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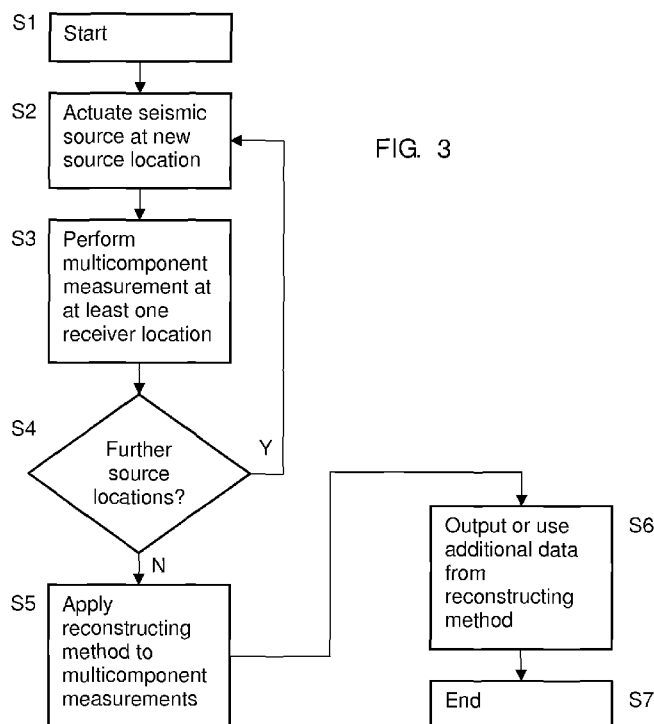
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(54) Title: METHOD OF PROVIDING SEISMIC DATA



(57) Abstract: A method of providing seismic data (such as marine seismic data) is disclosed. A seismic source is actuated at a plurality of source locations (S2, S4). For each source location, a multicomponent seismic measurement is performed at at least one receiver location (S3). A reconstructing method is applied to each multicomponent measurement to obtain additional data corresponding to source locations additional to the source locations at which the source was actuated (S5). The additional data are output and/or used (S6).



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Method of Providing Seismic Data

Technical field

- 5 The present invention relates to a method of providing seismic data. In particular, but not exclusively, the present invention relates to a method of providing marine seismic data.

Background

10

A number of texts cover the principles of acquisition of marine seismic data (e.g., Sheriff and Geldart, 1995; Ikelle and Amundsen, 2005). There are several configurations of source and receiver distributions; those commonly used for petroleum exploration are (1) towed-streamer acquisition, where sources and receivers are distributed horizontally in the water column near the sea surface; (2) ocean-bottom seismic (OBS) acquisition, where the sources are towed in the water column and the receivers are on the seafloor; and (3) vertical-cable (VC) acquisition, where the sources are towed near the sea surface as in towed-streamer and OBS acquisition but the receivers are distributed in the water in a vertical array.

20

The receiver systems in these configurations are (1) normally hydrophones but possibly also vertically oriented geophones for towed-streamer acquisition; (2) hydrophones and three-component (3-C) geophones or accelerometers for OBS acquisition; and (3) hydrophones for VC acquisition. In the OBS experiment, the geophones or accelerometers are in contact with the seafloor so that the recording of shear waves is enabled. If the horizontally oriented geophones or accelerometers were not in contact with the seafloor, they would produce a measurement of the horizontal derivative of the pressure field.

25

- 30 The benefits of 2-C streamers are well known (Berni, 1984; Ruehle, 1984; Amundsen, 2001; Carlson et al., 2007). When introduced in 2007 by PGS, the geostreamer provided a step change in marine seismic acquisition. The geostreamer is equipped with both hydrophones and vertically oriented geophones so that, among others, up/down wavefield decomposition or receiver-side deghosting can be achieved, thereby enabling the acquisition of broadband seismic data.
- 35

Three-dimensional (3-D) up/down decomposition of the wavefield in the water column requires the proper measurement of both pressure on a hydrophone and vertical component of particle velocity on a vertically oriented geophone. To date, such measurements are not available in towed streamer acquisition due to the large cross-
5 line separation between streamers, which typically is between 50-100 m.

Robertsson et al. (2006, 2008) state that 3-C geophone measurements would bring significant benefits to towed-marine seismic data if recorded and processed in conjunction with the pressure data. They show that particle velocity measurements
10 can increase the effective Nyquist wavenumber by a factor of two or three, depending on how they are used.

Singh et al (2009) propose seismic acquisition using a plurality of streamers, with a streamer having a plurality of compact clusters of hydrophones and/or particle motion
15 sensors. Cluster means a plurality of sensors of the same type that are used together. The streamer is adapted to provide gradient measurements of pressure with the objective to provide improved methods of interpolating seismic data between adjacent streamers.

20 **Summary**

In ocean-bottom seismic (OBS) and vertical-cable (VC) surveying, receiver stations are stationary e.g. on the sea floor while a source vessel shoots on a predetermined x-y grid on the sea surface. To reduce exploration cost, the shot point interval often is so
25 coarse that the data recorded at a given receiver station are undersampled and thus irrecoverably aliased. However, when the pressure field and its x- and y-derivatives are measured in the water column, the pressure can be reconstructed by interpolation. Likewise, if the vertical component of the particle velocity (or acceleration) and its x- and y-derivatives are measured, then also this component can be reconstructed by
30 interpolation. The interpolation scheme can be any scheme that reconstructs the field from its sampled values and sampled derivatives. In the case that the two field's first-order derivatives are recorded the number of components is e.g. six. When their second-order derivatives are also measured, the number of components is e.g. ten. The properly interpolated measurements of pressure and vertical component of particle
35 velocity from the multicomponent measurements allow proper up/down wavefield decomposition, or deghosting. New wavefield reconstruction methods as those

suggested here are of significant interest since, presently, the seismic industry is in the process of developing multicomponent cables or streamers, and is in the process of carrying out research on new multicomponent sensors.

- 5 According to a first aspect of the present invention, there is provided a method of providing seismic data. A seismic source is actuated at a plurality of source locations. For each source location, a multicomponent seismic measurement is performed at at least one receiver location. A reconstructing method is applied to each multicomponent measurement to obtain additional data corresponding to source
10 locations additional to the source locations at which the source was actuated.

Each of the additional locations may be disposed between ones of the source locations at which the source was actuated.

- 15 The additional data obtained from applying the reconstructing method may be considered as being for, or relating to, or being associated with, or relating to the wavefield at, the at least one receiver location at which the multicomponent seismic measurement was performed. For example, in the simple case of two source locations and a single receiver location, the additional data obtained from applying the
20 reconstructing method might be considered as relating to the wavefield at that receiver location, thereby providing additional data for that receiver location as if a seismic source had been actuated at an additional source location to the two source locations actually used.

- 25 The source locations at which the source was actuated may comprise a regular grid.

The grid may be one of a triangular grid, a rectangular grid and a hexagonal grid.

- For each source location, the multicomponent seismic measurement may be performed
30 at a plurality of receiver locations, and the method may comprise applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to receiver locations additional to the receiver locations at which the multicomponent measurement was performed.

- 35 According to a second aspect of the present invention, there is provided a method of providing seismic data, comprising the steps of: actuating a seismic source at at least

one source location; for each source location, performing a multicomponent seismic measurement at a plurality of receiver locations; and applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to receiver locations additional to the receiver locations at which the multicomponent measurement was performed.

Each of the additional receiver locations may be disposed between ones of the receiver locations at which the multicomponent measurement was performed.

