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- (71) **Applicant:** CGG SERVICES SA [FR/FR]; 27, Avenue Carnot, F-91300 Massy (FR).
- (72) **Inventors:** TANASE, Catalin; c/o CGG Services SA, 27, Avenue Carnot, F-91300 Massy (FR). DEBEYE, Harry; c/o CGG Services SA, 27, Avenue Carnot, F-91300 Massy (FR).
- (74) **Agents:** PETIT, Maxime et al.; Ipsilon Brema-Loyer, Le Centralis, 63 avenue du Général Leclerc, F-92340 Bourgl-la-Reine (FR).
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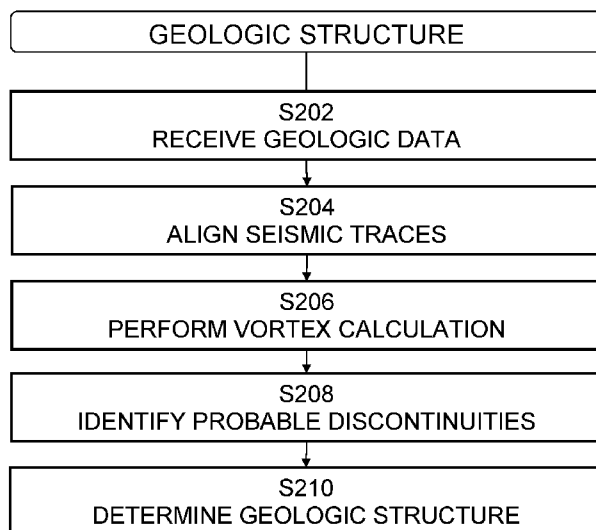


FIGURE 2

(57) **Abstract:** The present disclosure includes systems and methods for determining a geophysical profile from geophysical data. The systems and methods may include receiving geophysical data from a data source. The geologic data may include seismic traces corresponding to a region of earth. The systems and methods may transform the seismic traces into one or more characteristic values by vortex calculation. The vortex calculation comprises, for each particular portion of the region of earth, summing a plurality of shift values used to align traces located along a closed loop path within such particular portion. Each characteristic value may represent a portion of the region of earth and may quantify the likelihood that a structural discontinuity exists in the portion of the region of earth represented by such characteristic value.

## SYSTEMS AND METHODS FOR VORTEX CALCULATION AS ATTRIBUTE FOR GEOLOGIC DISCONTINUITIES

### 5 TECHNICAL FIELD

[0001] The present invention relates generally to subsurface exploration and, more particularly, to systems and methods for vortex calculation as attribute for geologic discontinuities.

### 10 BACKGROUND

[0002] In the oil and gas industry, seismic exploration techniques are commonly used to aid in locating subsurface deposits of hydrocarbons and other useful minerals. Seismic exploration, whether on land or at sea, is a method of detecting geologic structures below the surface of the earth by analyzing seismic energy that has  
15 interacted with the geologic structures. Generally, a seismic energy source (or “source”) imparts a force at the surface of the earth. The resulting mechanical stress propagates according to the elastic properties of the subsurface, and is at least partially reflected by subsurface seismic reflectors (interfaces between geologic structures that have different acoustic impedances). Seismic receivers (or  
20 “receivers”), placed at or near the earth’s surface, within bodies of water, or below the earth’s surface in wellbores, record the ground motion or fluid pressure resulting from the reflection. The recordings are processed to generate information about the location and physical properties of the subsurface geologic structures that reflected the seismic energy.

25 [0003] Conventionally, in seismic exploration, a plurality of seismic sources and receivers are distributed at a distance from each other. The seismic sources are activated to produce seismic waves that travel through the subsoil. These seismic waves undergo deviations as they propagate. They are refracted, reflected, and diffracted at the geological interfaces of the subsoil. Certain waves that have travelled  
30 through the subsoil are detected by seismic receivers and are recorded as a function of time in the form of signals (called “traces”). The recorded signals then are processed to obtain an image of underground geological structures.

[0004] A seismic trace represents the response of the elastic wave field to velocity and density contrasts across interfaces of layers of rock or sediments as energy travels

from the seismic source through the subsurface to a receiver or receiver array. An inversion operation may be performed on seismic traces. In particular, an inversion operation is an operation in which seismic reflection and diffraction data is transformed into a quantitative property description or a strata description of a subsurface location, which may, for example, be a reservoir containing fluids, such as oil or gas, or other natural resources.

[0005] It is important to obtain, in an efficient and accurate manner, information about geologic discontinuities, such as faults, channels, diapirs, and other discontinuities. In particular, the effectiveness of investigating subsurface bodies in two or three dimensions, especially in prospecting for oil or other underground resources, depends on the accuracy with which these discontinuities can be reconstructed and represented.

[0006] The identification and reconstruction of geological discontinuities is one of the first steps in geophysical model building. The final precision of the geophysical model significantly depends on the precision of identifying and reconstructing such discontinuities. A wide variety of methods are currently used in the geo-modeling software to reconstruct geological discontinuities. An example of one currently used method is the method of generating a coherency map set forth in K.J. Marfurt, R.L. Kirlin, S.L. Farmer, and M.S. Bahorich, 1998, "3-D seismic attributes using a semblance-based coherency algorithm", *Geophysics*, Vol. 63, Pp. 1150–1165. Most of the methods currently used in geo-modeling software, however, require a significant amount of processing time and cannot reconstruct complex geological formations with high precision.

[0007] Similar methods are also used, and may be applied in, fields other than the geosciences. For example, such methods are utilized in medicine, engineering, materials science, and a range of other fields to model the subsurface structure of materials. Such methods may be applicable to any field that utilizes image processing and/or model building.

[0008] The present invention is directed to alleviating the drawbacks of the currently used methods and to proposing systems and methods that can allow for non-homogeneous or highly diverse geometrical data and, for the anomalies described above and other anomalies, providing a less ambiguous model of the surface with an improved combination of accuracy, economic viability, and speed as compared to currently-used methods.

SUMMARY

[0009] In accordance with one or more embodiments of the present disclosure, methods for determining a geophysical profile from geophysical data now are described. The methods may include receiving geophysical data from a data source. The geophysical data may include traces corresponding to a region of earth. The methods may include performing a vortex calculation. The vortex calculation may transform the geophysical data into one or more characteristic values. Each characteristic value may represent a portion of the region of earth and may quantify the likelihood that a structural discontinuity exists in the portion of the region of earth represented by such characteristic value.

[0010] In accordance with one or more embodiments of the present disclosure, systems for determining a geophysical profile from geophysical data now are described. The systems may include a computing system. The computing system may be configured to receive geophysical data from a data source. The geophysical data may include traces corresponding to a particular region of earth. The computing system may be configured to perform a vortex calculation. The vortex calculation may transform the geophysical data into one or more characteristic values. Each characteristic value may represent a portion of the region of earth and may quantify the likelihood that a structural discontinuity exists in the portion of the region of earth represented by such characteristic value.

[0011] In accordance with one or more embodiments of the present disclosure, non-transitory computer-readable media storing computer-readable instructions that, when executed by a processing system, may instruct the processing system to perform processes for determining a geophysical profile from geophysical data now are described. The computer-readable instructions may instruct the processing system to perform a process of receiving geophysical data from a data source. The geophysical data may include traces corresponding to a particular region of earth. The computer-readable instructions may instruct the processing system to perform a vortex calculation. The vortex calculation may transform the geophysical data into one or more characteristic values. Each characteristic value may represent a portion of the region of earth and may quantify the likelihood that a structural discontinuity exists in the portion of the region of earth represented by such characteristic value.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0012] For a more complete understanding of the present disclosure and its features and advantages, reference is now made to the following description, taken in conjunction with the accompanying drawings, which may include drawings that are not to scale and wherein like reference numbers indicate like features, in which:

[0013] FIGURE 1 illustrates a schematic diagram of an example exploration network 100 in accordance with some embodiments of the present disclosure.

[0014] FIGURE 2 illustrates a flowchart of an example method for reconstructing a geologic structure from geophysical data in accordance with some embodiments of the present disclosure;

[0015] FIGURE 3 illustrates a flowchart of an example method for seismic trace alignment in accordance with some embodiments of the present disclosure;

[0016] FIGURE 4 illustrates a graphical example of trace alignment in accordance with some embodiments of the present disclosure;

[0017] FIGURE 5 illustrates a graphical example of vortex calculation in accordance with some embodiments of the present disclosure;

[0018] FIGURE 6 illustrates a flowchart of an example method vortex calculation in accordance with some embodiments of the present disclosure;

[0019] FIGURE 7A illustrates an example noise map generated by the vortex calculation process of FIGURE 6;

[0020] FIGURE 7B illustrates an example coherency map of the same region shown in FIGURE 7A that was generated using a typical process of geologic surface reconstruction and representation; and

[0021] FIGURE 8 illustrates a schematic diagram of an example system configured to reconstruct a geologic structure from geophysical data in accordance with some embodiments of the present disclosure.

## DETAILED DESCRIPTION

[0022] The following description of the 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 in the context of seismic data processing and, in particular, vortex calculation as attribute for geologic discontinuities.

[0023] However, similar methods may also be used in a wide variety of applications including, but not limited to, applications in engineering, medicine, materials science, or other fields in which it may be useful to model the properties of subsurface structures or other features.

5 [0024] 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 phrases “in one embodiment” or “in an embodiment” in various places throughout the specification is not necessarily  
10 referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

[0025] Vortex calculation, which is described below in more detail, is a process that may obtain a volume of data. This volume of data may provide a measure of geologic discontinuities such as faults, channels, and other features, and may provide  
15 an independent quality control measure that is distinct from other discontinuity seismic attributes such as coherency, semblance, and energy ratio. Vortex calculation refers to the loop summation of the relative shifts between input traces. The loop integral may be calculated within a window around each input sample, for example. This method may allow for reduced computational complexity and, therefore, high  
20 computational speed when developing geophysical or other models. While described herein in the context of geophysical data processing, the systems and methods disclosed herein may be applied to any interior modeling technique, such as those used in engineering, medicine, materials science, or other fields to determine the properties of subsurface structures.

25 [0026] Systems and methods disclosed herein may determine a geologic structure from geophysical data. The systems and methods may include receiving raw or pre-processed geophysical data from a data source, such as a receiver or a computing system. The systems and methods may include performing an alignment process to align seismic traces included in the geophysical data. The alignment process may  
30 generate shift values that may each correspond an amount by which one trace of a pair of traces is shifted to be in alignment with the other trace of the pair of traces. The systems and methods may include performing a vortex calculation using the shift values to assist in determining the locations of subsurface discontinuities. In particular, vortex calculation may include determining a sum of the shift values

around a loop (the sum being referred to herein as “noise” or equivalently “characteristic value”) and assigning the determined value to a particular point, such as the center of the loop, for example. When the sum of the shift values has a greater magnitude or absolute value, it is more likely that a discontinuity exists at the particular point than when the sum of the shift values has a lower magnitude or absolute value. The systems and methods may use this information to provide an improved representation of the subsurface structure that may depict discontinuities with improved contrast over existing methods of subsurface representation.

[0027] Such systems and methods may alleviate the drawbacks of currently used methods and may provide improved methods for analyzing and representing non-homogeneous or highly diverse geometrical data and, identifying the locations of discontinuities and other anomalies with improved accuracy, economic viability, and speed as compared to currently-used methods. Moreover, the systems and methods disclosed herein may be used to process a wide variety of geophysical data, including, but not limited to, land-based geophysical data, marine-based geophysical data, and ocean-bottom data.

[0028] FIGURE 1 illustrates a schematic diagram of an example exploration network 100 in accordance with some embodiments of the present disclosure. A survey of the acquisition area may include activation of a seismic source 104 that may radiate an elastic wavefield that may expand downwardly through the layers beneath the earth’s surface. The seismic wavefield may be reflected, refracted, or otherwise returned from the respective layers as a wavefront or head wave recorded by receivers 102a–102f.

[0029] In some embodiments, source 104 may be controlled to generate seismic waves in a seismic survey, and receivers 102a–102f may receive waves reflected by subsurface layers, oil or gas reservoirs, or other subsurface formations. Received waves may be converted to electrical signals and may be communicated to a computer system for processing, as described further below with respect to FIGURE 8. Exploration network 100 may include a plurality of strings 110a–110e containing a plurality of receivers, such as one or more of receivers 102a–102f, configured in a grid. For example, exploration network 100 may include approximately 4,000 receivers. Each receiver may be assigned a “station index” to identify the location of that particular receiver. Station indices may be assigned from south to north or using any other suitable assignment method.

[0030] In some embodiments, noise signals (and corresponding noise sources) may be identified by cross-correlating traces at two receivers. Cross-correlation is a measure of the similarity of two waveforms with a correction for any time lag between the two signals. Thus, cross-correlation of two traces may increase the amplitude readings for common points of the two waveforms and may neutralize, or reduce the noise associated with, the amplitude readings for non-common points.

