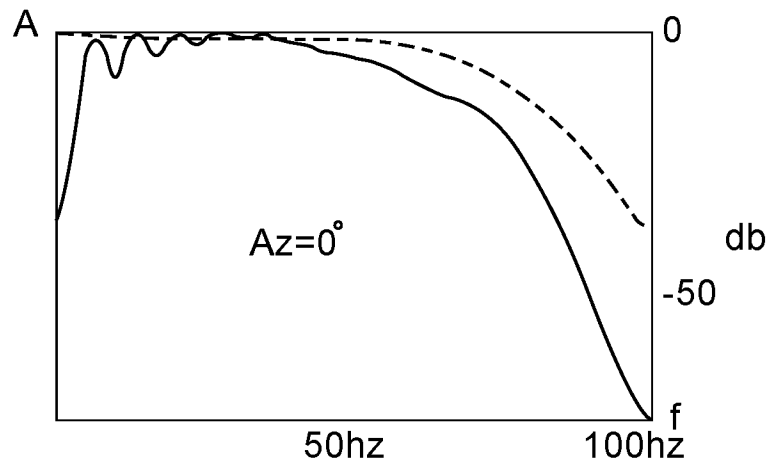


FIG. 9

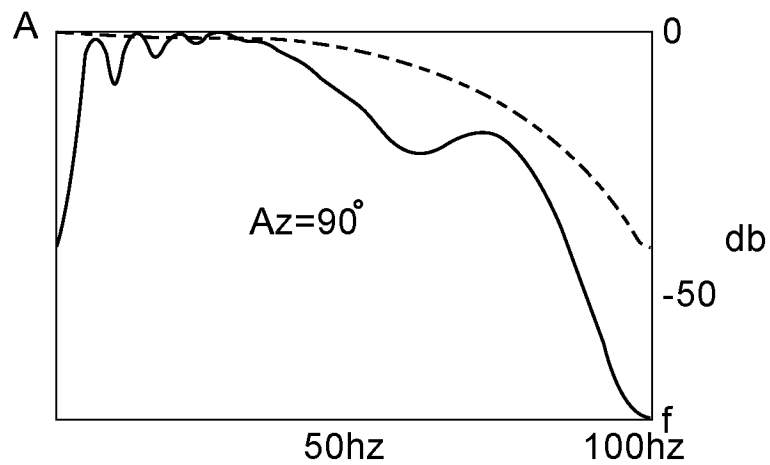


FIG. 10

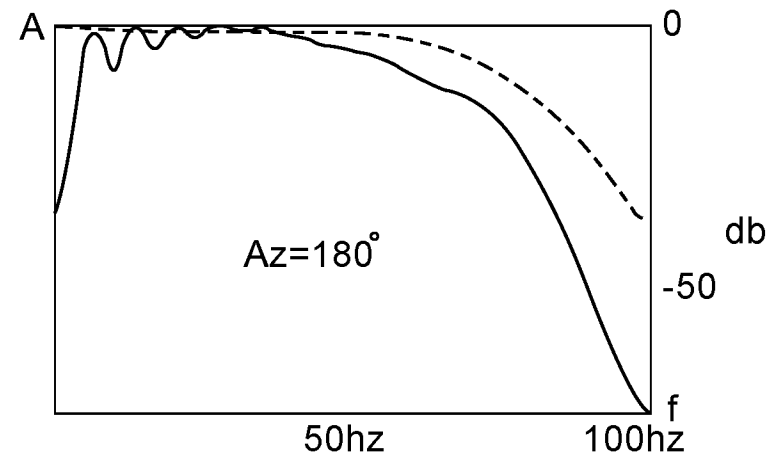


FIG. 11

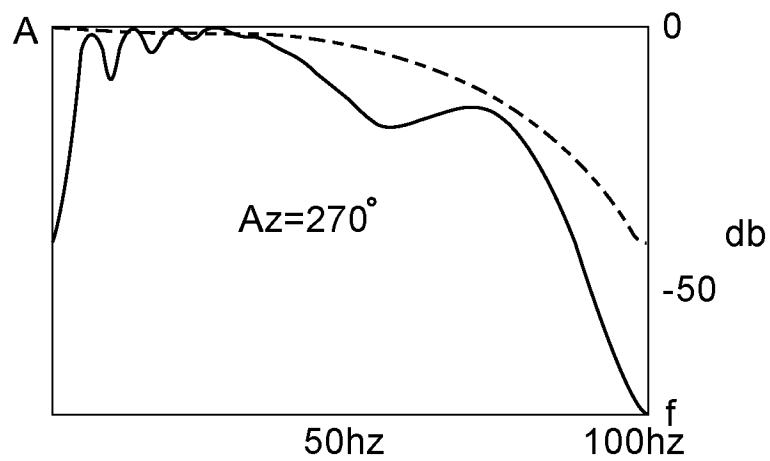


FIG. 12

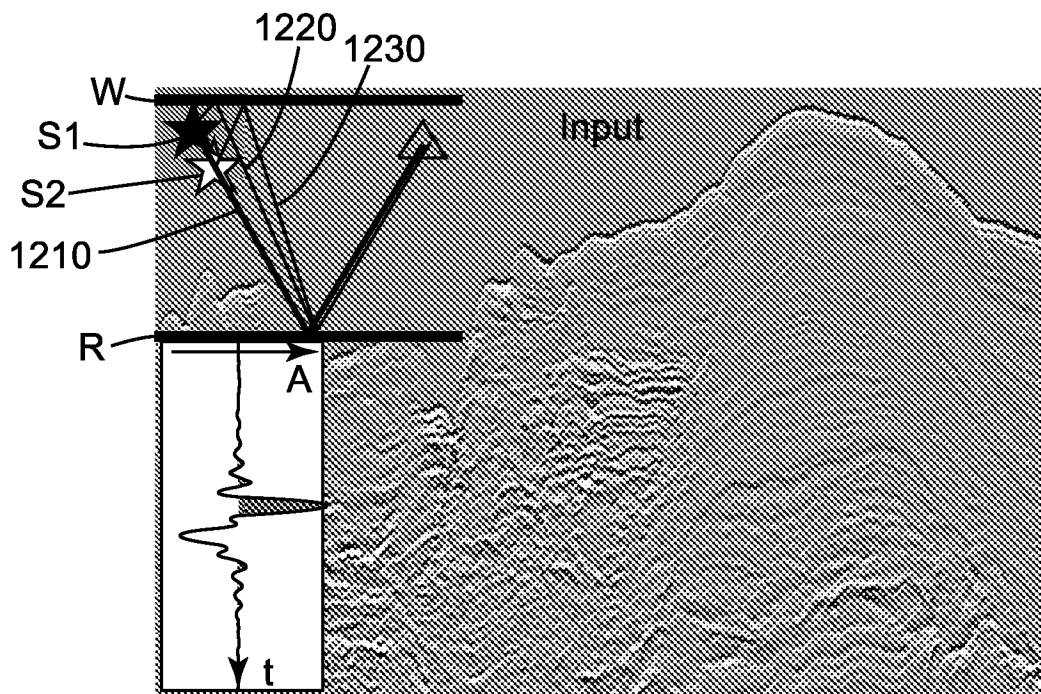


FIG. 13

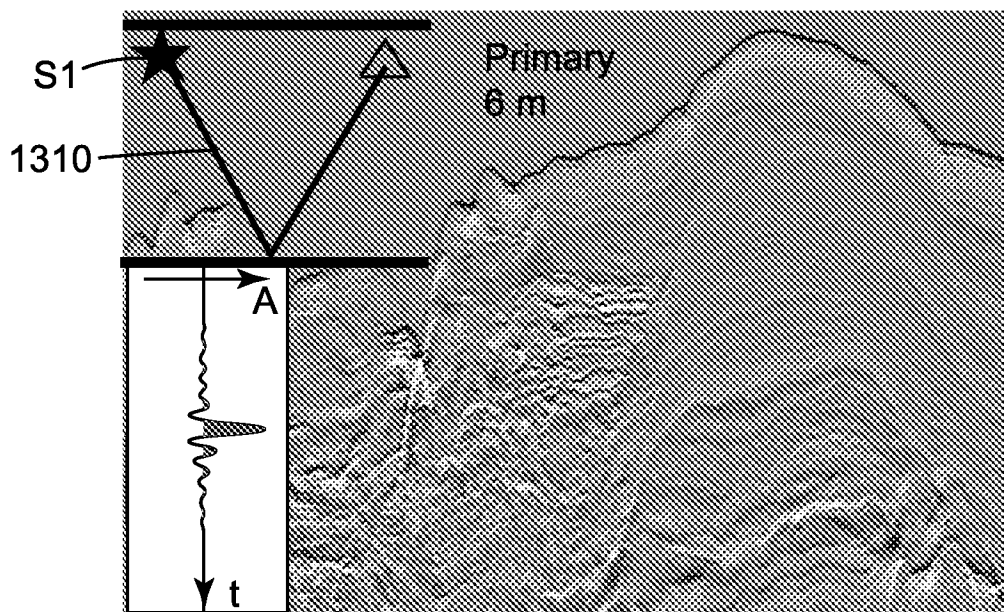


FIG. 14

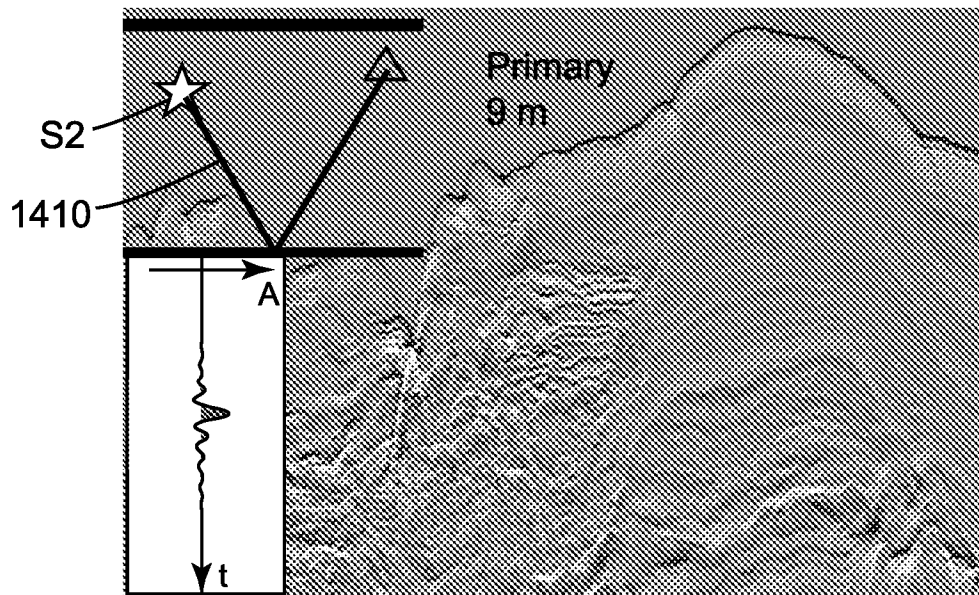


FIG. 15

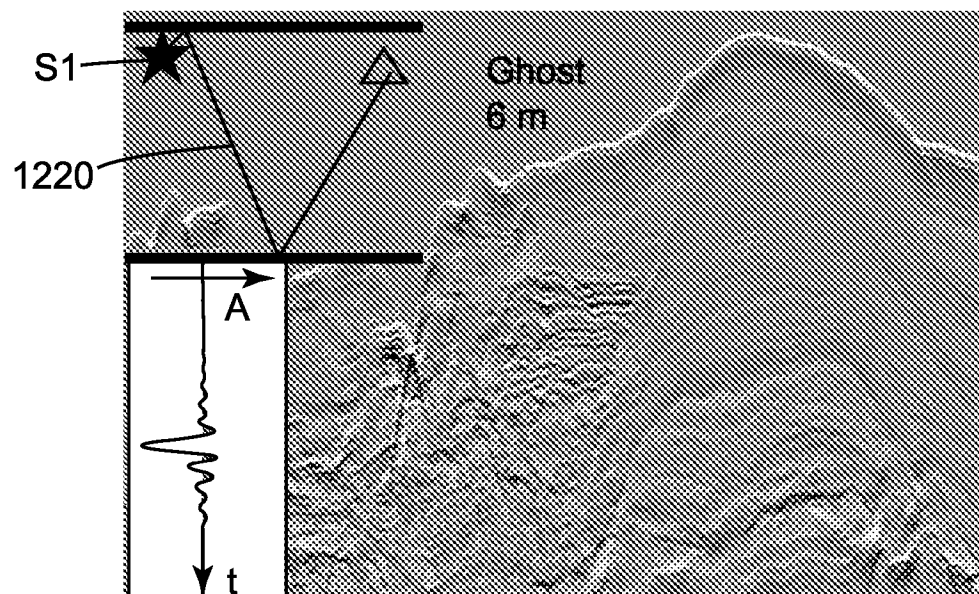


FIG. 16