The receiver locations at which the multicomponent measurement was performed may comprise a regular grid.

The grid may be one of a triangular grid, a rectangular grid and a hexagonal grid.

According to a third aspect of the present invention, there is provided a method of providing seismic data, comprising the steps of: actuating a seismic source at a plurality of source locations; for each source location, performing a multicomponent seismic measurement at a plurality of receiver locations; and applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to source locations additional to the source locations at which the source was actuated and/or additional data corresponding to receiver locations additional to the receiver locations at which the multicomponent measurement was performed.

The additional data may comprise data corresponding to at least one component of the multicomponent measurements.

The additional data may comprise pressure data.

The additional data may comprise upgoing and/or downgoing constituents of pressure data.

The additional data may comprise particle velocity related data.

The additional data may comprise vertical particle velocity component related data.

The additional data may comprise upgoing and/or downgoing constituents of vertical particle velocity component related data.

Each multicomponent measurement may comprise pressure data.

5

Each multicomponent measurement may comprise particle velocity related data.

The particle velocity related data may comprise at least one of particle velocity data, particle displacement data, and particle acceleration data.

10

Each multicomponent measurement may comprise pressure measurement and measures of derivatives of pressure with respect to first and second different directions.

The first and second directions may be Cartesian coordinate directions.

15

The first and second directions may be first and second horizontal directions.

The first and second directions may be first and second vertical directions.

20 Each multicomponent measurement may comprise vertical particle component velocity measurement and measures of derivatives of vertical particle component velocity with respect to third and fourth different horizontal directions.

25 The vertical particle component velocity measurement may be derived from a measure of a derivative of pressure with respect to a vertical direction.

The third and fourth directions may be horizontal Cartesian coordinate directions.

30 The or each derivative of the vertical particle component velocity with respect to a horizontal direction may be derived from a measure of a derivative of a horizontal particle component velocity with respect to a vertical direction.

35 The derivative of the vertical particle component velocity with respect to the third horizontal direction may be derived from a measure of a derivative with respect to a vertical direction of a particle component velocity in the third horizontal direction.

The derivative of the vertical particle component velocity with respect to the fourth horizontal direction may be derived from a measure of a derivative with respect to a vertical direction of a particle component velocity in the fourth horizontal direction.

- 5 The derivative of the vertical particle component velocity with respect to third and fourth different horizontal directions could be obtained by using data from angular rotation sensors on the seabed (measuring rotation or rotation rate around the two horizontal directions).
- 10 The derivatives of the vertical particle component velocity may be obtained from measurements of rotation or rotation rate around the third and fourth horizontal directions.

Each of the derivatives may be a first or second or third order derivative.

15

The reconstructing method may comprise applying a sinc squared or sinc cubed or sinc to the power four interpolation.

- Each derivative may be formed from a measurement of difference or particle displacement or particle velocity or particle acceleration.
- 20

The or each receiver location may be fixed.

- The or each receiver location may comprise a receiver station disposed on or above the seabed, and/or in at least one cable on the seabed and/or orientated vertically in the water column.
- 25

- The or each receiver location may comprise a receiver station deployed in a borehole on land or below the seabed.
- 30

The multicomponent measurement may be used to measure a strain field.

A stress field may be derived from the strain field.

- 35 The stress field may be derived from the strain field by Hooke's law.

At least one receiver location may comprises a receiver station comprising a cluster of pressure sensors, such as hydrophones. A separation between adjacent pressure sensors in the cluster may be from 1 cm to 10 m, for example from 1 cm to 1 m, or 5 cm to 1 m, or from 10 cm to 10 m.

5

A multicomponent unit could be arranged by use of multiple pressure sensors in a confined volume, involving numerous pressure sensors with a separation between 1 cm (or 10 cm) to 10 m, for example from 1 cm to 1 m or 5 cm to 1 m, to be recorded as individual sensor signals or "hardwired" to output only selected components.

10

Each recording station could be anchored to the seabed, and consist of several multicomponent units. The units could be distributed upwards in the watercolumn, by means of floating devices and rope or more rigid structures.

15 The method may further comprise measuring at least one non-seismic geophysical field.

The at least one non-seismic geophysical field may comprise at least one of an electromagnetic field, a gravity field and a magnetic field.

20

According to a fourth aspect of the present invention, there is provided a method of processing seismic data acquired by actuating a seismic source at a plurality of source locations and, for each source location, performing a multicomponent seismic measurement at at least one receiver location, the method comprising applying a
25 reconstructing method to each multicomponent measurement to obtain additional data corresponding to source locations additional to the source locations at which the source was actuated.

According to a fifth aspect of the present invention, there is provided a method of
30 processing seismic data acquired by actuating a seismic source at at least one source location and, for each source location, performing a multicomponent seismic measurement at a plurality of receiver locations, the method comprising applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to receiver locations additional to the receiver locations at which the
35 multicomponent measurement was performed.

According to a sixth aspect of the present invention, there is provided a method of processing seismic data acquired by actuating a seismic source at a plurality of source locations and, for each source location, performing a multicomponent seismic measurement at a plurality of receiver locations, the method comprising applying a
5 reconstructing method to each multicomponent measurement to obtain additional data corresponding to source locations additional to the source locations at which the source was actuated and/or additional data corresponding to receiver locations additional to the receiver locations at which the multicomponent measurement was performed.

10

The step of applying a reconstructing method may comprise applying a reconstructing and/or interpolating filter.

15

According to a seventh aspect of the present invention, there is provided a method of acquiring seismic data for processing by a method according to the fourth aspect of the present invention comprising actuating a seismic source at a plurality of source locations and/or, for each source location, performing a multicomponent seismic measurement at at least one receiver location.

20

According to an eighth aspect of the present invention, there is provided a method of acquiring seismic data for processing by a method according to the fifth aspect of the present invention comprising actuating a seismic source at at least one source location and/or, for each source location, performing a multicomponent measurement at a plurality of receiver locations.

25

According to a ninth aspect of the present invention, there is provided a method of acquiring seismic data for processing by a method according to the sixth aspect of the present invention comprising actuating a seismic source at a plurality of source locations and/or, for each source location, performing a multicomponent measurement
30 at a plurality of receiver locations.

The seismic data may comprise marine seismic data and the seismic source may comprise a marine seismic source.

35

Actuating a seismic source at a plurality of source locations may comprise actuating a seismic source at a plurality of source locations in turn.

According to a tenth aspect of the present invention, there is provided an apparatus for performing a method according to the seventh, eighth or ninth aspect of the present invention, comprising at least one receiver station for performing a multicomponent seismic measurement.

The or each receiver station may comprise multiple hydrophones to measure pressure and derive spatial derivatives (gradients) therefrom, and/or multiple geophones to measure particle velocities and derive particle velocity derivatives (gradients) or spatial pressure derivatives therefrom, and/or multiple accelerometers to measure accelerations and derive particle acceleration derivatives (gradients) or spatial pressure derivatives therefrom, and/or sensors to measure rotational motions around an axis to derive spatial derivatives of any physical fields such of particle component velocity.

At least one receiver station may be as described above.

At least one receiver station may be disposed on or above the seabed, and/or in at least one cable on the seabed and/or orientated vertically in the water column.

At least one receiver station may be deployed in a borehole on land or below the seabed.

At least one receiver station may comprise a cluster of pressure sensors, such as hydrophones, for example with a separation between adjacent pressure sensors in the cluster of 1 cm (or 10 cm) to 10 m, for example from 1 cm to 1 m or 5 cm to 1 m.