[0031] The cross-line direction in an array of receivers may be the direction perpendicular to the direction in which the seismic data was acquired. The in-line direction in an array of receivers may be the direction in which the seismic data was acquired. For example, receiver 102b and receiver 102d in FIGURE 1 may be described as sitting on the same line in the in-line direction, whereas receiver 102a and receiver 102c may be described as sitting on the same line in the in-line direction.

[0032] FIGURE 2 illustrates a flowchart of an example method for reconstructing a geologic structure from geophysical data in accordance with some embodiments of the present disclosure. Systems and methods described herein, such as seismic exploration system 700 described below with reference to FIGURE 8, may reconstruct geological structures from geophysical data, such as seismic traces. The processes of the method of FIGURE 2 may be performed by a user, various computer programs, models, systems configured to simulate, design, and analyze data from seismic exploration signal systems, apparatuses, or devices, or any combination thereof. The programs and models may include instructions stored on a computer-readable medium and may, when executed, instruct a processor or other suitable device to perform one or more of the processes described above. The computer-readable media may include any system, apparatus, or device configured to store and retrieve programs or instructions such as a hard disk drive, a compact disc, flash memory, or any other suitable device. The programs and models may be configured to direct a processor or other suitable device to retrieve and execute the instructions from the computer-readable media. Collectively, the user or computer programs and models used to simulate, design, and analyze data from seismic exploration systems may be referred to as a “computing system.”

[0033] In S202, the computing system obtains, compiles, or otherwise receives geophysical data, including seismic traces, from one or more data source. The geophysical data may include a plurality of seismic traces (called a “data volume”). Some of the seismic traces from the same data volume may have been collected or

received at different times, such that a lag time exists between these traces. For example, a first seismic trace may have been received by a seismic receiver at a first time. A second seismic trace may have been received by the seismic receiver at a second time. Accordingly, the difference between the second time and the first time  
5 corresponds to a first lag time between the time of receiving the first seismic trace and the time of receiving the second seismic trace.

[0034] In certain configurations, the data volume may include a plurality of traces, and each trace may be assigned with particular in-line and cross-line coordinates. In other configurations, the data volume may include a plurality of  
10 seismic traces, and each seismic trace may have the same in-line and cross-line coordinates, which are also assigned as the coordinates of the data volume itself. Such a data volume may be referred to as a “gather.” Each of the traces that belong to the same gather may correspond to different offsets (with units of length, for example). Further, a plurality of gathers may be referred to as a “gather data volume,” and each  
15 gather of the gather data volume may be assigned with particular in-line and cross-line coordinates. Gathers may be based on any of a number of properties, such as length, time, angle, azimuth, or other properties, for example.

[0035] In seismic exploration systems that utilize a plurality of seismic sources, lag times such as the first lag time may exist because it may take a longer time for a  
20 seismic wave to travel from a first seismic source to a seismic receiver than to travel from a second seismic source to the seismic receiver. In seismic exploration systems that utilize a plurality of seismic receivers, lag times such as the first lag time may exist because it may take a longer time for a seismic wave to travel from a seismic source to a first seismic receiver than to travel from the seismic source to a second  
25 seismic receiver.

[0036] In S204, the computing system aligns two or more seismic traces in an alignment process. In particular, the computing system performs a process of shifting at least one of the two or more seismic traces by the lag time between such seismic trace and another seismic trace, so that these seismic traces are aligned. For example,  
30 the second seismic trace described above may be shifted by the first lag time to align the second seismic trace with the first seismic trace. The alignment process of S204 may be used as a preprocessing operation to generate shift values for use in a vortex calculation, which is described below in more detail. FIGURE 3 below illustrates an example of the process of S204 in more detail.

[0037] In particular, FIGURE 3 illustrates a flowchart of an example method for reconstructing a geologic structure from geophysical data in accordance with some embodiments of the present disclosure. The processes of the method of FIGURE 3 may be performed by a user, various computer programs, models, systems configured to simulate, design, and analyze data from seismic exploration signal systems, apparatuses, or devices, or any combination thereof. The programs and models may include instructions stored on a computer-readable medium and may, when executed, instruct a processor or other suitable device to perform one or more of the processes described above. The computer-readable media may include any system, apparatus, or device configured to store and retrieve programs or instructions such as a hard disk drive, a compact disc, flash memory, or any other suitable device. The programs and models may be configured to direct a processor or other suitable device to retrieve and execute the instructions from the computer-readable media. Collectively, the user or computer programs and models used to simulate, design, and analyze data from seismic exploration systems may be referred to as a “computing system.”

[0038] In S302, the computing system may shift a seismic trace artificially by a candidate shift amount in a particular shift dimension. For example, shift dimension may be one of time and distance in a “vertical” direction orthogonal to the in-line and cross-line directions (*e.g.*, normal to the plane formed by the in-line and cross-line directions). The candidate shift amount may be a pre-determined value. For example, the computing system may shift the second seismic trace artificially by the candidate shift amount relative to the first seismic trace.

[0039] In S304, the computing system determines a correlation value between a pair of seismic traces, including the artificially shifted seismic trace and another seismic trace (called a “target seismic trace” for convenience). The correlation value may be determined based on and represent any similarity measure, such as correlation, quasi-correlation, normal root mean square, goodness of fit, for example. The following discussion uses correlation as an example similarity measure for simplicity of discussion, but one of skill in the art will appreciate that any other similarity measure may be used. In some configurations, the artificially shifted seismic trace and target seismic trace may be aligned in one of a cross-line direction, which may be any reference direction, and an in-line direction that is orthogonal to the cross-line direction. In certain configurations, for example, the in-line and cross-line directions may be defined based on the arrangement of receivers 102a–102f. For

example, the cross-line direction may be a direction perpendicular to the direction that the seismic data was acquired, as described above with reference to FIGURE 1. In particular configurations, the artificially shifted seismic trace and the seismic trace may be adjacent traces in one of the cross-line and in-line direction. For example, the computing system may determine a correlation value between the artificially shifted second seismic trace and the first seismic trace and index or designate the determined correlation value based on the relationship between the first and second seismic traces in the cross-line or in-line direction. In still other configurations, however, the artificially shifted seismic trace and the seismic trace may be aligned in some direction other than the cross-line or in-line direction.

[0040] In S308, the computing system may determine whether to repeat S302 and S304 for the same pair of traces with a different candidate shift time based on a predetermined criteria. In some embodiments, the computing system may be configured to repeat processes S302 and S304 for a pair of traces a predetermined number of times with the candidate shift time being increased by a predetermined interval each iteration, such that a plurality of correlation values in the cross-line and in-line directions are determined. In some embodiments, the computing system may be configured to repeat processes S302 and S304 for a pair of traces until the correlation value (or a magnitude thereof) between the two traces in one or more of the in-line direction and the cross-line direction is greater than or equal to some threshold value. Thus, if the computing system determines that the criteria is not yet satisfied (for example, S302 and S304 have not yet been repeated the predetermined number of times or a large enough correlation value has not been calculated) (S308: NO), computing system may repeat processes S302, S304, and S308 with a new candidate shift time. If the computing system determines that the criteria is satisfied (for example, S302 and S304 have been repeated the predetermined number of times or a large enough correlation value has been calculated) (S308: YES), computing system may proceed to S310.

[0041] In S310, the computing system may compare the plurality of determined correlation values for the pair of traces and may determine the largest correlation value determined for the pair of traces during all of the iterations of processes S302 and S304. The computing system then may store, as a relative shift value between the two traces in the pair of traces, the value of the shift amount for the artificially shifted seismic trace corresponding to the largest correlation value between the artificially

shifted seismic trace and the target seismic trace in each of the cross-line and in-line directions. Continuing the example discussed above, the computing system may determine the largest correlation value for the artificially shifted second seismic trace and the first seismic trace. The computing system then may store the value of the shift  
5 amount for the artificially shifted second seismic trace corresponding to the largest correlation value.

[0042] While the process of alignment described above seeks to determine shift values by identifying the largest correlation value for the artificially shifted second seismic trace and the first seismic trace, other dissimilarity measure. For example, the  
10 process of alignment may determine the shift values by identifying extreme values using one or more of quasi-correlation, goodness of fit, normal root mean square, and predictability methods.

[0043] Processes S302, S304, S308, and S310 may be repeated for a plurality of pairs of traces, such that a plurality of shift values are stored corresponding to the  
15 relative shift values between the two traces in each pair of traces. In some configurations, each pair of traces may include two traces that are adjacent in one of the cross-line and in-line directions, for example, and processes S302, S304, S308, and S310 may be repeated for all pairs of adjacent traces aligned into the in-line direction and for all pairs of adjacent traces aligned into the cross-line direction.  
20 Specifically, in S312, computing system may determine whether all of the traces to be processed together have been adequately processed. The traces to be processed together may be all traces in a selected region of interest or all traces in a subset of the selected region of interest. In some embodiments, computing device may determine that all of the traces to be processed together have been adequately processed if each  
25 trace to be processed has been included in two different pairs during iterations of S302, S304, S308, and S310. If the computing system determines that all of the traces to be processed together have not been adequately processed (S312: NO), computing system may repeat processes S302, S304, S308, and S310 for another pair of traces. If the computing system determines that all of the traces to be processed together have  
30 been adequately processed (S312: YES), computing system may end the process of seismic trace alignment. In some embodiments, the computing system may proceed to S314 if the computing system determines that all of the traces to be processed together have been adequately processed (S312: YES). In other embodiments, S314 may be omitted, and the alignment process of FIGURE 3 may terminate if the

computing system determines that all of the traces to be processed together have been adequately processed (S312: YES).

[0044] In S314, the computing system may align the seismic traces by shifting the seismic traces by the shift amounts determined in S310, so that the traces may be analyzed together. In particular, all traces that are to be analyzed in a particular operation may be shifted to align with a particular target trace. With respect to the example described above, the first seismic trace may be the particular target trace with which the other traces are to be aligned. The aligned traces may then be ready for additional processing to generate a reconstruction of the geologic structure in the region under investigation. In some embodiments, the alignment process of S314 may be incorporated into a process performed distinctly from the other processes shown in FIGURE 3. S314 may be performed optionally and is not required for performing the vortex calculation in S206, which is described below in more detail. Consequently, S314 may be omitted in certain embodiments.

[0045] An example of the alignment process of FIGURE 3 now is described with reference to FIGURE 4. FIGURE 4 illustrates a graphical example of trace alignment in accordance with some embodiments of the present disclosure. FIGURE 4 shows traces A and B in the vertical direction orthogonal to the plane defined by the in-line and cross-line directions (shown below in FIGURE 5). FIGURE 4 also may analogously represent other configurations in which time is used as the shift dimension rather than depth or distance in the vertical direction. In other configurations, the shift dimension may be based on still other units and is not limited to time, depth, or distance. Moreover, while FIGURE 4 depicts trace alignment along the vertical direction (depth or time), the systems and methods described herein are limited to the vertical direction and may be aligned or otherwise compared along any direction, such as the in-line direction or the cross-line direction, for example.

[0046] As shown in FIGURE 4, the undulations of trace A and trace B are out of phase prior to alignment, but after trace B is shifted relative to trace A by shift amount S during an alignment process, the undulations of trace A and trace B are almost perfectly in phase. In particular, the alignment process increases the correlation between trace A and trace B by causing trace A and trace B to become more in phase in the shift dimension. Furthermore, in some configurations, while the coordinate in the vertical direction or time for the shifted trace is changed during the alignment

process, the coordinates of the shifted trace (and the target trace) in the cross-line and in-line directions are not shifted and, thus, remain the same.

[0047] Information obtained during the alignment process of FIGURE 3 now is described with reference to an example that includes eight seismic traces 1 through 8 (represented in FIGURE 5, which is described below in more detail) and eight pairs of seismic traces. In a first pair of traces in this example, the first seismic trace 1 may be the target seismic trace with respect to the second seismic trace 2. The value of the relative shift amount corresponding to the largest correlation between the first seismic trace 1 and the second seismic trace 2 determined in S310 may be referred to as shift  $S_{CLI}$  because trace 1 and trace 2 are aligned into the cross-line direction, as shown in FIGURE 5.

[0048] In a second pair of traces in this example, the second seismic trace 2 may be the target seismic trace with respect to a third seismic trace 3. The value of the relative shift amount corresponding to the largest correlation between the second seismic trace 2 and the third seismic trace 3 determined in S310 may be referred to as shift  $S_{CL2}$  because trace 2 and trace 3 are aligned into the cross-line direction, as shown in FIGURE 5.

[0049] In a third pair of traces in this example, the third seismic trace 3 may be the target seismic trace with respect to a fourth seismic trace 4. The value of the relative shift amount corresponding to the largest correlation between the third seismic trace 3 and the fourth seismic trace 4 determined in S310 may be referred to as shift  $S_{ILI}$  because trace 3 and trace 4 are aligned into the in-line direction, as shown in FIGURE 5.