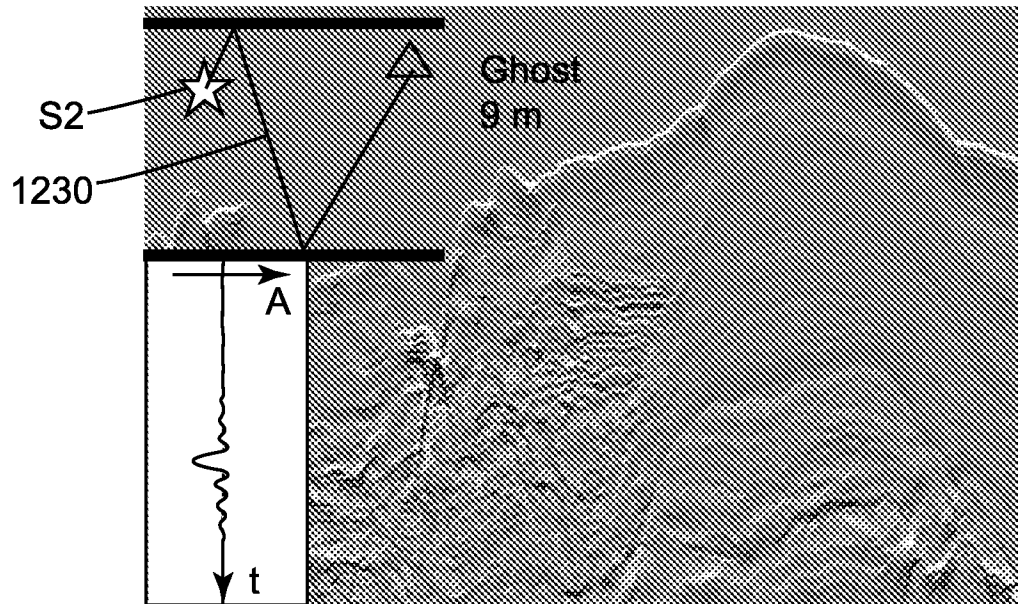


FIG. 17

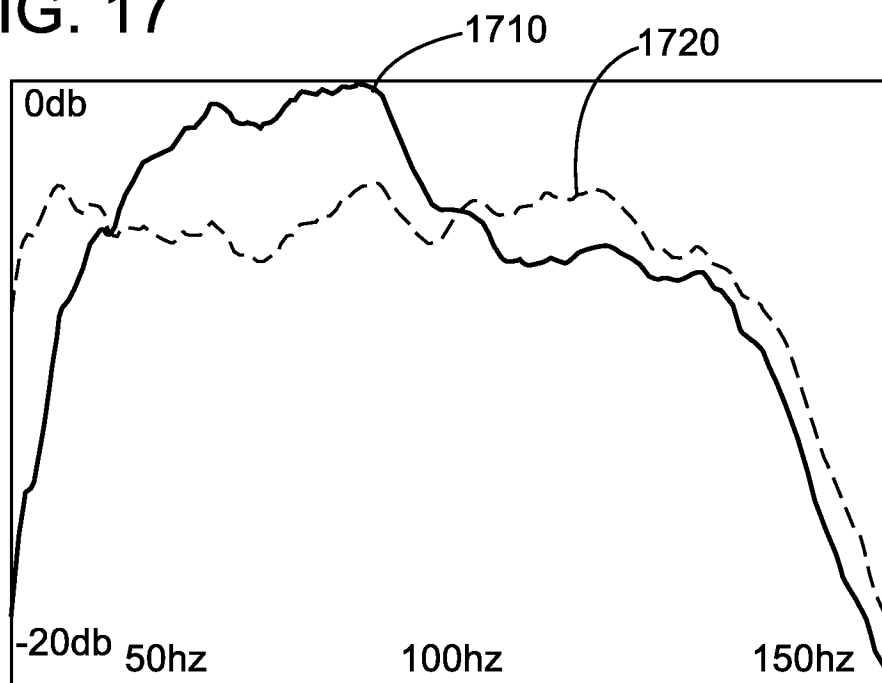
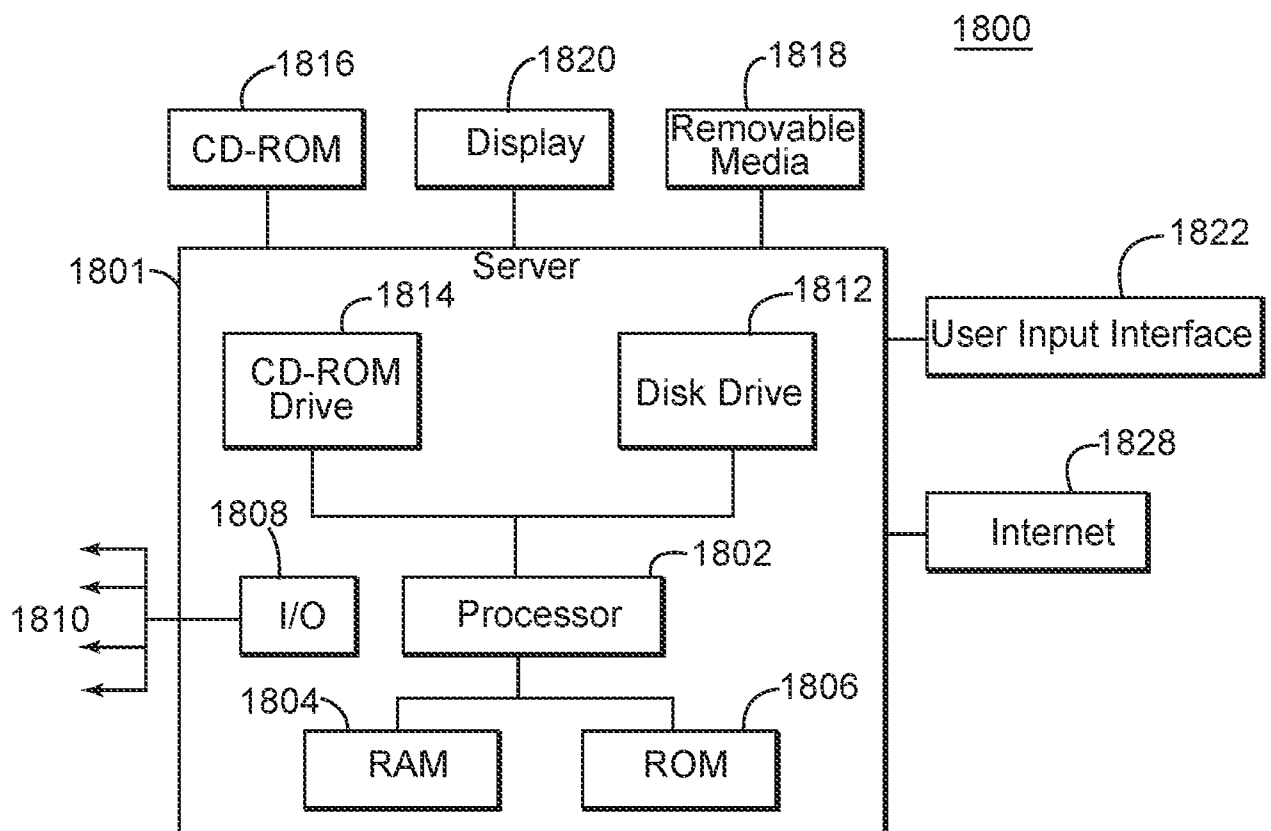


FIG. 18



INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2015/002485

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01V1/36 G01V1/38
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	paragraphs [0012], [0013], [0019], [0035], [0040], [0041], [0043], [0045]	3,4,12, 13
A	paragraphs [0047], [0059], [0060]	2,5,7,8, 11,14, 16,17,20
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Further documents are listed in the continuation of Box C.



See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search

18 March 2016

Date of mailing of the international search report

29/03/2016

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Authorized officer

Mirkovic, Olinka

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2015/002485

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	abstract Section Modeling	2,5,6,9, 11,14, 15,18
Y	----- GORDON POOLE ET AL: "Shot-to-shot directional signature using near-field hydrophone data", SEG TECHNICAL PROGRAM EXPANDED ABSTRACTS 2013, 27 September 2013 (2013-09-27), pages 4236-4240, XP055211201, DOI: 10.1190/segam2013-0550.1	3,4,12, 13
A	Section Designature operator derivation	2,5,7,8, 11,14, 16,17,20
A	----- US 2013/226463 A1 (VAN BORSELEN ROALD [NL] ET AL) 29 August 2013 (2013-08-29) the whole document	2,5,6,9, 11,14, 15,18,20
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Information on patent family members

International application No

PCT/IB2015/002485

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