According to a further aspect of the present invention, there is provided a method of providing marine seismic data, the method comprising the steps of:

actuating a marine seismic source at a plurality of source locations in turn;
for each source location, performing a multicomponent seismic measurement at at least one receiver location; and
applying a reconstructing and/or interpolating filter to the or each multicomponent measurement to obtain pressure data and/or vertical particle velocity component related data corresponding to source locations additional to the source locations at which the source was actuated.

Preferably, the vertical velocity component related data comprises at least one of vertical velocity component data, vertical particle displacement component data, and vertical acceleration component data.

- 5 Preferably, each of the additional locations is disposed between ones of the source locations at which the source was actuated.

Preferably, the source locations at which the source was actuated comprise a regular grid. The grid is preferably one of a triangular grid, a rectangular grid and a hexagonal
10 grid.

Preferably, each multicomponent measurement comprises pressure data and particle velocity related data.

- 15 Preferably, each multicomponent measurement comprises pressure measurement and measures of derivatives of pressure with respect to first and second different horizontal directions. The first and second directions are preferably horizontal Cartesian coordinate directions.

- 20 Preferably, each multicomponent measurement comprises vertical particle component velocity measurement and measures of derivatives of vertical particle component velocity with respect to third and fourth different horizontal directions. The third and fourth directions are preferably horizontal Cartesian coordinate directions.

- 25 Each of the derivatives is preferably a first or second or third order derivative, and the interpolating filter may be a sinc squared or sinc cubed or sinc to the power four interpolation filter.

Each derivative is preferably formed from a measurement of difference.

30

Preferably, the or each receiver location is fixed.

- Preferably, the or each receiver location comprises a receiver station disposed on or above the seabed, and/or in at least one cable on the seabed and/or orientated
35 vertically in the water column.

Preferably, the or each receiver location comprises a receiver station deployed in a borehole on land or below the seabed. The multicomponent measurement may be used to measure a strain field. A stress field may be derived from the strain field. The stress field may be derived from the strain field by Hooke's law.

5

Preferably, the method further comprises measuring at least one non-seismic geophysical field. The at least one non-seismic geophysical field preferably comprises at least one of an electromagnetic field, a gravity field and a magnetic field.

10 According to a further aspect of the present invention, there is provided a method of processing marine seismic data acquired by actuating a marine seismic source at a plurality of source locations in turn and, for each source location, performing a multicomponent seismic measurement at at least one receiver location, the method comprising applying a reconstructing and/or interpolating filter to the or each
15 multicomponent measurement to obtain pressure data and/or vertical particle velocity component related data corresponding to source locations additional to the source locations at which the source was actuated.

Preferably, the method comprises actuating a marine seismic source at a plurality of
20 source locations in turn and, for each source location, performing a multicomponent seismic measurement at at least one receiver location.

According to a further aspect of the present invention, there is provided an apparatus for performing a method of processing marine seismic data acquired by actuating a
25 marine seismic source at a plurality of source locations in turn and, for each source location, performing a multicomponent seismic measurement at at least one receiver location, the method comprising applying a reconstructing and/or interpolating filter to the or each multicomponent measurement to obtain pressure data and/or vertical particle velocity component related data corresponding to source locations additional to
30 the source locations at which the source was actuated. The apparatus comprises at least one receiver station for performing a multicomponent seismic measurement.

Preferably, the or each receiver station comprises multiple hydrophones to measure pressure and derive spatial derivatives (gradients) therefrom, and/ or multiple
35 geophones to measure particle velocities and derive particle velocity derivatives (gradients) therefrom, and/or multiple accelerometers to measure accelerations and

derive particle acceleration derivatives (gradients) therefrom, and/or sensors to measure rotational motions around an axis to derive spatial derivatives of any physical fields.

- 5 A program is also proposed for controlling an apparatus to perform a method as herein proposed, or which, when loaded into an apparatus, causes the apparatus to become an apparatus as herein proposed. The program may be carried on a carrier medium. The carrier medium may be a storage medium. The carrier medium may be a transmission medium. An apparatus programmed by such a program is also
10 envisaged, as is a storage medium containing such a program.

Brief description of the drawings

- Figure 1(a) illustrates fifteen hydrophones (represented by dots) in a cluster. The
15 seven dots with diagonal hatching are oriented along the axes of a Cartesian coordinate system at locations $(0, 0, 0)$, $(\pm 1, 0, 0)$, $(0, \pm 1, 0)$ and $(0, 0, \pm 1)$. The four dots with horizontal hatching are at locations $(\pm 1, 0, \pm 1)$. The four dots with vertical hatching are at locations $(0, \pm 1, \pm 1)$. The hydrophone spacing along axes is unity.

- 20 Figure 1(b) illustrates the same fifteen hydrophones of Figure 1(a), but more clearly shown in three layers of hydrophones.

- Figure 2 provides a comparison of sinc and sinc^2 interpolation on simple synthetic vertical component of particle velocity data. (a) Reference data (ideal result), (b) data
25 after 2:1 decimation, (c) sinc interpolation, (d) sinc^2 interpolation. $t - x$ data are displayed above their $f - k$ spectra.

Figure 3 is a schematic representation of a method embodying the present invention.

- 30 Figures 4(a) and 4(b) are schematic illustrations of apparatus used in an embodiment of the present invention, in a marine and non-marine environment respectively.

- Figure 5: (a) Two different sinusoids that produce the samples marked with white dots having solid outline. (b) and (c) The red signal is sampled at the white dots with
35 solid outline. The dots with diagonal hatching, vertical hatching and horizontal hatching

are reconstructed values with the sampling theorems A.7, A.8, and A.9, called sinc, sinc² and sinc³ interpolation, respectively.

Figure 6. Procedure for data reconstruction: (a) Data are sampled in locations marked
5 with solid-outline white circles. (b) Data are reconstructed in locations marked with
circles having interior shading and diagonal hatching.

Detailed description

10 As mentioned above, to reduce 3-D marine seismic acquisition cost the receiver
spacing is often made larger than desirable. As a consequence, the recorded
wavefield is spatially aliased. Specifically, in towed streamer acquisition, the sampling
challenge is the large streamer separation, typically 50-100 m. In ocean-bottom
seismic (OBS) or vertical cable (VC) acquisition, where data can be processed as
15 common-receiver gathers, it is the coarse shot interval spacing, typically chosen 50 m
by 50 m or more, that leads to undersampling. The undersampling of the wavefield
causes challenges for 3-D up/down decomposition or deghosting of the recorded
wavefield, which is one of the data preprocessing steps applied before seismic
imaging.

20

We introduce the concept of multicomponent (e.g. six-component or 6-C) wavefield
measurements in the water column while the source vessel, just like in OBS and VC
surveying, traverses the surface shooting on a predetermined grid. At least six
wavefield components – the pressure and the vertical component of the particle
25 velocity and their horizontal first-order derivatives in x- and y-directions – are
suggested for proper reconstruction of the undersampled pressure and vertical
component of particle velocity. When the second-order derivatives are recorded, the
number of components is ten. This reconstruction allows the step of 3-D up/down
decomposition or deghosting of common receiver station recordings to be achieved in
30 the frequency-wavenumber domain (Amundsen, 1993). New wavefield reconstruction
methods such as those presented here are of interest since, presently, the seismic
industry is in the process of developing multicomponent cables or streamers
(Robertsson, 2006; Singh et al., 2009). Further, the industry is actively carrying out
research on and testing new multicomponent sensors (H. Lund, pers. comm.). Here,
35 multicomponent refers to a combination of sensors that includes two or more closely-
spaced sensors such as a hydrophone, a geophone, an accelerometer, a rotational

seismometer, a pressure derivative configuration of hydrophones, or a vertical particle velocity derivative configuration of hydrophones. The derivatives can be a first order derivative, a second order derivative or a higher order derivative. Rotational seismometers are designed for measurements of the rotational components (angular velocity) of x-, y- or z-axis oriented vibrations.