[0050] In a fourth pair of traces in this example, the fourth seismic trace 4 may be the target seismic trace with respect to a fifth seismic trace 5. The value of the relative shift amount corresponding to the largest correlation between the fourth seismic trace 4 and the fifth seismic trace 5 determined in S310 may be referred to as shift  $S_{IL2}$  because trace 4 and trace 5 are aligned into the in-line direction, as shown in FIGURE 5.

[0051] In a fifth pair of traces in this example, the fifth seismic trace 5 may be the target seismic trace with respect to the sixth seismic trace 6. The value of the relative shift amount corresponding to the largest correlation between the fifth seismic trace 5 and the sixth seismic trace 6 determined in S310 may be referred to as shift  $S_{CL3}$

because trace 5 and trace 6 are aligned into the cross-line direction, as shown in FIGURE 5.

[0052] In a sixth pair of traces in this example, the sixth seismic trace 6 may be the target seismic trace with respect to a seventh seismic trace 7. The value of the relative shift amount corresponding to the largest correlation between the sixth seismic trace 6 and the seventh seismic trace 7 determined in S310 may be referred to as shift  $S_{CL4}$  because trace 6 and trace 7 are aligned into the cross-line direction, as shown in FIGURE 5.

[0053] In a seventh pair of traces in this example, the seventh seismic trace 7 may be the target seismic trace with respect to an eighth seismic trace 8. The value of the relative shift amount corresponding to the largest correlation between the seventh seismic trace 7 and the eighth seismic trace 8 determined in S310 may be referred to as shift  $S_{IL3}$  because trace 7 and trace 8 are aligned into the in-line direction, as shown in FIGURE 5.

[0054] In an eighth pair of traces in this example, the eighth seismic trace 8 may be the target seismic trace with respect to the first seismic trace 1. The value of the relative shift amount corresponding to the largest correlation between the eighth seismic trace 8 and the first seismic trace 1 determined in S310 may be referred to as shift  $S_{IL4}$  because trace 8 and trace 1 are aligned into the in-line direction, as shown in FIGURE 5.

[0055] The units of shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  may be units of time, such as milliseconds. In other embodiments, the units of shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  may be units of distance or depth, such as feet, meters, or any other relevant units.

[0056] To align the eight seismic traces of the example described above with the first trace 1 in the vertical direction, for example, the second trace 2 is shifted by  $S_{CL1}$ ; the third trace 3 is shifted by the sum of  $S_{CL1}$  and  $S_{CL2}$ ; the fourth trace 4 is shifted by the sum of  $S_{CL1}$ ,  $S_{CL2}$ , and  $S_{IL1}$ ; the fifth trace 5 is shifted by the sum of  $S_{CL1}$ ,  $S_{CL2}$ ,  $S_{IL1}$ , and  $S_{IL2}$ ; the sixth trace 6 is shifted by the sum of  $S_{CL1}$ ,  $S_{CL2}$ ,  $S_{IL1}$ ,  $S_{IL2}$ , and  $S_{CL3}$ ; the seventh trace 7 is shifted by the sum of  $S_{CL1}$ ,  $S_{CL2}$ ,  $S_{IL1}$ ,  $S_{IL2}$ ,  $S_{CL3}$ , and  $S_{CL4}$ ; and the eighth trace 8 is shifted by the sum of  $S_{CL1}$ ,  $S_{CL2}$ ,  $S_{IL1}$ ,  $S_{IL2}$ ,  $S_{CL3}$ ,  $S_{CL4}$ , and  $S_{IL3}$ . Further, if noise were not present in the data, the same alignment result could be achieved by reversing the loop and shifting the second trace 2 by the sum of  $-S_{CL2}$ ,  $-S_{IL1}$ ,  $-S_{IL2}$ ,  $-S_{CL3}$ ,  $-S_{CL4}$ ,  $-S_{IL3}$ , and  $-S_{IL4}$ ; shifting the third trace 3 by the sum of  $-S_{IL1}$ ,  $-S_{IL2}$ ,  $-S_{CL3}$ , -

$S_{CL4}$ ,  $-S_{IL3}$ , and  $-S_{IL4}$ ; shifting the fourth trace 4 by the sum of  $-S_{IL2}$ ,  $-S_{CL3}$ ,  $-S_{CL4}$ ,  $-S_{IL3}$ , and  $-S_{IL4}$ ; shifting the fifth trace 5 by the sum of  $-S_{CL3}$ ,  $-S_{CL4}$ ,  $-S_{IL3}$ , and  $-S_{IL4}$ ; shifting the sixth trace 6 by the sum of  $-S_{CL4}$ ,  $-S_{IL3}$ , and  $-S_{IL4}$ ; shifting the seventh trace 7 by the sum of  $-S_{IL3}$  and  $-S_{IL4}$ ; and shifting the eighth trace 8 by  $-S_{IL4}$ .

5 [0057] Thus, the process of aligning seismic traces in FIGURE 3 may calculate and store the relative shifts (also called “dips”) between seismic traces both in the in-line and cross-line directions.

[0058] Modifications, additions, or omissions may be made to the processes illustrated in FIGURE 3 without departing from the scope of the present disclosure.

10 For example, the order of the processes may be performed in a different manner than that described and some processes may be performed at the same time. Additionally, each individual process may include additional processes without departing from the scope of the present disclosure. Further, more processes may be added or processes may be removed without departing from the scope of the disclosure.

15 [0059] Alternatively or additionally, the alignment process of FIGURE 3 may be used for a number of purposes other than generating relative shift values for use in a vortex calculation. For example, the alignment process may be used to remove residual misalignment of volumes of gather seismic data, which may increase the accuracy of further processing methods. Further, the alignment process may be used  
20 for 4D alignment in which the datasets to be aligned may include, for example, two or more independent seismic data sets from different years that were collected for the purposes of reservoir monitoring. In order to compare and analyze the changes in between two vintages caused by extraction of oil, for example, the alignment process may be used to produce a metric showing high similarity where no changes in earth  
25 have been caused by extraction of oil and low similarity where the oil or gas was extracted. In addition, the alignment process may be used for the calculation of specific volume attributes or for dip steering calculations that may be useful in determining other specific attributes.

[0060] The method applies as well with even better results for higher dimensions  
30 as well (4D data like 4D time lapse data, or gather data, which is also 4D; also to 5D data wide azimuth seismic data for example and so on). The method is having an even better performance because having more data a higher statistical consistency is of benefit. Gather data benefit from AVO effects for example.

[0061] Moreover, the alignment process of FIGURE 3, including S314, may be performed as a preprocessing operation so that the seismic traces from a gather or data volume may be combined together or summed (called “stacking”) to increase the signal to noise ratio of the seismic data. Stacking multiple traces improves the signal to noise ratio (“SNR”) over non-stacked results because the non-coherent (or non-consistent) data will be stacked out or nullified. The “order” of the stack indicates the number of traces that are stacked. For example, each data volume may be assigned to a given set of coordinates in the in-line and cross-line directions and may, by itself, include a set of traces with the same coordinates in the in-line and cross-line directions as the gather. Each trace for a particular gather may correspond to a different offset between a source and a receiver, for example. The result of stacking all traces from a particular gather may be a trace.

[0062] In S206 of FIGURE 2, the computing system performs a vortex calculation. In particular, the vortex calculation may be performed mathematically by calculating a line integral, or loop integral, of the relative shift amounts determined in S310 of FIGURE 3. The loop integral may be calculated within a time slice around each seismic sample. Each seismic sample may be a value that represents the seismic amplitude at a particular point in space, which may be specified by three coordinates: one “vertical” coordinate, such as time or depth; and two “horizontal” coordinates, such as a coordinate in an in-line direction and a coordinate in a cross-line direction. For example, the particular point could be represented by a set of Cartesian coordinates. The totality of seismic samples along the vertical direction for a given pair of coordinates in the horizontal direction may represent a seismic trace; and a set of available seismic traces may be referred to as a seismic data volume. In practice, the loop integral may be calculated by adding together the shift amounts between seismic traces determined in S308 for the seismic traces that are aligned together in S310. For example, the seismic traces used in the loop integral may correspond to all seismic traces contained within a specified seismic data volume. The process of vortex calculation is described in more detail with respect to FIGURE 5.

[0063] FIGURE 5 illustrates a graphical example of vortex calculation in accordance with some embodiments of the present disclosure. In particular, FIGURE 5 shows a graphical summation of shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  for the seismic traces 1 through 8 described in the example above. As noted above, shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  may be determined as part of the alignment process

shown in FIGURE 3 and their respective values may depend on the arrangement of exploration network 100 and the composition and structure of the region being investigated. The vertical axis in FIGURE 5 represents the cross-line direction, and the horizontal axis in FIGURE 5 represents the in-line direction. For simplicity of illustration, FIGURE 5 shows configurations in which traces 1-8 are spaced apart in a uniform and periodic grid. In some configurations, however, the spacing between traces 1-8 in the cross-line and in-line directions may not be uniform or periodic. As also noted above, shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  may be expressed in units of time or units of depth or distance, for example. The arrows shown in FIGURE 5 indicate the direction of the alignment for which shift values  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  shown in FIGURE 5 are calculated (e.g., clockwise). In other configurations, the direction of the alignment for which shift values  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  may be another direction, such as counterclockwise, for example.

[0064] Vortex calculation for the eight seismic traces may be performed by adding together the shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  in the following manner:

$$S_{CL1} + S_{CL2} + S_{IL1} + S_{IL2} + S_{CL3} + S_{CL4} + S_{IL3} + S_{IL4} = N$$

### Equation 1

In Equation 1, the variable  $N$  represents a scalar sum of the shifts and corresponds to noise in the seismic data. The value of noise  $N$  is an example of a characteristic value.

[0065] In an ideal alignment process, the loop integral would have a theoretical value of zero. For example, the seventh seismic trace 7 could be aligned with the first seismic trace 1 by shifting the seventh seismic trace 7 by  $S_{CL1} + S_{CL2} + S_{IL1} + S_{IL2} + S_{CL3} + S_{CL4}$ . Alternatively, the seventh seismic trace 7 could be aligned with the first seismic trace 1 by shifting the seventh seismic trace 7 by  $-S_{IL4} - S_{IL3}$ . In an ideal alignment process, these shifts would be equivalent, such that:

$$S_{CL1} + S_{CL2} + S_{IL1} + S_{IL2} + S_{CL3} + S_{CL4} = -S_{IL4} - S_{IL3}$$

### Equation 2

By rearranging Equation 2, it may be shown that the sum of shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  is equal to zero ( $S_{CL1} + S_{CL2} + S_{IL1} + S_{IL2} + S_{CL3} + S_{CL4} + S_{IL3} + S_{IL4} = 0$ ) in an ideal alignment process. Consequently, the noise  $N$  would also be zero in the ideal alignment process.

Therefore, the loop integral of the shifts, or dips, in a particular volume of the sampled region including a plurality of traces has the theoretical value of zero under ideal conditions.

[0066] In practical applications, however, the loop integrals of the dips have non-zero values for various reasons, among which are the systematic errors. For example, shifting the seventh seismic trace 7 by  $S_{CL1} + S_{CL2} + S_{IL1} + S_{IL2} + S_{CL3} + S_{CL4}$  (referred to herein as “Path A”) and shifting the seventh seismic trace 7 by  $-S_{IL4} - S_{IL3}$  (referred to herein as “Path B”) may not be exactly the same, and the noise  $N$  may not equal zero. There may be several reasons for this. For example, rounding, estimation, approximation, or other calculation errors in processes S302, S304, S306, and S310 may result in differences between the total shift in Path A and the total shift in Path B. This may produce a mismatch and cause noise  $N$  to be nonzero. Further, extraneous vibrations, environmental factors, and other interference occurring during the data collection process may introduce errors into the received seismic data, which may also result in differences between the total shift in Path A and the total shift in Path B. This also may produce a mismatch and cause noise  $N$  to be nonzero.

[0067] The presence of a geologic discontinuity, however, may often be an even greater contributor to the amount of noise  $N$ . In particular, geologic discontinuities may affect the shape of a seismic trace. Consequently, such discontinuities may make it difficult to accurately identify correlations between traces in processes S302, S304, and S310. Thus, discontinuities significantly impact the process of selecting shift values in S310 and may result in errors greater than those associated with the calculation errors and environmental factors. Accordingly, a large value of noise  $N$  may indicate the presence of a discontinuity in the volume of the sampled region related to the aligned seismic traces.

[0068] Thus, the statistical content of noise in particular region of a seismic sample, as represented by noise  $N$ , may be locally dependent on geological structure in that region. Consequently, the vortex calculation may highlight discontinuities, such as faults, diapirs, channels, and discontinuities within the seismic data, which would otherwise be difficult to identify directly from the seismic data using existing techniques. Further, vortex calculation is an available quality control for seismic discontinuities that is also independent of other currently-used methods that utilize coherency, semblance, or energy.

[0069] In other words, patterns in calculated loops from Equation 1 may reflect patterns within a prospected geological structure. Consequently, the value of the noise at given points within the model may indicate the likely presence of geological discontinuities within the prospected geological structure. For example, the greater the value of noise for a given point, the more likely it may be that a discontinuity exists within the loop used to determine the noise value. Therefore, the loop summation using Equation 1 may assist a model builder (or a model user) in identifying discontinuity features more readily than direct inspection of the input data. More specifically, the value of noise  $N$  may be a characteristic value that quantifies the likelihood that a structural discontinuity exists in a region represented by the value of noise  $N$ .

[0070] The vortex calculation of S206 now is described with reference to FIGURE 6. FIGURE 6 illustrates a flowchart of an example method vortex calculation in accordance with some embodiments of the present disclosure. The processes of the method of FIGURE 3 may be performed by a user, various computer programs, models, systems configured to simulate, design, and analyze data from seismic exploration signal systems, apparatuses, or devices, or any combination thereof. The programs and models may include instructions stored on a computer-readable medium and may, when executed, instruct a processor or other suitable device to perform one or more of the processes described above. The computer-readable media may include any system, apparatus, or device configured to store and retrieve programs or instructions such as a hard disk drive, a compact disc, flash memory, or any other suitable device. The programs and models may be configured to direct a processor or other suitable device to retrieve and execute the instructions from the computer-readable media. Collectively, the user or computer programs and models used to simulate, design, and analyze data from seismic exploration systems may be referred to as a “computing system.”

[0071] In S502, the computing system may select a particular loop representing a portion of a subsurface region to be further investigated. For example, the particular loop could be the loop shown in FIGURE 5 that includes seismic traces 1 through 8. In S504, the computing system may sum together all of the relative shift values between neighboring traces in a particular loop to calculate a value for noise  $N$  for the particular loop. For example, the value of noise  $N$  for the loop shown in FIGURE 5 is given by Equation 1. In S506, the computing system may then assign the calculated

value for noise  $N$  to a particular point (having particular coordinates in the in-line and cross-line directions, as well as a time coordinate or a coordinate in the vertical direction). The particular point may be a central point within the loop (formed by the arrows shown in FIGURE 5) and may have a time coordinate or a coordinate in the vertical direction that is the same as the time coordinate or coordinate in the vertical direction of the seismic sample around which the vortex is calculated. In the example configuration of FIGURE 5, the point P is shown as central point of the loop formed by the arrows. The time/depth coordinate or coordinate in the vertical direction of the point P is not shown in FIGURE 5. In particular, the plane shown in the example configuration of FIGURE 5 may represent a slice in which all of the grid points on this plane, including the point P, have the same vertical coordinate that corresponds to the slice depicted. In some configurations described herein, the slice may correspond to a common time or depth. Nevertheless, slices described herein are not limited to time or depth and may represent any conceivable variable or unit, including higher dimensional (*e.g.*, fifth dimension, sixth dimension) variables. For convenience of explanation, time or depth slices are described herein, but slices of other variables may readily be used in relation to the methods and systems described herein.

[0072] In the example of FIGURE 5, the value of noise  $N$  may be assigned to the central point P at the center of the loop. In S508, the computing system may determine whether all of the loops related to the subsurface region to be further investigated have been processed in the vortex calculation process. For example, a region being investigated may be represented by a grid of points, such as a plurality of points similar to point P arranged in a grid, and each point may correspond to a particular loop. Thus, the computing system may need to perform S504 and S506 for each point on the grid before making an affirmative determination in S508. In other configurations, the computing system may make an affirmative determination in S508 only after all traces deemed to be related to the subsurface region to be further investigated have been included in at least one loop.

[0073] If all of the loops related to the subsurface region to be further investigated have not been processed in the vortex calculation process (S508: NO), the computing system may return to S502 and select another loop for processing. Consequently, the vortex calculation process of summing shifts in S504 may be repeated a plurality of times for a plurality of different loops related to the region being investigated. If all of the loops in the subsurface region to be further investigated have been processed in

the vortex calculation process (S508: YES), the computing system may proceed to S510 and generate a map of values for noise  $N$  that represents the structural features of the subsurface region to be further investigated.

[0074] For example, a region of earth being studied may be represented by a plurality of time/depth slices, and each time/depth slice may be represented by a plurality of points  $P$  arranged in a grid. Each of the plurality of points  $P$  in the grid for each time/depth slice may be surrounded by one loop, and each loop may be the smallest complete loop that surrounds a respective point  $P$  in the time/depth slice, for example. The shift values included in each loop may be combined in a vortex calculation to determine a value for each respective point  $P$  in a time/depth slice. This process may further be repeated for each time/depth slice representing the region of earth being studied. This example process may be referred to as a single loop calculation.

[0075] The map generated in S510 may be a pictorial representation of the region being investigated. The map may be a 2D map, a 3D map, a 4D map or a map of any other number of dimensions. The map may be represented in greyscale or in one or more colors. In particular, different noise values  $N$  may be represented by different levels of hue or shading, so that such differences in the noise value  $N$  between different portions of the region being investigated may be readily contrasted with each other upon visual inspection of the map.

[0076] Modifications, additions, or omissions may be made to the processes illustrated in FIGURE 6 without departing from the scope of the present disclosure. For example, the order of the processes may be performed in a different manner than that described and some processes may be performed at the same time. Additionally, each individual process may include additional processes without departing from the scope of the present disclosure. Further, more processes may be added or processes may be removed without departing from the scope of the disclosure.

[0077] In some embodiments of the vortex calculation, the absolute values of the shift values, rather than the signed shift values, may be added together to calculate the noise  $N$ . In particular, rather than utilizing Equation 1 in S504, the absolute values of the shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$  may be added together in the following manner to determine the noise  $N$ :

$$|S_{CL1}| + |S_{CL2}| + |S_{IL1}| + |S_{IL2}| + |S_{CL3}| + |S_{CL4}| + |S_{IL3}| + |S_{IL4}| = N$$

**Equation 3**

In Equation 3,  $|S_{CL1}|$  through  $|S_{CL4}|$  and  $|S_{IL1}|$  through  $|S_{IL4}|$  represent the absolute values of the shifts  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$ , respectively. By determining the value of noise  $N$  using Equation 3, the contrast between regions likely to include discontinuities and regions less likely to include discontinuities may be higher than the contrast between such regions when determining the value of noise  $N$  using Equation 1. Thus, the presence of discontinuities may be more apparent if Equation 3 is used to determine the values of noise  $N$ , rather than Equation 1. Further, the statistical contents, such as the average value and standard deviation, of the values of noise  $N$  calculated using Equation 3 may be locally dependent on the geological structure.

[0078] The noise value determined using Equation 3 may provide improved contrast for discontinuity features than that of Equation 1 without loss of lateral resolution. For example faults may be highlighted by having a higher average value than any other continuous regions for the noise calculated using Equation 3. As a result the noise calculated with Equation 3 may provide improved image definition for the user in tracking discontinuities.

[0079] In some embodiments, a plurality of values of noise  $N$  may be calculated for a particular point and some combination of the plurality of values of noise  $N$ , such as an average of the plurality of values of noise  $N$  for example, may be assigned to the particular point. For example, S502 and S504 may initially be performed in the manner described above using a first loop to determine a first value for noise  $N$  at a particular point P using the shift values associated with traces 1-8. Prior to S506, however, S502 may be repeated and a second loop including other traces surrounding the particular point P may be selected. The other traces may include traces with coordinates in the in-line and cross-line directions that are further from the particular point P than the coordinates of traces 1-8, such that the second loop is larger than the first loop. Consequently, the second loop may surround more traces than the first loop. Accordingly, in some embodiments, the second loop may encompass traces 1-8 in addition to the other traces. After selecting the second loop in S502, S504 may be repeated for the second loop using Equation 1, Equation 3, or a similar equation utilizing the relative shift values for the traces in the second seismic sample. S502 and S504 may be repeated with increasingly larger loops until some criteria is met, such as the loop including a particular number of traces or reaching a particular distance away from the particular point P, performing a particular number of iterations of S502

and S504, or until the size of the loop spans the entire region being investigated. Alternatively, S502 and S504 may be repeated with increasingly smaller loops until some similar criteria is met. Once the stopping criteria is met, the values of noise  $N$  calculated for each of the loops surrounding the particular point P may be combined, such as by averaging. The combined value of noise  $N$  may be assigned to the particular point P in S506. Thereafter, this process may be repeated for a plurality of points similar to point P in a grid representing the region being investigated. By calculating a plurality of values of noise  $N$  for a particular point and combining these values, the reported noise result may be smoothed. This may produce a more visually appealing noise map. While the foregoing example involves performing a vortex calculation for 8 traces, such calculations are not limited to 8 traces and may involve more than 8 traces or fewer than 8 traces as appropriate. In some configurations, at least 4 traces may be required to complete a vortex calculation. Nevertheless, other configurations may not be so-limited.

[0080] For example, a region of earth being studied may be represented by a plurality of time/depth slices, and each time/depth slice may be represented by a plurality of points P arranged in a grid. Each of the plurality of points P in the grid for each time/depth slice may be surrounded by a plurality of loops, such that a plurality of loops with different sizes surround each point P in the time/depth slice, for example. The shift values included in each loop may be combined in a vortex calculation to determine a loop value for each loop. For each point P in the time/depth slice, all of the loop values for loops surrounding the respective point P may be combined, such as by averaging the loop values, to determine a value for the respective point P. This process may further be repeated for each time/depth slice representing the region of earth being studied. This example process may be referred to as a multiple loop calculation.

[0081] In certain configurations, for example, a weighting factor equal to  $1/(\text{number of grid cells or grid points enclosed by a respective loop})$  may be applied to the respective loop value for the respective loop when combining (*e.g.*, averaging) the loop values of a plurality of loops to determine the value for a point P. In other configurations, for example, a weighting factor equal to  $1/(\text{number of relative shifts used to close a respective loop or the length of the respective loop})$  may be applied to the respective loop value for the respective loop when combining (*e.g.*, averaging) the loop values of a plurality of loops to determine the value for a point P.

[0082] In some configurations, the loop summation of dips for multiple loops and/or the average between multiple loops may be used to determine the characteristic value. For example, loops of different sizes may be selected, by enclosing different numbers of grid cells. Further, the central position of the loops is not necessarily coincident with a real trace coordinate from the input seismic data. The attributes may be calculated for any of such loops with the help of Equation 1 or Equation 3, for example, and the output may be calculated as an average between multiple loops by choosing as weighting factors either  $1/(\text{number of grid cells enclosed by loop})$  or  $1/(\text{number of dips along the contour of the loop})$ . In the alternative, other convenient choices for weighting the average may be used.

[0083] For purposes of explanation, the composition of shifts shown in FIGURE 5 may be assembled by picking all of the relative shift values (*e.g.*, shift values  $S_{CL1}$  through  $S_{CL4}$  and  $S_{IL1}$  through  $S_{IL4}$ ) from the same time/depth slice. This produces an approximation of geologic structure that is has higher accuracy when the relative shift values are constant along the vertical direction (*e.g.*, in time or depth). Nevertheless, this approximation has reduced accuracy in practice when the relative shift values are often not constant along the vertical direction.

[0084] In other words, calculated shifts may actually vary along traces. For example, shifts may be calculated locally over a finite averaging window. This may lead to calculated shifts that vary vertically along traces, for example. Consequently, while the methods described herein may be used to process static shifts that are constant along traces, the methods described herein are not so limited and may be used to process dynamic shifts that vary along traces.

[0085] In some configurations, the approximation of geologic structure may be produced with increased accuracy by utilizing the method of “following the horizon.” The method of following the horizon may be used (*e.g.*, in the alignment process of FIGURE 3) to produce an approximation of geologic structure that has increased accuracy, even when the relative shift values are not constant along the vertical direction. When assembling the composition of shifts using the method of following the horizon, the relative shift values (*e.g.*, the individual entries for the sum of shifts) may be picked from different times/depths, which are given by the previous shift values that have been combined together (*e.g.*, that have been entered into the sum of relative shift values). For example, in the method of following the horizon, the composition of shifts may take the general form of  $S_1 + S_2 + \dots + S_{i-1} + S_i + \dots$  in

which each entry value  $S_i$  is picked from a time/depth that is defined by the previous composition of shifts  $S_1 + S_2 + \dots + S_{i-1}$ .

[0086] In configurations in which the alignment process is performed utilizing the method of following the horizon, the shift values that follow the horizon may be combined together in the vortex calculation, rather than the shift values corresponding to the time/depth slice as shown in FIGURE 5. Consequently, the loop corresponding to the vortex calculation may include shift values corresponding to many different depths in the vertical direction or time slices, rather than shift values corresponding to one particular time/depth slice.