Before we describe further and demonstrate the use of 6-C and 10-C common-receiver recordings for reconstruction of pressure and vertical component of particle velocity the reader is again referred to the above-provided brief review of the state-of-the-art and possible new trends in marine seismic acquisition. With regard to the Robertsson et al. (2006, 2008) disclosure, it is noted that a true multi-C streamer would enable accurate pressure data reconstruction in the crossline direction with cable separations for which pressure-only data would be irrecoverably aliased. The major purpose of having a hydrophone/3-C geophone streamer is thus to achieve crossline pressure field reconstruction by interpolation using pressure and its crossline derivative. But without introducing assumptions such a streamer will not enable the reconstruction of the vertical component of the particle velocity in the crossline direction that is needed to achieve the 3-D up/down decomposition objective.

In marine OBS or VC surveying, the shot grid interval is seldom less than 50 m by 50 m to avoid excessive exploration cost. The 50 m by 50 m shot grid implies that any recorded pressure and vertical component of particle velocity data alone at a receiver station will be undersampled even for moderate frequencies of the source signal. For example, a seismic event with water speed will be aliased above 15 Hz.

With the purpose to achieve a proper 3-D up/down wavefield decomposition of undersampled seismic data, we suggest to record six components or more of the wavefield in OBS or VC surveying configurations. The six-components are the pressure and its horizontal first-order derivatives in x- and y-directions, and the vertical component of the particle velocity and this component's horizontal first-order derivatives in x- and y-directions. The additional recordings of second-order derivatives give a ten-component measurement.

There are many ways to measure the first-order x- and y-derivatives of the pressure wavefield in the water column. One way is to use horizontally oriented geophones

since the equation of motion relates measured particle velocities (v_x , v_y) to spatial derivatives of the pressure p . In particular, in the frequency (ω) domain, for a fluid

$$\partial_x p = i\omega \rho v_x, \quad \partial_y p = i\omega \rho v_y, \quad (1)$$

5

where ρ is density. Accelerations are related to particle velocities as $(a_x, a_y) = -i\omega(v_x, v_y)$. Another option is to construct a cluster of hydrophones with known separation between each hydrophone so that the spatial derivatives of the pressure can be derived by pressure field differencing.

10

Likewise, there are several ways to measure the first-order x - and y -derivatives of the vertical component of the particle velocity v_z in the water column. One way is to use rotational seismometers designed for measurements of the rotational components (angular velocity) of seismic z -axis oriented vibrations. Another possibility is to

15 construct a cluster of vertically oriented geophones with known separation between each geophone so that the spatial derivatives of the particle velocity can be derived by velocity field differencing.

In the processing of OBS and VC data, one takes advantage of the principle of acoustic reciprocity (Ikelle and Amundsen, 2005). For hydrophone data, reciprocity states that a

20 monopole point source of volume injection and a receiver can be interchanged without affecting the recorded signal. This principle holds also for the derivatives of the acoustic data. Therefore, the multicomponent common receiver gather can be considered as a multicomponent common shot gather to which we apply 3D data

25 reconstruction, up/down wavefield decomposition, wave-equation demultiple, and shot-profile waveequation migration to obtain a partial image of the subsurface geology. The sum of all partial images, one from each receiver in the OBS experiment, then gives the full seismic image.

30 Another example of a receiver system that could provide the six or ten components of the wavefield suggested for wavefield reconstruction and proper up/down wavefield decomposition would be fifteen clustered hydrophones as illustrated in Figure 1(a) where three are staggered in the vertical direction at depths z and $z \pm \Delta z$ at horizontal

35 positions (x, y) , $(x \pm \Delta x, y)$, and $(x, y \pm \Delta y)$. A ten hydrophone cluster could consist of two hydrophone layers at depths z and $z + \Delta z$, each layer having five hydrophones at

horizontal positions (x, y) , $(x \pm \Delta x, y)$, and $(x, y \pm \Delta y)$. The fifteen hydrophone cluster is similar but has an additional layer of five hydrophones at depth $z - \Delta z$, and compared to the ten hydrophone cluster offers redundancy and improved signal/noise ratio as the vertical derivatives of the pressure can be calculated from hydrophone measurements in three ways. A five-hydrophone cluster could have a single hydrophone layer at depth z , with hydrophones at horizontal positions (x, y) , $(x \pm \Delta x, y)$, and $(x, y \pm \Delta y)$; such a cluster can only measure the pressure field and its horizontal derivatives. Figure 1(b) shows more clearly these three layers making up the five-, ten- and fifteen-hydrophone clusters.

Thus, the pressure wavefield can be recorded in 10 or 15 neighboring points in space, allowing all the ten sought-after components of the field to be derived by simple field differencing operations. Such a system can be designed and installed in a receiver station deployed on the sea floor or in a vertical cable system.

Then, the pressure wavefield would be recorded in fifteen closeby points in space, allowing all the six sought-after components of the field to be derived by simple field differencing operations. Such a system can be designed and installed in a receiver station deployed on the sea floor.

This hydrophone layout not only allows the first order spatial derivatives to be evaluated, it also allows the computation of second order spatial derivatives. The art of numerical differentiation is well known in the field of mathematics and is described in standard mathematical textbooks (e.g., Abramowitz and Stegun, 1972).

It will also be appreciated that $\partial_x v_z = \partial_z v_x$ and $\partial_y v_z = \partial_z v_y$, so that $\partial_x v_z$ and $\partial_y v_z$ may be found by measuring $\partial_z v_x$ and $\partial_z v_y$ respectively instead, which may be easier in practice.

A numerical example will now be described.

We generate a simple synthetic shot gather of pressure and its horizontal derivatives, $(p, \partial_x p, \partial_y p)$, and vertical component of particle velocity and its horizontal derivatives, $(v_z, \partial_x v_z, \partial_y v_z)$, to illustrate the significance of multicomponent (e.g. 6-C) recordings for the reconstruction of pressure and vertical component of particle velocity data between recording locations. Any interpolation technique that uses and benefits from field and

field derivative measurements can be applied. In Appendix A one class of such reconstruction methods based on the extended sampling theorem is outlined, discussed and exemplified. In the case that only the field is measured, the sampling theorem reduces to the well-known sinc interpolation. When the field and its first
 5 derivatives are measured and used in the extended sampling theorem, we call the method for sinc² interpolation. In the case that the field and its first and second derivatives are measured and used, we call the method for sinc³ interpolation.

We consider a homogeneous halfspace of water below a free surface. A point source
 10 is located at position $(x_s, y_s, z_s) = (0, 0, 300)$ m. The source wavelet has frequencies up to 30 Hz. The receivers are located over a horizontal plane at depth $z_r = 100$ m. The offset range is ± 3 km in both horizontal directions. In the numerical example, we select the receiver spacing interval $\Delta x = \Delta y = 50$ m but every second line is staggered by $\Delta x/2$ as discussed in Appendix B and shown in Figure 6. The data at the receiver
 15 plane simply consist of an upgoing wave from the source and a downgoing wave reflected at the free surface.