10 [0087] FIGURE 7A illustrates an example noise map generated by the vortex calculation process of FIGURE 6. In the noise map of FIGURE 7A, which represents a subsurface region being investigated, the value of the noise  $N$  assigned to each point is depicted by a point with a level of darkness based on the respective magnitude of the value of noise  $N$  at that point. In FIGURE 7A, for example, darker points represent values of noise  $N$  that are higher in magnitude, and lighter points represent values of noise  $N$  that are lower in magnitude. The points are positioned in the noise map based on the coordinates in the cross-line and in-line directions to which each value of noise  $N$  was assigned in S506. Accordingly, darker regions in the noise map of FIGURE 7A represent regions of high noise  $N$ . Because high values of noise  $N$  often coincide with the presence of discontinuities, the darker regions in the noise map of FIGURE 7A may also indicate the likely presence of discontinuities in these portions of the region being investigated. The values of noise  $N$  used to construct FIGURE 7A were calculated using Equation 3. Nevertheless, the values of noise  $N$  may be calculated using another equation, such as Equation 1, to generate a noise map similar to FIGURE 7A. Such a noise map generated with values of noise  $N$  calculated using another equation may have a different level of contrast than FIGURE 7A, and discontinuities may be more or less apparent than in FIGURE 7A depending on the level of contrast.

[0088] FIGURE 7B illustrates an example coherency map of the same region shown in FIGURE 7A that was generated using a typical process of geologic surface reconstruction and representation. In particular, the coherency map of FIGURE 7B was generated using a coherency (or cross-correlations product) method that is often used to generate structural representations from collected seismic data. Similarly to FIGURE 7A, FIGURE 7B represents structural features in a plane defined by the in-

line and cross-line directions. In the seismic map of FIGURE 7B, darker regions also represent discontinuities.

[0089] Upon closer comparison of FIGURES 7A and 7B, however, it can be seen that FIGURE 7A represents discontinuities (dark regions) with greater contrast to the background (white or grey regions) than FIGURE 7B. Specifically, the vortex calculation process used to generate FIGURE 7A makes it easier to observe patterns in the region being investigated and assists with one or more of the determination of whether discontinuities are real, the determination of which types of discontinuities are present, and the determination of where discontinuities are located.

[0090] In S208, the computing system or a user thereof may analyze the noise map generated using the vortex calculation of S206 (or the noise data produced during the vortex calculation), such as the noise map shown in FIGURE 7A, to make one or more of a determination whether discontinuities exist, a determination of the types of discontinuities present, and a determination of where discontinuities are located.

[0091] In S210, the computing system or a user may utilize the noise map generated using the vortex calculation of S206 and the information about probable discontinuities determined in S208 in combination with other analysis techniques (for example, in combination with the seismic map of FIGURE 7B generated using a coherency method) to make an ultimate determination of the geologic structure of the region being investigated. For example, the information gained from a plurality of analysis techniques including, for example, vortex calculation, coherency methods, and certain methods utilizing stacking, may be used to create a composite representation of the structural features of a region being investigated that provides a more complete picture of the structure than any one of the methods by itself. By synthesizing the data generated using several techniques, such as vortex calculation, coherency methods, and certain methods utilizing stacking, the computing system or user may obtain a more complete understanding of the structure of the region being investigated that may enable a prospector to make an informed decision of whether to extract resources from an investigated region.

[0092] In some embodiments, after determining the geologic structure of the region being studied in S210, the computing system may render a reconstructed image of such region, including any discontinuities. The image may be displayed on a display device (not shown) or printed on a recording medium by a printer (not shown)

for further review by a prospector. Thereafter, the processes illustrated in FIGURE 2 may end.

[0093] The processes of FIGURES 2, 3, and 6 may provide several advantages when determining and reconstructing the geological structure of a prospected region.

5 For example, such processes may provide an attribute, in the form of the noise  $N$  calculated during vortex calculation, as a measure for geologic discontinuities. Further, such processes may be implemented and executed at a faster speed than processes using other seismic attributes for geologic discontinuity picking, such as processes using coherency or energy ratio that implement computationally intensive  
10 and time-consuming calculations.

[0094] Modifications, additions, or omissions may be made to the processes illustrated in FIGURE 2, as well as to the processes illustrated in FIGURES 3 and 6, without departing from the scope of the present disclosure. For example, the order of the processes may be performed in a different manner than that described and some  
15 processes may be performed at the same time. Additionally, each individual process may include additional processes without departing from the scope of the present disclosure. Further, more processes may be added or processes may be removed without departing from the scope of the disclosure.

[0095] While particular examples of the invention have been described above  
20 using 3-dimensional systems, the inventive concept is not limited to 3-dimensional systems and may be readily applied in 4 or more dimensions. In some configurations, for example, the systems and methods described herein may produce useful results for higher dimensions as well (*e.g.*, 4D data like 4D time lapse data, or gather data, which is also 4D; 5D data, such as wide azimuth seismic data). In such configurations,  
25 having more data may beneficially provide higher statistical consistency.

[0096] FIGURE 7A represents a noise map rendered using the processes illustrated in FIGURES 2, 3, and 6 applied to seismic samples in a particular time slice or at a particular depth in the region being investigated. Thus, the processes of FIGURE 2, including the alignment process of FIGURE 3 and the vortex calculation  
30 of FIGURE 6, may be repeated for different points in time or different subsurface depths to generate additional noise maps that may provide further information about the region being investigated, such as changes in the region over time or changes in the region based on subsurface depth.

[0097] FIGURE 8 illustrates a schematic diagram of an example seismic exploration system 700 configured to collect geophysical data and reconstruct geologic structures from the geophysical data in accordance with some embodiments of the present disclosure. Seismic exploration system 700 may be configured to produce images of subsurface geological formations for further evaluation and study.

[0098] Seismic exploration system 700 includes one or more seismic energy seismic energy sources 730, one or more receivers 740, and computing system 710, which may be communicatively coupled via network 720. Computing system 710 may generate composite seismic images based on signals generated by a wide variety of sources 730. For example, computing system 710 may operate in conjunction with sources 730 and receivers 740 having any structure, configuration, or function described above with respect to FIGURES 1-7.

[0099] Seismic energy sources 730 and receivers 740 may be located within a pre-determined exploration area 750. FIGURE 8 shows seismic energy sources 730 and receivers 740 disposed at the upper surface 752 of exploration area 750, but seismic energy sources 730 and receivers 740 may be disposed anywhere in or near exploration area 750. Exploration area 750 may be any defined area selected for seismic survey or exploration. Survey of the exploration area may include the activation of a seismic energy source 730 that may radiate an acoustic wave field that expands downwardly through the layers beneath the earth's surface. The seismic wave field may then be partially reflected from the respective layers as a wave front recorded by receivers 740. For example, seismic energy source 730 may generate seismic waves and receivers 740 may record rays 732 and 734, which may be reflected by interfaces between subsurface layers 754, 756, and 758, oil and gas reservoirs, such as target reservoir 760, or other subsurface structures. Subsurface layers 754, 756, and 758 may have various densities, thicknesses, or other characteristics. Target reservoir 760 may be separated from surface 752 by multiple subsurface layers 754, 756, and 758. As the embodiment depicted in FIGURE 8 is an example, there may be more or fewer layers 754, 756, or 758 or target reservoirs 760. Similarly, there may be more or fewer rays 732 and 734. Additionally, some source waves may not be reflected, as illustrated by ray 736. Source 104 and receivers 102a-102f (described above with reference to FIGURE 1) may be examples of seismic energy sources 730 and receivers 740.

[00100] Seismic energy source 730 may be referred to as an acoustic source, seismic source, energy source, and source 730. In some embodiments, source 730 may be located on or proximate to surface 752 of the earth within exploration area 750. A particular source 730 may be spaced apart from other similar sources. Source  
5 730 may be operated by a central controller that coordinates the operation of several sources 730. Further, a positioning system, such as a global positioning system (“GPS”), may be utilized to locate and time-correlate sources 730 and receivers 740. Multiple sources 730 may be used to improve testing efficiency, provide greater azimuthal diversity, improve the signal to noise ratio, or improve spatial sampling.  
10 The use of multiple sources 730 may also input a stronger signal into the ground than a single, independent source 730.

[00101] Source 730 may comprise any type of seismic device that generates controlled seismic energy used to perform reflection or refraction seismic surveys, such as a seismic vibrator, vibroseis, dynamite, an air gun, a thumper truck, or any  
15 other suitable seismic energy source. Source 730 may radiate seismic energy into surface 752 and subsurface formations during a defined interval of time. Source 730 may impart energy through a sweep of multiple frequencies or at a single monofrequency, or through a combination of at least one sweep and at least one monofrequency. In some embodiments, sources 730 may be impulsive (such as, for  
20 example, explosives or air guns) or vibratory. Impulsive sources may generate a short, high-amplitude seismic signal while vibratory sources may generate lower-amplitude signals over a longer period of time. Vibratory sources may be instructed, by means of a pilot signal, to generate a target seismic signal with energy at one or more desired frequencies, and these frequencies may vary over time.

[00102] Receiver 740 may be located on or proximate to surface 752 of the earth within an exploration area. Receiver 740 may be any type of instrument that is operable to transform seismic energy or vibrations into a voltage signal. For example, receiver 740 may be a vertical, horizontal, or multicomponent geophone, accelerometers, or optical fiber with wire or wireless data transmission, such as a  
30 three component (“3C”) geophone, a 3C accelerometer, or a 3C Digital Sensor Unit (“DSU”). A plurality of receivers 740 may be utilized within an exploration area to provide data related to multiple locations and distances from sources 730. Receivers 740 may be positioned in a plurality of configurations, such as linear, grid, array, or any other suitable configuration. In some embodiments, receivers 740 may be

positioned along one or more strings 742. Each receiver 740 may be spaced apart from adjacent receivers 740 in the string 742. Spacing between receivers 740 in string 742 may be approximately the same preselected distance, or span, or the spacing may vary depending on a particular application, exploration area topology, or any other suitable parameter. One or more receivers 740 may transmit raw seismic data from reflected seismic energy, via network 720, to computing system 710. Strings 110a-110f (described above with reference to FIGURE 1) may be examples of strings 742.

[00103] The seismic data collection process (called a “survey”) may be repeated at various time intervals to determine changes in target reservoir 760, for example. The time intervals may be months or years apart. Data may be collected and organized based on offset distances, such as the distance between a particular source 730 and a particular receiver 740 and the amount of time it takes for rays 732 and 734 from a particular source 730 to reach a particular receiver 740. Data collected during a survey by receivers 740 may be reflected in traces that may be gathered, processed, and utilized to generate a model of the subsurface structure or variations of the structure, for example continuous seismic monitoring.

[00104] Sources 730 and receivers 740 may be communicatively coupled to computing system 710. In some embodiments, one or more receivers 740 may transmit raw seismic data from received seismic energy via network 720 to computing system 710 and computing system 710 may perform pre-processing operations or may transmit the raw seismic data to other computing systems for pre-processing. In some embodiments, a particular computing system 710 may transmit raw seismic data to other computing systems or other site via a network, such as network 720 or any other suitable network. In some embodiments, one or more receivers 740 may transmit raw seismic data from received seismic energy via network 720 to another computing system that may perform pre-processing and subsequently transmit the pre-processed seismic data to computing system 710 for further processing. Computing system 710 may receive data recorded by receivers 740 (in raw or pre-processed format) and may process the data to generate a composite image or may prepare the data for interpretation. Computing system 710 may be operable to perform the processing techniques described above with respect to FIGURES 1–8.

[00105] Computing system 710 may include any instrumentality or aggregation of instrumentalities operable to compute, classify, process, transmit, receive, store, display, record, or utilize any form of information, intelligence, or data. For example,

computing system 710 may be one or more mainframe servers, desktop computers, laptops, cloud computing systems, storage devices, or any other suitable devices and may vary in size, shape, performance, functionality, and price. For example, computing system 710 may include random access memory ("RAM"), one or more  
5 processing resources such as a central processing unit ("CPU") or hardware or software control logic, or other types of volatile or non-volatile memory. Additional components of computing system 710 may include one or more disk drives, one or more network ports for communicating with external devices, various input and output 7 devices, such as a keyboard, a mouse, and a video display. Computing  
10 system 710 may be configured to permit communication over any type of network 720.

[00106] For example, computing system 710 may comprise input and output ("I/O") device 716, memory 712, and processing system 714. Memory 712 may store computer-readable instructions that may instruct computing system 710 to perform  
15 certain processes. For example, when executed by processing system 714, the computer-readable instructions stored in memory 712 may instruct processing system 714 to perform one or more of the processes described above with respect to FIGURES 1-3. In some embodiments, memory 712 may store data received by computing system 710. In some embodiments, computing system 710 may include  
20 other memory that may store such received data.

[00107] Memory 712 and other memory described herein may include, for example, one or more computer readable media. The computer readable media may be one or more computer readable storage medium, for example. A computer readable storage medium may be, for example, an electronic, magnetic, optical,  
25 electromagnetic, or semiconductor system or device or any suitable combination of the foregoing. Examples of such systems or devices include, but are not limited to: a portable computer diskette, a hard disk, a random access memory ("RAM"), a read-only memory ("ROM"), an erasable programmable read-only memory ("EPROM" or flash memory), an appropriate optical fiber with a repeater, a portable compact disc  
30 read-only memory ("CD-ROM"), an optical storage device, a magnetic storage device, or a combination of the foregoing. As described herein, a computer readable storage medium may include any tangible medium able to contain or store a program for use by or in connection with an instruction execution system or device.