In this numerical example the benefit of sinc² interpolation is demonstrated. We generate a 6-C component data gather that consists of pressure and its horizontal
 20 derivatives, $(p, \partial_x p, \partial_y p)$, and vertical component of particle velocity and its horizontal derivatives, $(v_z, \partial_x v_z, \partial_y v_z)$. The source wavelet has dominant frequency of 14 Hz. Its amplitude spectrum is tapered to zero above 30 Hz.

Figure 2 shows the results of two interpolation and reconstruction tests for p . The
 25 results for v_z are not shown here but are similar. The upper and lower parts show selected 2-D gathers in time-offset (t - x) and frequency-wavenumber (f - k) domains, respectively. The t - x gather is that for $y = y_s$. Figure 2(a) shows modeled reference data sampled at 25 m that would be the ideal result from any reconstruction technique. These data are now decimated spatially by a factor of two so that the sampling interval
 30 is 50 m, see Figure 2(b). Aliasing is clearly visible in the f - k domain.

In the subsequent tests, these data are now interpolated.

First, we apply traditional sinc interpolation using as input p data to reconstruct p data
 35 and v_z data to reconstruct v_z data. Sinc interpolation of aliased data makes no attempt

to de-alias the data before interpolation. Thus, when aliasing is present in single component data acquisition, it is not possible to identify the correct waveforms from the acquired samples, unless assumptions are introduced. Therefore, not surprisingly, the aliased components of the events are interpolated incorrectly as seen in Figure 2(c) where data are band-limited in the spatial sampling bandwidth.

Second, we apply sinc^2 interpolation band-limited up to twice the spatial Nyquist frequency, as introduced in Appendix A. Input data $(p, \partial_x p, \partial_y p)$ are used to reconstruct p , and input data $(v_z, \partial_x v_z, \partial_y v_z)$ are used to reconstruct v_z (not shown). Figure 2(d) shows that the data are well reconstructed. The data derivative information effectively has doubled the spatial Nyquist frequency, so that the data are not aliased.

In conclusion, we have shown that recordings of the horizontal derivatives of pressure and vertical component of particle velocity in OBS or VC surveying have the potential to reduce aliasing by a factor of at least two and three compared to recording only pressure and vertical component of particle velocity data alone. Using a simple synthetic data set, we demonstrated the potential that these new measurements have to reconstruct data at desired locations in between the original shot grid.

Any interpolation technique that uses sampled values of the field and field horizontal derivatives can be applied in the data reconstruction. Here, the extended sampling theorem was used in the form of sinc^2 and sinc^3 interpolation. Compared with conventional sinc interpolation, sinc^2 and sinc^3 interpolation doubles and triples the effective Nyquist wavenumber, respectively. Input to sinc^2 interpolation is the field and its first-order horizontal derivatives. Sinc^3 interpolation has as input, in addition, the second-order horizontal derivatives.

To apply sinc^2 interpolation before 3D OBS or VC up/down wavefield decomposition, wave-equation demultiple and wave-equation migration, six wavefield components are acquired. Similarly, for sinc^3 interpolation, ten wavefield components are acquired.

A method according to an embodiment of the present invention is illustrated schematically in the flowchart of Figure 3. A method embodying the present invention will be described with reference first to Figure 4(a), in which the method is performed within a marine environment to provide marine seismic data. However, the method is equally applicable to a non-marine environment, and the application to a non-marine

environment will then be briefly discussed with reference to Figure 4(b). Illustrated in Figures 4(a) and 4(b) are a sea surface 1, a sea floor 2, a sub-surface structure 3, a seismic source 4, at least one receiver 5, and a land surface 6. Within the context of Figure 4(a), the seismic source 4 is a marine seismic source. It is noted that the
5 arrangements in Figures 4(a) and 4(b) are intended to be schematic rather than literal.

An embodiment of the present invention within the context shown in Figure 4(a) relates to a method of providing marine seismic data. As discussed previously, there are various ways of providing the at least one receiver 5, as well as various ways of
10 providing the marine seismic source 4 and moving it between desired source locations. For example, the at least one receiver 5 could be provided by towed streamer, fixed to the sea floor 2, arranged off the sea floor 2, and so on. Similarly, there could be a single source 4 moved to different source locations, or a plurality of sources 4 at different respective source locations – which could be fixed – or a combination of
15 these. The details are not important within the context of an embodiment of the present invention.

The method starts at step S1. In a marine environment as illustrated in Figure 4(a), the marine seismic source 4 is actuated at a plurality of source locations in turn. This is
20 illustrated by step S2 of Figure 3, with step S4 being a check to determine whether there are any further source locations; if there are further source locations then the method loops back to step S2, and if not then the method proceeds to step S5. The seismic waves from the source 4 are reflected by sub-surface structure, as up-going waves, towards the at least one receiver 5. For each source location, a
25 multicomponent seismic measurement is performed by the at least one receiver 5 at at least one corresponding respective receiver location (step S3 of Figure 3). A reconstructing (or interpolating) method (or filter) is applied to each multicomponent measurement in step S5 to obtain additional data corresponding to source locations additional to the source locations at which the source was actuated. The additional
30 data are output and/or used in step S6. The method ends at step S7.

In a non-marine environment such as that illustrated in Figure 4(b), the method is entirely equivalent, even if the locations of the seismic source 4 and the at least one receiver 5 are different. In the example shown in Figure 4(b), the seismic source 4 and
35 the at least one receiver 5 are provided at or near the land surface 6. Again, there are various ways of providing the at least one receiver 5, as well as various ways of

providing the seismic source 4 and moving it between desired source locations. There could be a single source 4 moved to different source locations, or a plurality of sources 4 at different respective source locations – which could be fixed – or a combination of these. The at least one receiver 5 and/or the seismic source 4 may be located within at least one corresponding respective borehole rather than being arranged at or near the land surface 6. The details are not important within the context of an embodiment of the present invention.

Various subsidiary features of an embodiment of the present invention, as well as additional aspects of the present invention, are set out in the Summary section above.

It will be appreciated by the person of skill in the art that various modifications may be made to the above described embodiments without departing from the scope of the present invention.

In particular, it will be appreciated that rather than (or in addition to) having a plurality of source locations and at least one receiver location, with reconstruction/interpolation of additional data corresponding to additional source locations, it is also possible to provide at least one source location and a plurality of receiver locations, with reconstruction/interpolation of additional data corresponding to additional receiver locations. Reconstruction or interpolation based on receiver locations would be achieved in a manner entirely analogous to reconstruction or interpolation based on source locations as described herein, and the skilled person would readily be able to put this into practice based on the disclosure herein. Such a method of providing seismic data would comprise the steps of: actuating a seismic source at at least one source location; for each source location, performing a multicomponent seismic measurement at a plurality of receiver locations; and applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to receiver locations additional to the receiver locations at which the multicomponent measurement was performed (the schematic flowchart of Figure 3 applies to this method, though step S3 would be one of performing a multicomponent seismic measurement at a plurality of receiver locations). For example, with one shot and several receivers the data registered by the receivers can be used to interpolate between them. Reconstructing in this way between multicomponent receivers, in particular reconstructing between stationary multicomponent receivers at or close to

the seabed, or between receivers in vertical cables, is not envisaged by known techniques.