[00108] Memory 712 may store, permanently or temporarily, data, operational software, or other information for processing system 714, other components of computing system 710, or other components of system 700. Memory 712 may include any one or a combination of volatile or nonvolatile local or remote devices suitable for storing information. For example, memory 712 may include RAM, ROM, flash memory, magnetic storage devices, optical storage devices, network storage devices, cloud storage devices, solid-state devices, external storage devices, any other suitable information storage device, or a combination of these devices. Memory 712 may store information in one or more databases, file systems, tree structures, any other suitable storage system, or any combination thereof. Furthermore, different types of information stored in memory 712 may use any of these storage systems. Moreover, information stored in memory 712 may be encrypted or unencrypted, compressed or uncompressed, and static or editable. Computing system 710 may have any suitable number, type, and/or configuration of memory 712. Memory 712 may include any suitable information for use in the operation of computing system 710. For example, memory 712 may store computer-executable instructions operable to perform the steps discussed above with respect to FIGURES 1–7 when executed by processing system 714. Memory 712 also may store any seismic data or related data such as, for example, raw seismic data, reconstructed signals, velocity models, seismic images, well logs, or any other suitable information.

[00109] I/O device 716 may transmit data to one or more other devices or networks or may transmit a notification or other information. I/O device 716 may receive data from one or more other devices or networks or may receive input or control signals from a user or another device. Further, I/O device 716 may implement or facilitate one or more of wireless and wired communication between computing system 710 and other devices via direct communication or through a network, such as network 720 or any other suitable communication mechanism. For example, I/O device 716 may be one or more of a user interface device, such as a keyboard, a mouse, a touch-based device, or a display, and a communications device, such as a communication port.

[00110] For example, I/O device 716 may represent any suitable device operable to receive information from network 720, transmit information through network 720, perform suitable processing of information, communicate with other devices, or any combination thereof. I/O device 716 may be any port or connection, real or virtual,

including any suitable hardware and/or software (including protocol conversion and data processing capabilities) that communicates through a LAN, WAN, or other communication system. This communication may allow computing system 710 to exchange information with network 720, other computing systems 710, sources 730, receivers 740, or other components of system 700. Computing system 710 may include any suitable number, type, and/or configuration of I/O device 716.

[00111] Processing system 714 may include one or more processing devices, such as a central processing unit (“CPU” or “processor”), a graphical processing unit (“GPU”), an application specific integrated circuit (“ASIC”), a controller, or any other suitable solid state or analog processing device. Processing system 714 may communicatively couple to I/O device 716 or memory 712 and may control the operation and administration of computing system 710 by processing information received from I/O device 716 or memory 712. Processing system 714 may any hardware or software that operates to control and process information. In some embodiments, processing system 714 may one or more programmable logic device, one or more microcontroller, one or more microprocessor, one or more suitable processing device, or any suitable combination of the preceding. Computing system 710 may include any suitable number, type, and/or configuration of processing system 714. For example, in some embodiments, processing system 714 may be a distributed system of processors with various operations being performed in various data centers. In some embodiments, processing system 714 may be in integrated unit, such as a personal computer or a server. Processing system 714 may execute one or more sets of computer-readable instructions to implement the generation of a composite image based on geophysical data, including the steps described above with respect to FIGURES 1–7. Processing system 714 may also execute any other suitable programs to facilitate the generation of composite images, such as, for example, user interface software to present one or more graphical user interfaces (“GUI”s) to a user.

[00112] Network 720 may be a wireless network, a local area network (“LAN”), a wide area network (“WAN”) such as the Internet, or any other suitable type of network. For example, network 720 may communicatively couple receivers 740 with computing system 710. Further, network 720 may communicatively couple a particular receiver 740 with other receivers 740.

[00113] Although discussed generally with reference to a land implementation, embodiments of the present disclosure are also useful in sea bed applications. In a

seabed acquisition application, in which receivers 740 are placed on the seabed, receivers 740 may include 3C geophones and hydrophones, for example.

[00114] This disclosure encompasses all changes, substitutions, variations, alterations, and modifications to the example embodiments herein that a person  
5 having ordinary skill in the art would comprehend. Similarly, where appropriate, the appended claims encompass all changes, substitutions, variations, alterations, and modifications to the example embodiments herein that a person having ordinary skill in the art would comprehend. Moreover, reference in the appended claims to an apparatus or system or a component of an apparatus or system being adapted to,  
10 arranged to, capable of, configured to, enabled to, operable to, or operative to perform a particular function encompasses that apparatus, system, component, whether or not it or that particular function is activated, turned on, or unlocked, as long as that apparatus, system, or component is so adapted, arranged, capable, configured, enabled, operable, or operative.

[00115] Herein, “or” is inclusive and not exclusive, unless expressly indicated otherwise or indicated otherwise by context. Therefore, herein, “A or B” means “A, B, or both,” unless expressly indicated otherwise or indicated otherwise by context. Moreover, “and” is both joint and several, unless expressly indicated otherwise or indicated otherwise by context. Therefore, herein, “A and B” means “A and B, jointly  
20 or severally,” unless expressly indicated otherwise or indicated otherwise by context.

[00116] Any of the steps, operations, or processes described herein may be performed or implemented with one or more hardware or software modules, alone or in combination with other devices. In one embodiment, a software module is implemented with a computer program product comprising a computer-readable  
25 medium containing computer program code, which can be executed by a computer processor for performing any or all of the steps, operations, or processes described. In certain embodiments, the computer-readable medium may be non-transitory.

[00117] Embodiments of the invention may also relate to an apparatus for performing the operations herein. This apparatus may be specially constructed for the  
30 required purposes, or it may comprise a general-purpose computing device selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a tangible computer readable storage medium or any type of media suitable for storing electronic instructions, and coupled to a computer system bus. Furthermore, any computing systems referred to in the

specification may include a single processor or may be architectures employing multiple processor designs for increased computing capability.

[00118] The preceding detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. Some of the preceding  
5 embodiments are discussed, for simplicity, with regard to the terminology and structure of geologic surface reconstruction using implicit potential functions with a minimal bending energy concept. The embodiments, however, are not limited to these configurations, and may be extended to other arrangements.

[00119] Reference throughout the specification to “one embodiment” or “an  
10 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  
15 characteristics may be combined in any suitable manner in one or more embodiments.

[00120] Although the present invention has been described with several embodiments, a myriad of changes, variations, alterations, transformations, and modifications may be suggested to one skilled in the art, and it is intended that the present invention encompass such changes, variations, alterations, transformations,  
20 and modifications as fall within the scope of the appended claims. Moreover, while the present disclosure has been described with respect to various embodiments, it is fully expected that the teachings of the present disclosure may be combined in a single embodiment as appropriate.

[00121] The written description uses examples of the subject matter disclosed to  
25 enable any person skilled in the art to practice the same, including making and using the described devices or systems and performing any of the described 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 examples are intended to be within the scope of the claims.

WHAT IS CLAIMED IS:

1. A method for determining a geophysical profile from geophysical data, the method comprising:
  - receiving geophysical data from a data source, the geophysical data including
  - 5 a plurality of traces corresponding to a region of earth; and
  - performing a vortex calculation to transform the geophysical data into a plurality of characteristic values, each characteristic value representing a particular portion of the region of earth and quantifying the likelihood that a structural discontinuity exists in the particular portion of the region of earth represented by such
  - 10 characteristic value.
2. The method of claim 1, wherein performing the vortex calculation comprises, for each particular portion of the region of earth, combining a plurality of shift values used to align particular traces, which are related to such particular portion,
- 15 to determine the characteristic value representing such particular portion, the plurality of traces included in the geophysical data including the particular traces.
3. The method of claim 2, wherein the plurality of shift values correspond to shifts in at least four dimensions.
- 20
4. The method of claim 2, wherein combining the plurality of shift values used to align particular traces comprises determining absolute values of the plurality of shift values and combining the absolute values of the plurality of shift values together.
- 25
5. The method of claim 2,
  - wherein the plurality of shift values correspond to shifts performed over a plurality of different slices, and
  - wherein performing the vortex calculation further comprises using a method of
  - 30 following the horizon when combining the plurality of shift values.

6. The method of claim 1, wherein performing the vortex calculation comprises, for each particular portion of the region of earth:

combining a first plurality of shift values used to align first particular traces to determine a first preliminary value representing such particular portion;

5 combining a second plurality of shift values used to align second particular traces, which are related to such particular portion, to determine a second preliminary value representing such particular portion;

performing an averaging process on the first preliminary value and the second preliminary value to determine the characteristic value representing such particular  
10 portion,

wherein the plurality of traces included in the geophysical data includes the first particular traces and the second particular traces, and

wherein the first particular traces and the second particular traces are related to such particular portion.

15

7. The method of claim 1, further comprising:

generating a pictorial representation of the region of earth in which each particular portion of the region of earth is depicted with at least one of a hue value and a shading value that is proportional to the characteristic value representing such  
20 particular portion, wherein the at least one of the hue value and the shading indicates the likelihood that a structural discontinuity exists in such particular portion.

8. A system for determining a geophysical profile from geophysical data, the system comprising:

25 a computing system configured to:

receive geophysical data from a data source, the geophysical data including a plurality of traces corresponding to a region of earth; and

perform a vortex calculation to transform the geophysical data into a plurality of characteristic values, each characteristic value representing a particular  
30 portion of the region of earth and quantifying the likelihood that a structural discontinuity exists in the particular portion of the region of earth represented by such characteristic value.

9. The system of claim 8, wherein the computing system, when performing the vortex calculation, is configured to, for each particular portion of the region of earth, combine a plurality of shift values used to align particular traces, which are related to such particular portion, to determine the characteristic value  
5 representing such particular portion, the plurality of traces included in the geophysical data including the particular traces.

10. The system of claim 9, wherein the computing system, when combining the plurality of shift values used to align particular traces, is configured to  
10 determine absolute values of the plurality of shift values and combine the absolute values of the plurality of shift values together.

11. The system of claim 9,  
wherein the plurality of shift values correspond to shifts performed over a  
15 plurality of different slices, and  
wherein the computing system, when performing the vortex calculation, is further configured to use a method of following the horizon when combining the plurality of shift values.

20 12. The system of claim 8, wherein the computing system, when performing the vortex calculation, is configured to, for each particular portion of the region of earth:

combine a first plurality of shift values used to align first particular traces to determine a first preliminary value representing such particular portion;

25 combine a second plurality of shift values used to align second particular traces, which are related to such particular portion, to determine a second preliminary value representing such particular portion;

perform an averaging process on the first preliminary value and the second preliminary value to determine the characteristic value representing such particular  
30 portion,

wherein the plurality of traces included in the geophysical data includes the first particular traces and the second particular traces, and

wherein the first particular traces and the second particular traces are related to such particular portion.

13. The system of claim 8, wherein the computing system is further configured to:

5 generate a pictorial representation of the region of earth in which each particular portion of the region of earth is depicted with at least one of a hue value and a shading value that is proportional to the characteristic value representing such particular portion, wherein the at least one of the hue value and the shading indicates the likelihood that a structural discontinuity exists in such particular portion.

10 14. A non-transitory computer-readable medium storing computer-readable instructions that, when executed by a processing system, instruct the processing system to perform processes for determining a geophysical profile from geophysical data, the processes comprising:

15 receiving geophysical data from a data source, the geophysical data including a plurality of traces corresponding to a region of earth; and

performing a vortex calculation to transform the geophysical data into a plurality of characteristic values, each characteristic value representing a particular portion of the region of earth and quantifying the likelihood that a structural discontinuity exists in the particular portion of the region of earth represented by such  
20 characteristic value.

15. The non-transitory computer-readable medium of claim 14, wherein performing the vortex calculation comprises, for each particular portion of the region of earth, combining a plurality of shift values used to align  
25 particular traces, which are related to such particular portion, to determine the characteristic value representing such particular portion, the plurality of traces included in the geophysical data including the particular traces.

16. The non-transitory computer-readable medium of claim 15, wherein  
30 the plurality of shift values correspond to shifts in at least four dimensions.

17. The non-transitory computer-readable medium of claim 15, wherein combining the plurality of shift values used to align particular traces comprises

determining absolute values of the plurality of shift values and combining the absolute values of the plurality of shift values together.

18. The non-transitory computer-readable medium of claim 15,  
5 wherein the plurality of shift values correspond to shifts performed over a plurality of different slices, and  
wherein performing the vortex calculation further comprises using a method of following the horizon when combining the plurality of shift values.

10 19. The non-transitory computer-readable medium of claim 14, wherein performing the vortex calculation comprises, for each particular portion of the region of earth:

combining a first plurality of shift values used to align first particular traces to determine a first preliminary value representing such particular portion;

15 combining a second plurality of shift values used to align second particular traces, which are related to such particular portion, to determine a second preliminary value representing such particular portion;

performing an averaging process on the first preliminary value and the second preliminary value to determine the characteristic value representing such particular  
20 portion,

wherein the plurality of traces included in the geophysical data includes the first particular traces and the second particular traces, and

wherein the first particular traces and the second particular traces are related to such particular portion.