The present application is based on GB 1005574.7 and US 61/321,670, and the reader
5 is also referred to those earlier applications; if necessary, the entire content of those
earlier applications is hereby incorporated by reference in order to provide explicit basis
in this application for resolving any possible discrepancies in the present application
(for example in converted mathematical expressions and equations) and/or for the
benefit of any color-related information included on filing those earlier applications.

10 The present application is also to be read in conjunction with Amundsen et al. (2010),
the entire content of which is hereby incorporated by reference. Amundsen et al.
(2010) discloses the same underlying technique as disclosed herein, but contains
some additional analysis relevant to the present application, for example equations (12)
15 and (13) and associated description and references thereto. Also, while Figure 2 of
Amundsen et al. (2010) corresponds to Figure 2 of the present application, Amundsen
et al. (2010) also contains additional examples and analysis in Figures 3 to 6 and
associated description, including an additional section entitled "sinc³ interpolation" just
before the Conclusion section which refers to Figure 6 of Amundsen et al. (2010).

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Appendix A: The extended sampling theorem

In this section we show that the extended sampling theorem (Poularikas, 1996) gives one possible basis for data reconstruction.

5

Let Δ denote a sampling interval and $\kappa_N = \frac{1}{2\Delta}$ the Nyquist wavenumber. Let $p(x)$ be a continuous function with finite Fourier transform $F(k)[F(k) = 0 \text{ for } |k| > 2\pi\kappa_N]$. Introduce the points

$$10 \quad x_m = m\Delta, \quad m = 0, \pm 1, \pm 2, \dots \quad (\text{A.1})$$

and define

$$h = (R+1)\Delta, \quad R = 0, 1, 2, \dots \quad (\text{A.2})$$

15

The extended sampling theorem (Poularikas, 1996) shows how the function can be reconstructed from itself and its derivatives $p^{(R)}$ up to order R at the points $mh = (R+1)x_m$ via the formula

$$20 \quad p(x) = \sum_{m=-\infty}^{\infty} \left[p(mh) + (x-mh)g^{(1)}(mh) + \dots + \frac{(x-mh)^R}{R!} g^{(R)}(mh) \right] \times \text{sinc}^{(R+1)} \left[\frac{1}{h}(x-mh) \right] \quad (\text{A.3})$$

where

$$25 \quad g^{(j)}(mh) = \sum_{i=0}^j \binom{j}{i} \left(\frac{\pi}{h} \right)^{j-i} \Gamma_{R+1}^{(j-i)} p^{(i)}(mh) \quad (\text{A.4})$$

$$\text{sinc}(t) = \frac{\sin(\pi t)}{\pi t} \quad (\text{A.5})$$

and

$$\Gamma_{\alpha}^{(\beta)} = \frac{d^{\beta}}{dt^{\beta}} \left[\left(\frac{t}{\sin t} \right)^{\alpha} \right]_{t=0} \quad \text{and in particular:}$$

$$\Gamma_{\alpha}^{(0)} = 1, \quad \Gamma_{\alpha}^{(2)} = \frac{\alpha}{3}, \quad \Gamma_{\alpha}^{(4)} = \frac{\alpha(5\alpha+2)}{15}, \dots, \quad \Gamma_{\alpha}^{(\beta)} = 0 \text{ for odd } \beta \quad (\text{A.6})$$

In the case only the function is sampled, use $R = 0$ in equation A.4. Then $h = \Delta$ and
 5 Shannon's sampling theorem is obtained:

$$p(x) = \sum_{m=-\infty}^{\infty} p(x_m) \text{sinc} \left[\frac{1}{\Delta} (x - x_m) \right] \quad (\text{A.7})$$

This result is known also as sinc interpolation.

10

When the function and its first-order derivative are available, use $R = 1$ in equation A.4. Then $h = 2\Delta$, $g^{(1)} = p^{(1)}$, and we obtain the multichannel sampling theorem (Linden, 1959; Robertsson et al., 2008)

$$15 \quad p(x) = \sum_{m=-\infty}^{\infty} \left[p(2x_m) + (x - 2x_m) p^{(1)}(2x_m) \right] \times \text{sinc}^2 \left[\frac{1}{2\Delta} (x - 2x_m) \right] \quad (\text{A.8})$$

From equation A.8, we note that when the function and its derivative is sampled, we can reconstruct functions sampled twice as coarsely as those reconstructed when only the function is available. Observe that the sinc function in the multichannel sampling
 20 theorem is squared. Therefore, for brief, we call this result for sinc² interpolation.

In the case that the function and its first and second order derivatives are sampled, use $R = 2$ in equation A.4. Then $h = 3\Delta$. Further, $\Gamma_3^{(2)} = 1$, $g^{(2)} = ap + p^{(2)}$ where $a = \left(\frac{\pi}{3\Delta}\right)^2$. The function then can be reconstructed via the formula

25

$$p(x) = \sum_{m=-\infty}^{\infty} \left[p(3x_m) + (x - 3x_m) p^{(1)}(3x_m) + \frac{(x - 3x_m)^2}{2} (ap(3x_m) + p^{(2)}(3x_m)) \right] \\ \times \text{sinc}^3 \left[\frac{1}{3\Delta} (x - 3x_m) \right] \quad (\text{A.9})$$

From equation A.9, we observe that when the function and its first and second-order derivatives are known, we can reconstruct functions sampled three times as coarsely as those reconstructed when only the function is available. Herein, we refer to this
5 result as sinc^3 interpolation.

Appendix A.1: Reconstruction of sinusoid

Aliasing is an effect that causes different continuous signals to become indistinguishable (or aliases of one another) when sampled. When this happens, the original signal cannot be uniquely reconstructed from the sampled signal.

To illustrate reconstruction of signals by the use of the sampling theorems A.7, A.8, or A.9 we use sinusoid functions. Realistic signals are often modeled as the summation of many sinusoids of different frequencies and amplitudes (with a Fourier transform). Understanding what aliasing does to the individual sinusoids is useful in predicting what happens to their sum. In this section we consider sinusoids sampled at time $t = m\Delta$ where m takes integer values and the sample-interval is $\Delta = 1s$. The sample-rate is $f_s = 1/\Delta = 1\text{Hz}$.

In Figure 5(a) the plot shows a set of samples (white dots with solid black outline), and two different sinusoids that could have produced the samples. The two sinusoids (or signals) are labeled and referred to herein as “red” and “black” (their actual color is not meaningful and/or relevant). Seven and a half cycles of the red sinusoid and two and a half cycles of the black sinusoid span an interval of 10s. The respective sinusoid frequencies are $f_{red} = 0.75\text{ Hz}$ and $f_{black} = 0.25\text{ Hz}$. Specifically, the continuous signals are

$$\gamma_{red} = \cos(2\pi f_{red} t) \quad (\text{A.10})$$

$$\gamma_{black} = \cos(2\pi f_{black} t) \quad (\text{A.11})$$

25

Generally, when a sinusoid of frequency f is sampled with frequency f_s the resulting samples are indistinguishable from those of another sinusoid of frequency $f_{image}(n) = |f - nf_s|$ for any integer n . Most reconstruction techniques produce the minimum of these frequencies.

30

A sufficient condition for signal reconstruction without aliasing is that $f_N = f_s/2 > f$ where f_N is commonly called the Nyquist frequency of a system that samples at rate f_s . Stated differently, as long as the signal frequency is lower than the Nyquist

frequency, $f < f_N$, no aliasing occurs. But, as seen in this appendix, if derivatives of the signal are measured along with the signal, this situation changes. In the case that the signal and its first derivative are sampled, aliasing is avoided when $f < f_s = 2f_N$. Further, when the signal and its first and second derivatives are sampled, aliasing does
 5 not occur as long as $f < \frac{3}{2}f_s = 3f_N$.