25

20. The non-transitory computer-readable medium of claim 15, wherein the computer-readable instructions, when executed by the processing system, instruct the processing system to perform processes further comprising:

generating a pictorial representation of the region of earth in which each  
30 particular portion of the region of earth is depicted with at least one of a hue value and a shading value that is proportional to the characteristic value representing such particular portion, wherein the at least one of the hue value and the shading indicates the likelihood that a structural discontinuity exists in such particular portion.

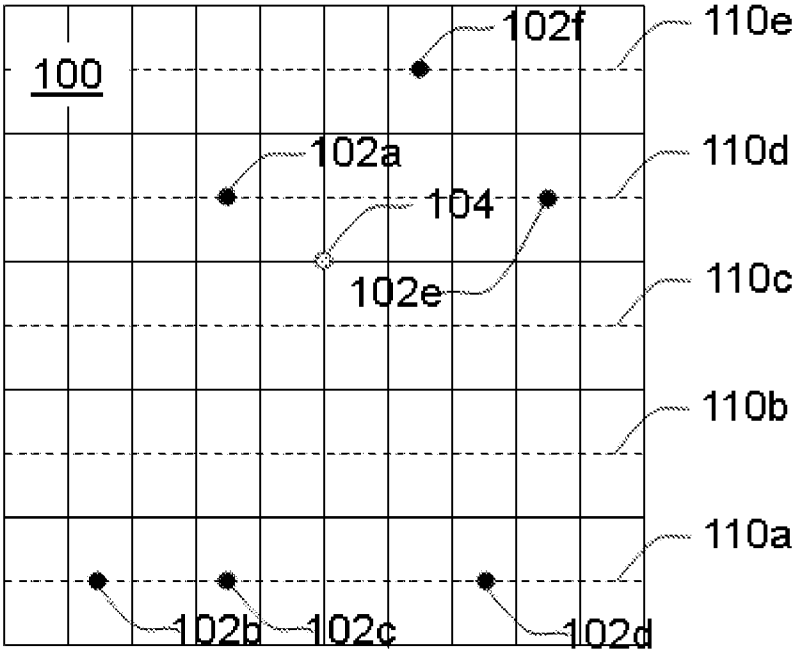


FIGURE 1

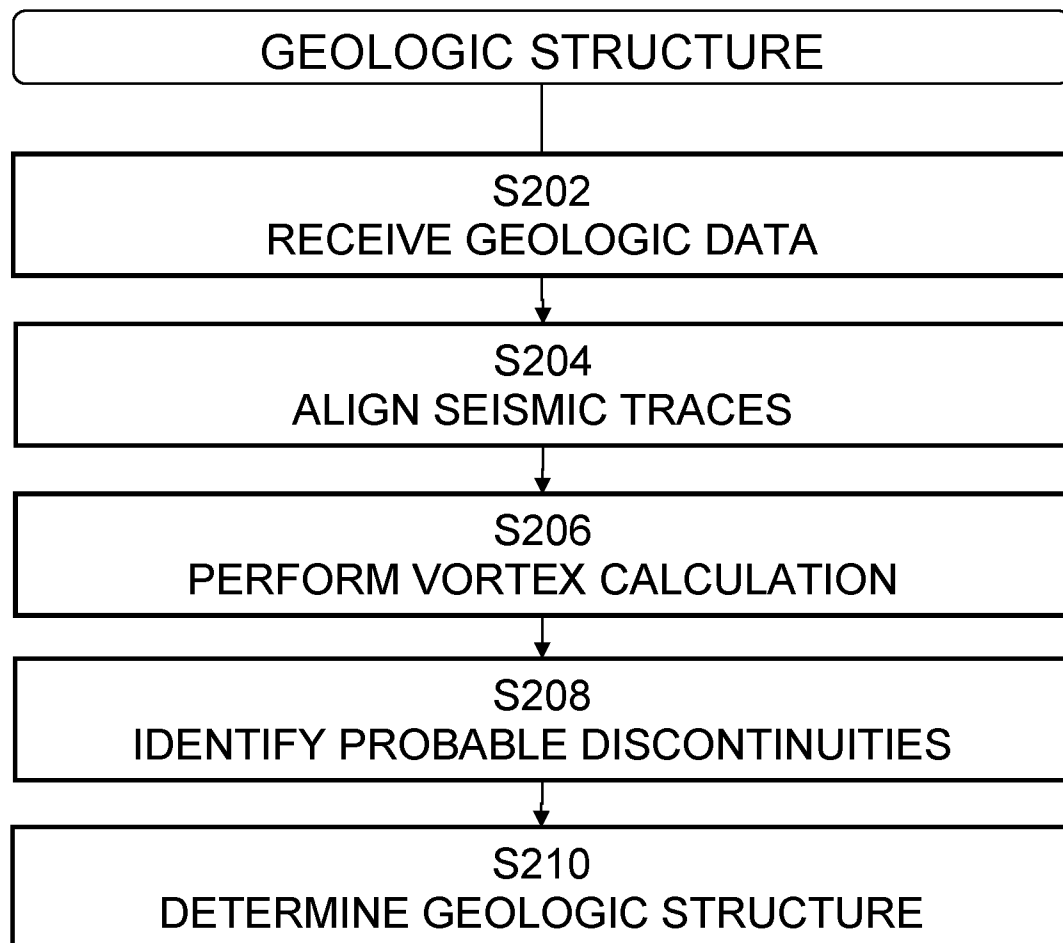


FIGURE 2

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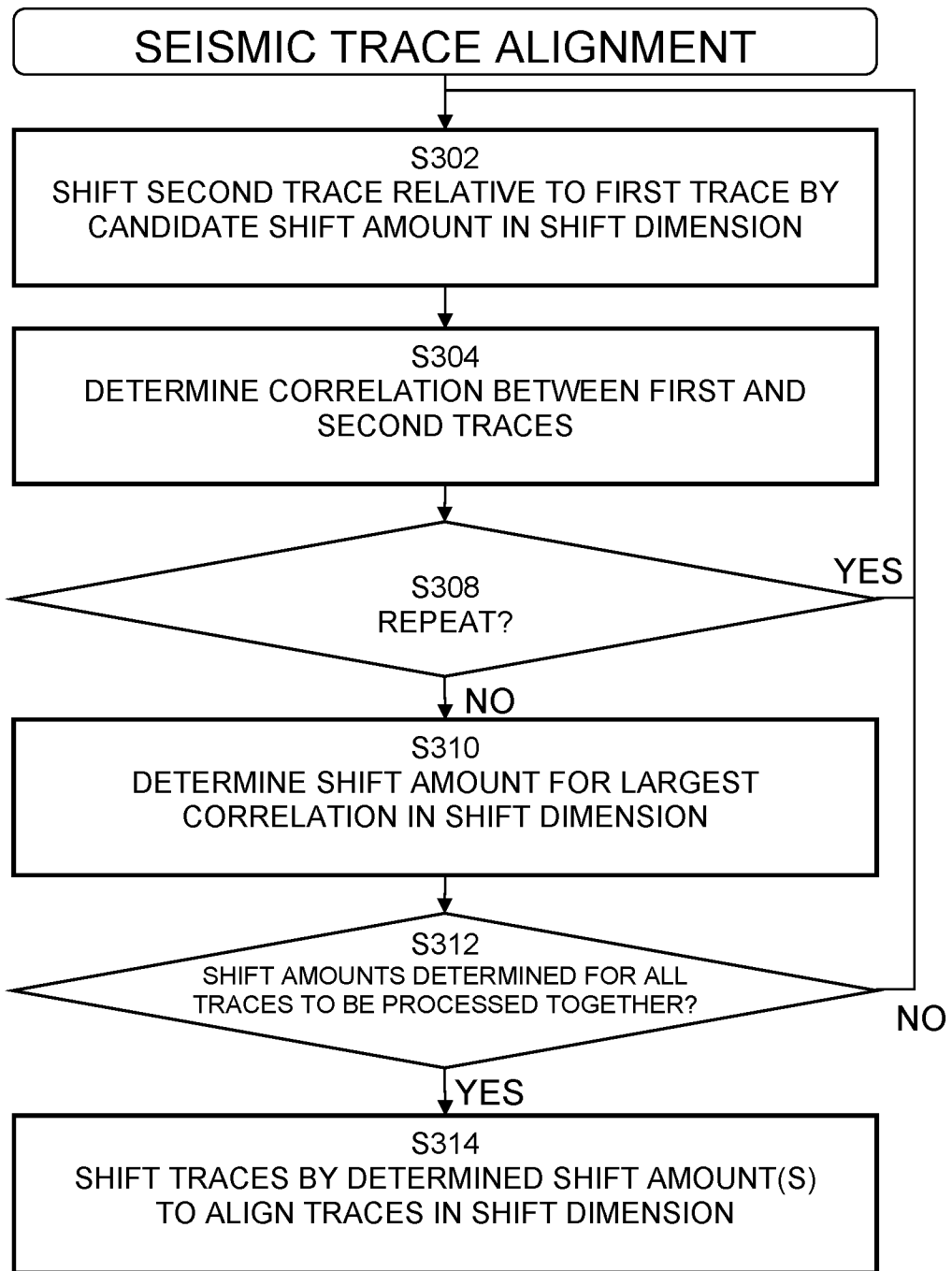