Assume that γ_{red} is the original red signal with frequency $f = 0.75$ Hz and that the white dots with solid black outline are the digital samples taken to record it. Observe that $f_N < f < 2f_N$. The objective is to use one of the sampling theorems A.7, A.8, or
 10 A.9 to reconstruct the signal at sample locations $t = (m + \frac{1}{2})\Delta$. In the case only the signal is sampled, γ_{red} obviously is undersampled, and sinc interpolation reconstructs the samples in Figure 5(b) marked with dots having diagonal hatching. Clearly, the wrong signal γ_{black} with image frequency $f_{image}(1) = |0.75 - 1| \text{ Hz} = 0.25 \text{ Hz} = f_{black}$ is obtained by sinc interpolation. Since aliasing is present, it is not possible to identify the
 15 correct signal from the samples of signal alone.

Assume therefore that the first and second derivatives of the original red signal are taken together with the signal at the locations of the white dots with solid black outline. Applying sinc^2 and sinc^3 interpolation we reconstruct the samples marked with vertical
 20 and horizontal hatching, respectively, where we see that the horizontal hatching dots (sinc^3) are on top of the vertical hatching (sinc^2) dots. In this case, γ_{red} together with its derivatives, is well-sampled, and both sinc^2 and sinc^3 interpolation reconstruct the proper samples. Even though the red and black signals have the same amplitudes on the sample locations, their derivatives at the sample locations are different. In this
 25 case, only the red signal has derivatives that fit the sampled derivatives of the signal. This example illustrates in an intuitive way why sinc^2 and sinc^3 interpolate beyond the Nyquist rate.

The red signal shown in Figure 5(c) has frequency $f = 1.25$ Hz so that $2f_N < f < 3f_N$.
 30 Again, sinc interpolation reconstructs the samples marked with dots having diagonal hatching, fitting the black signal with image frequency $f_{image}(1) = |1.25 - 1| \text{ Hz} = 0.25 \text{ Hz}$. Since the frequency of the red signal is above $2f_N$, now sinc^2 interpolation which

- utilizes both the signal and its first derivative at the sampling points cannot reconstruct the signal (see dots with vertical hatching). Note that sinc^2 interpolation amplifies relative to the original red signal the reconstructed amplitude values of the aliased signal marked with dots having vertical hatching. However, sinc^3 interpolation which
- 5 uses both the signal and its first and second derivatives at the sampling points reconstructs the signal properly at the locations marked with dots having horizontal hatching. This example illustrates in a simple way why sinc^3 interpolates beyond twice the Nyquist rate.

Appendix B: Data reconstruction from staggered shooting

In OBS swath or inline shooting the source vessel normally tows two airgun arrays while shooting ‘flip-flop’. Assume that the sail lines in the x-direction are separated a cross-line distance 2Δ . The source lines where the shot interval is Δ have a cross-line offset of $\Delta/2$ from the sail line. As a consequence of the flip-flop shooting, the shot locations of every second source line are staggered by the distance $\Delta/2$. The shot point geometry is depicted in Figure 6(a) where the solid-outline white circles denote the shot positions.

Our objective is to use the sampled data from these shot positions to construct data in a desired shot grid that is regular with shot interval $\Delta/2$. To this end, the first data reconstruction is performed along x-lines so that data are reconstructed at positions illustrated with circles having a shaded interior in Figure 6(b). Second, data reconstruction is performed along diagonal lines normal to each other as shown in Figure 6(a), where the shot interval is $\sqrt{5}\Delta/2$. Now data are reconstructed at positions marked with dotted-outline white circles in Figure 6(b). Considering the dotted-outline white circle reconstructed shot locations along x-lines we observe that these locations are offset by $\Delta/4$ relative to shot locations in the desired grid. These offset shot locations can, without loss of precision, be shifted by interpolation a distance $\Delta/4$ in the x-direction to fit the shot locations in the desired grid, marked with circles having diagonal hatching. The locations of the “solid-outline white”, “shaded interior” and “diagonally hatched” circles are the locations of the reconstructed data, which if not spatially aliased, can be transformed to the frequency-wavenumber domain for up/down wavefield decomposition.

The procedure is the same when the objective is to construct data in a desired shot grid that is regular with shot interval $\Delta/4$, and so on.

In the case that the sail lines are separated the crossline distance $\sqrt{3}\Delta/2 \approx 0.87\Delta$, the shot sampling in Figure 6(a) is known as hexagonal sampling (Bardan, 1997).

Claims

1. A method of providing seismic data, comprising the steps of:
actuating a seismic source at a plurality of source locations;
5 for each source location, performing a multicomponent seismic measurement at
at least one receiver location; and
applying a reconstructing method to each multicomponent measurement to
obtain additional data corresponding to source locations additional to the source
locations at which the source was actuated.
- 10 2. A method as claimed in claim 1, in which each of the additional source locations
is disposed between ones of the source locations at which the source was actuated.
3. A method as claimed in claim 1 or 2, in which the source locations at which the
source was actuated comprise a regular grid.
4. A method as claimed in claim 3, in which the grid is one of a triangular grid, a
15 rectangular grid and a hexagonal grid.
5. A method as claimed in any preceding claim, wherein, for each source location,
the multicomponent seismic measurement is performed at a plurality of receiver
locations, and comprising applying a reconstructing method to each multicomponent
measurement to obtain additional data corresponding to receiver locations additional to
20 the receiver locations at which the multicomponent measurement was performed.
6. A method of providing seismic data, comprising the steps of:
actuating a seismic source at at least one source location;
for each source location, performing a multicomponent seismic measurement at
a plurality of receiver locations; and
25 applying a reconstructing method to each multicomponent measurement to
obtain additional data corresponding to receiver locations additional to the receiver
locations at which the multicomponent measurement was performed.
7. A method as claimed in claim 6, in which each of the additional receiver
locations is disposed between ones of the receiver locations at which the
30 multicomponent measurement was performed.

8. A method as claimed in claim 6 or 7, in which the receiver locations at which the multicomponent measurement was performed comprise a regular grid.
9. A method as claimed in claim 8, in which the grid is one of a triangular grid, a rectangular grid and a hexagonal grid.
- 5 10. A method as claimed in any preceding claim, wherein the additional data comprise data corresponding to at least one component of the multicomponent measurements.
11. A method as claimed in any preceding claim, wherein the additional data comprise pressure data.
- 10 12. A method as claimed in claim 11, wherein the additional data comprise upgoing and/or downgoing constituents of pressure data.
13. A method as claimed in any preceding claim, wherein the additional data comprise particle velocity related data.
14. A method as claimed in claim 13, wherein the additional data comprise vertical
15 particle velocity component related data.
15. A method as claimed in claim 14, wherein the additional data comprise upgoing and/or downgoing constituents of vertical particle velocity component related data.
16. A method as claimed in any preceding claim, in which each multicomponent measurement comprises pressure data.
- 20 17. A method as claimed in any preceding claim, wherein each multicomponent measurement comprises particle velocity related data.
18. A method as claimed in claim 13 or 17, wherein the particle velocity related data comprise at least one of particle velocity data, particle displacement data, and particle acceleration data.