FIGURE 3

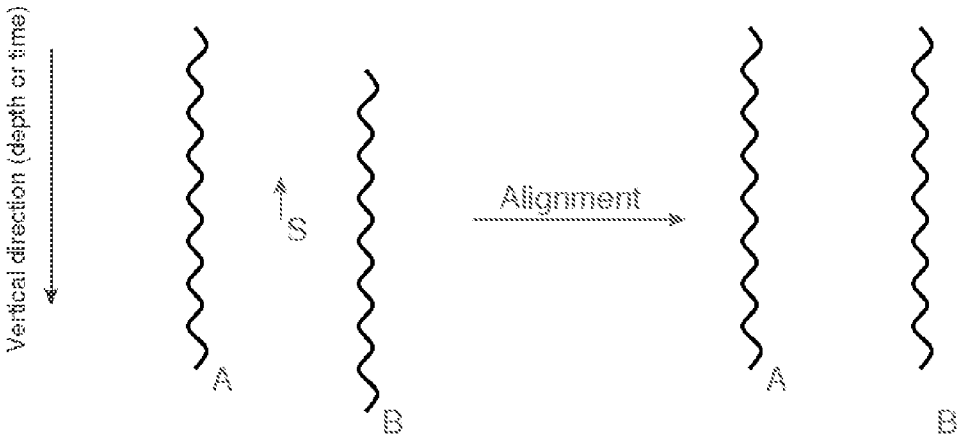


FIGURE 4

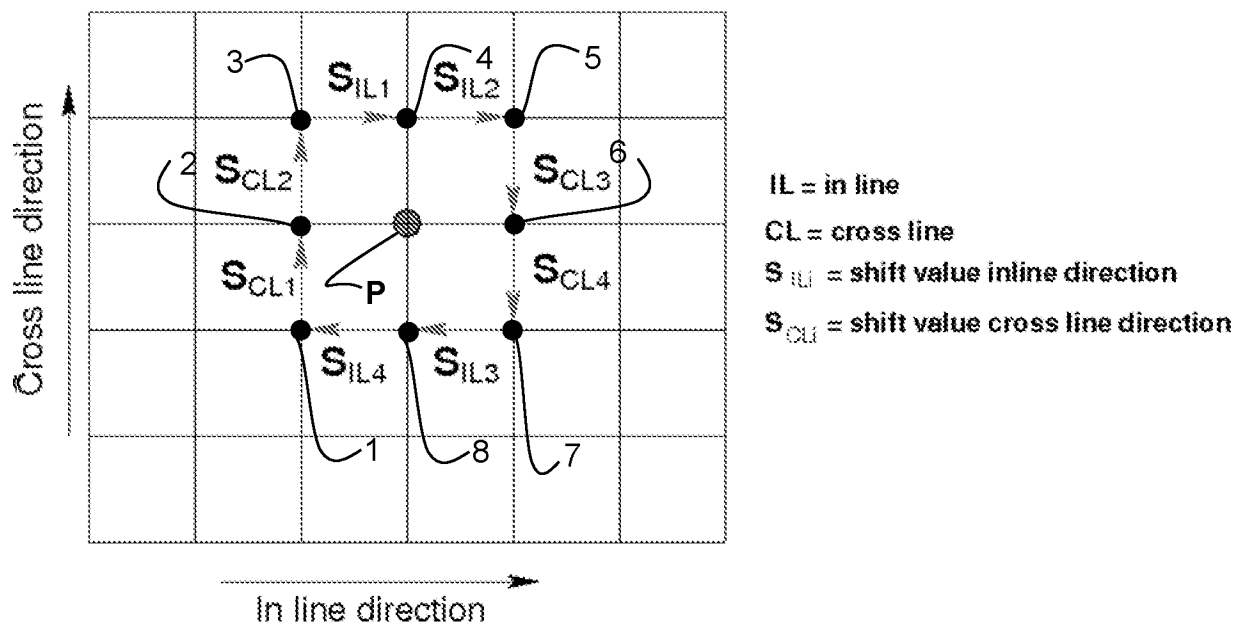


FIGURE 5

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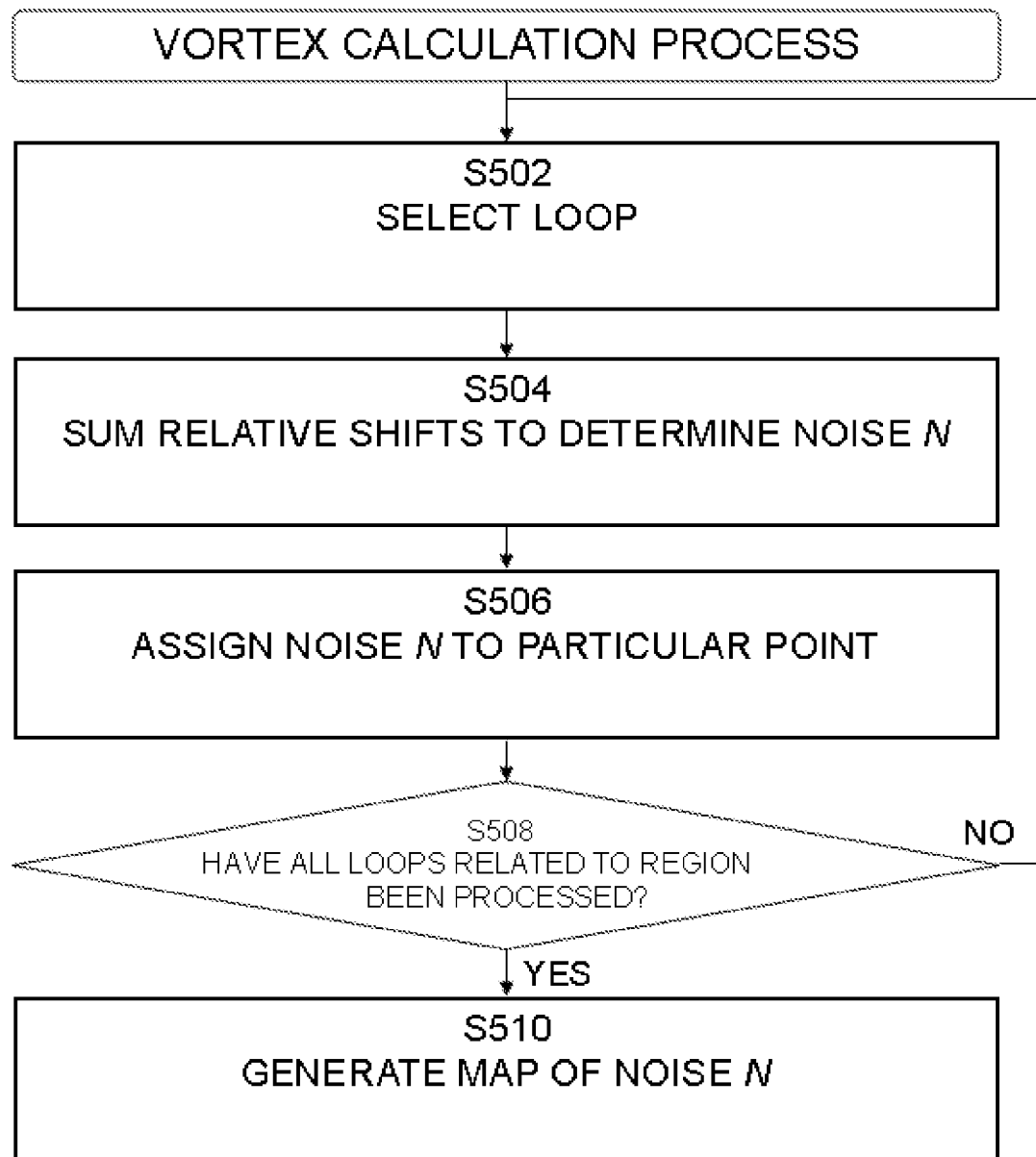


FIGURE 6

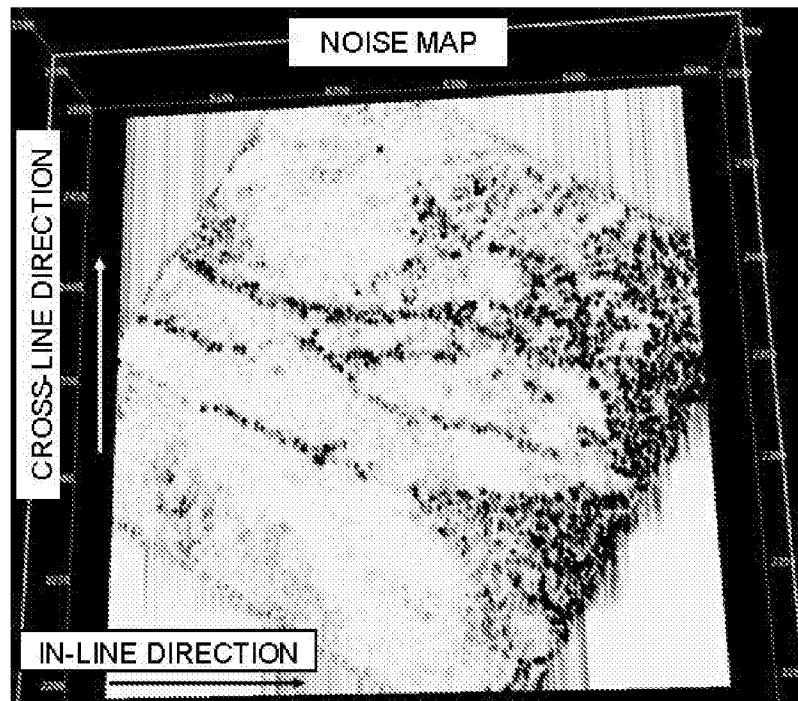


FIGURE 7A

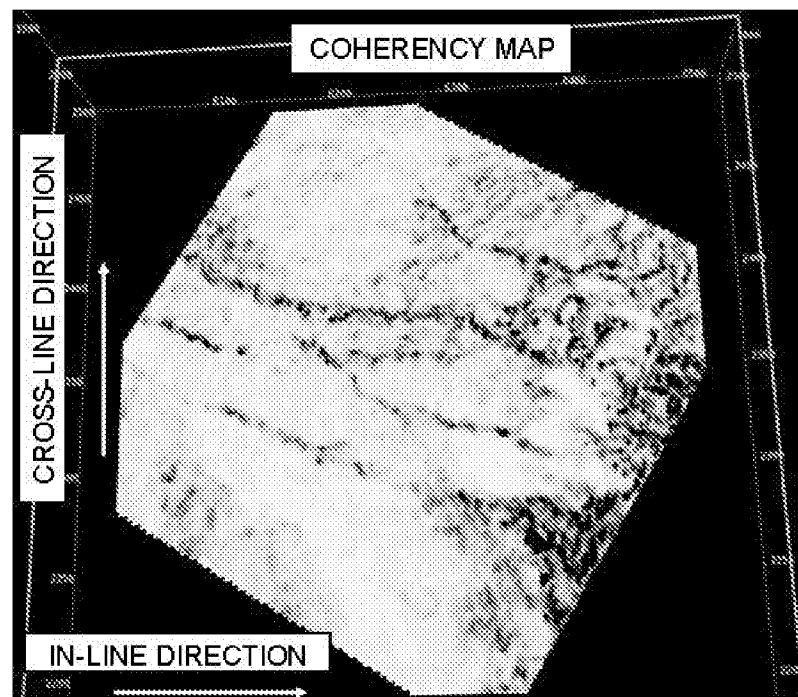
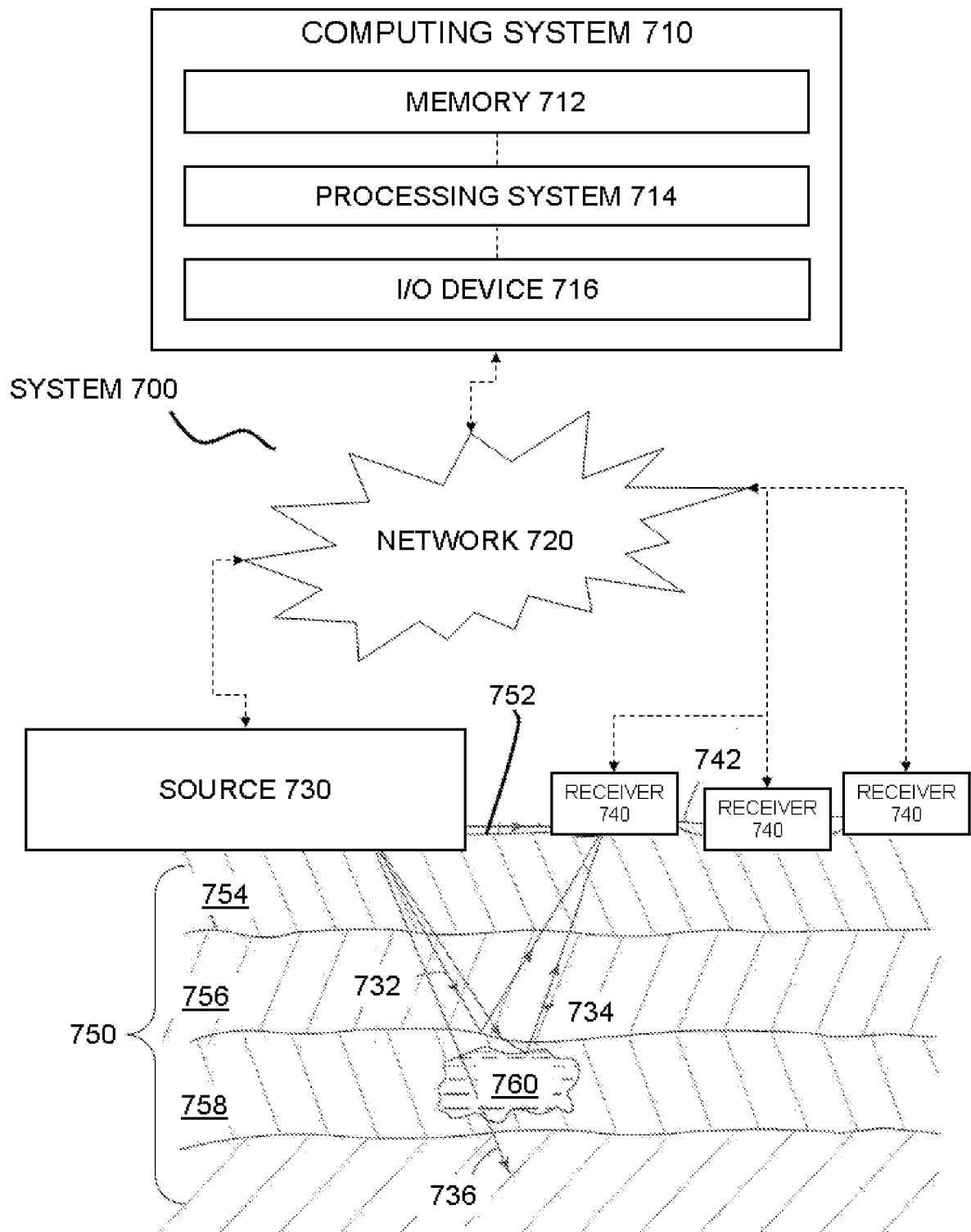


FIGURE 7B

**FIGURE 8**

# INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2014/002731

## A. CLASSIFICATION OF SUBJECT MATTER

INV. G01V1/30

ADD. G01V1/34

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

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                       | Relevant to claim No. |
|-----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X         | AFTAB ALAM ET AL: "Dip, azimuth and fault from continuous phase spectrum", SEG/NEW ORLEANS 2006 ANNUAL MEETING TECHNICAL PROGRAM EXPANDED ABSTRACTS 2006, 2 October 2006 (2006-10-02), pages 998-1002, XP055197048, DOI: 10.1190/1.2370424 page 998 - page 1001<br>----- | 1-20                  |
| X         | US 2009/292475 A1 (ALAM AFTAB [US] ET AL) 26 November 2009 (2009-11-26) paragraphs [0048] - [0050], [0077] - [0081], [0084] - [0091], [0092] - [0107] paragraphs [0108] - [0111], [0113] - [0118], [0123] - [0134], [0137] figures 8-17<br>-----<br>-/--                 | 1-20                  |



Further documents are listed in the continuation of Box C.



See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

1 July 2015

Date of mailing of the international search report

10/07/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040,  
Fax: (+31-70) 340-3016

Authorized officer

Sartoni, Giovanni

## INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2014/002731

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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