19. A method as claimed in any preceding claim, in which each multicomponent measurement comprises pressure measurement and measures of derivatives of pressure with respect to first and second different directions.
20. A method as claimed in claim 19, in which the first and second directions are
5 Cartesian coordinate directions.
21. A method as claimed in claim 19 or 20, wherein the first and second directions are first and second horizontal directions.
22. A method as claimed in claim 19 or 20, wherein the first and second directions are first and second vertical directions.
- 10 23. A method as claimed in any preceding claim, in which each multicomponent measurement comprises vertical particle component velocity measurement and measures of derivatives of vertical particle component velocity with respect to third and fourth different horizontal directions.
24. A method as claimed in claim 23, wherein the vertical particle component
15 velocity measurement is derived from a measure of a derivative of pressure with respect to a vertical direction.
25. A method as claimed in claim 23 or 24, in which the third and fourth directions are horizontal Cartesian coordinate directions.
26. A method as claimed in claim 23, 24 or 25, wherein the or each derivative of the
20 vertical particle component velocity with respect to a horizontal direction is derived from a measure of a derivative of horizontal particle component velocity with respect to a vertical direction.
27. A method as claimed in claim 26, wherein the derivative of the vertical particle
25 component velocity with respect to the third horizontal direction is derived from a measure of a derivative with respect to a vertical direction of a particle component velocity in the third horizontal direction.

28. A method as claimed in claim 26 or 27, wherein the derivative of the vertical particle component velocity with respect to the fourth horizontal direction is derived from a measure of a derivative with respect to a vertical direction of a particle component velocity in the fourth horizontal direction.
- 5 29. A method as claimed in any one of claims 23 to 28, wherein the derivatives of the vertical particle component velocity are obtained from measurements of rotation or rotation rate around the third and fourth horizontal directions.
30. A method as claimed in any one of claims 19 to 29, in which each of the derivatives is a first or second or third order derivative.
- 10 31. A method as claimed in claim 30, in which the reconstructing method comprises applying a sinc squared or sinc cubed or sinc to the power four interpolation.
32. A method as claimed in any one of claims 19 to 31, in which each derivative is formed from a measurement of difference or particle displacement or particle velocity or particle acceleration.
- 15 33. A method as claimed in any preceding claim, in which the or each receiver location is fixed.
34. A method as claimed in any preceding claim, in which the or each receiver location comprises a receiver station disposed on or above the seabed, and/or in at least one cable on the seabed and/or orientated vertically in the water column.
- 20 35. A method as claimed in any preceding claim except claim 26 or any claim dependent on claim 26, in which the or each receiver location comprises a receiver station deployed in a borehole on land or below the seabed.
36. A method as claimed in claim 35, in which the multicomponent measurement is used to measure a strain field.
- 25 37. A method as claimed in claim 36, in which a stress field is derived from the strain field.

38. A method as claimed in claim 37, in which the stress field is derived from the strain field by Hooke's law.

39. A method as claimed in any preceding claim, in which at least one receiver location comprises a receiver station comprising a cluster of pressure sensors, such as hydrophones, preferably with a separation between adjacent pressure sensors in the cluster of 1 cm to 10 m, more preferably with a separation between adjacent pressure sensors in the cluster of 5 cm to 1 m, more preferably with a separation between adjacent pressure sensors in the cluster of 1 cm to 1 m.

40. A method as claimed in any preceding claim, further comprising measuring at least one non-seismic geophysical field.

41. A method as claimed in claim 40, in which the at least one non-seismic geophysical field comprises at least one of an electromagnetic field, a gravity field and a magnetic field.

42. A method of processing seismic data acquired by actuating a seismic source at a plurality of source locations and, for each source location, performing a multicomponent seismic measurement at at least one receiver location, the method comprising applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to source locations additional to the source locations at which the source was actuated.

43. A method of acquiring seismic data for processing by a method as claimed in claim 42, comprising actuating a seismic source at a plurality of source locations and/or, for each source location, performing a multicomponent seismic measurement at at least one receiver location.

44. A method of processing seismic data acquired by actuating a seismic source at at least one source location and, for each source location, performing a multicomponent seismic measurement at a plurality of receiver locations, the method comprising applying a reconstructing method to each multicomponent measurement to obtain additional data corresponding to receiver locations additional to the receiver locations at which the multicomponent measurement was performed.

45. A method of acquiring seismic data for processing by a method as claimed in claim 44, comprising actuating a seismic source at at least one source location and/or, for each source location, performing a multicomponent measurement at a plurality of receiver locations.
- 5 46. A method as claimed in any preceding claim, wherein the step of applying a reconstructing method comprises applying a reconstructing and/or interpolating filter.
47. A method as claimed in any preceding claim, wherein the seismic data comprises marine seismic data and wherein the seismic source comprises a marine seismic source.
- 10 48. A method as claimed in any preceding claim, wherein actuating a seismic source at a plurality of source locations comprises actuating a seismic source at a plurality of source locations in turn.
49. An apparatus for performing a method as claimed in claim 43 or 45, or any one of claims 46, 47 or 48 when dependent on claim 43 or 45, comprising at least one
15 receiver station for performing a multicomponent seismic measurement.
50. An apparatus as claimed in claim 49, in which the or each receiver station comprises multiple hydrophones to measure pressure and derive spatial derivatives (gradients) therefrom, and/or multiple geophones to measure particle velocities and derive particle velocity derivatives (gradients) or spatial pressure derivatives therefrom,
20 and/or multiple accelerometers to measure accelerations and derive particle acceleration derivatives (gradients) or spatial pressure derivatives therefrom, and/or sensors to measure rotational motions around an axis to derive spatial derivatives of any physical fields such of particle component velocity.
51. An apparatus as claimed in claim 49 or 50, wherein at least one receiver station
25 is as claimed in any one of claims 33 to 41.
52. A method of providing marine seismic data, comprising the steps of:
actuating a marine seismic source at a plurality of source locations in turn;
for each source location, performing a multicomponent seismic measurement at
at least one receiver location; and

applying a reconstructing and/or interpolating filter to the or each multicomponent measurement to obtain pressure data and/or vertical particle velocity component related data corresponding to source locations additional to the source locations at which the source was actuated.

- 5 53. A method as claimed in claim 52, in which the vertical velocity component related data comprise at least one of vertical velocity component data, vertical particle displacement component data, and vertical acceleration component data.

54. A method as claimed in claim 52 or 53, in which each of the additional locations is disposed between ones of the source locations at which the source was actuated.

- 10 55. A method as claimed in claim 52, 53 or 54, in which the source locations at which the source was actuated comprise a regular grid.

56. A method as claimed in claim 55, in which the grid is one of a triangular grid, a rectangular grid and a hexagonal grid.

- 15 57. A method as claimed in any one of claims 52 to 56, in which each multicomponent measurement comprises pressure data and particle velocity related data.

58. A method as claimed in any one of claims 52 to 57, in which each multicomponent measurement comprises pressure measurement and measures of derivatives of pressure with respect to first and second different horizontal directions.

- 20 59. A method as claimed in claim 58, in which the first and second directions are horizontal Cartesian coordinate directions.

60. A method as claimed in any one of claims 52 to 59, in which each multicomponent measurement comprises vertical particle component velocity measurement and measures of derivatives of vertical particle component velocity with
25 respect to third and fourth different horizontal directions.

61. A method as claimed in claim 60, in which the third and fourth directions are horizontal Cartesian coordinate directions.

62. A method as claimed in any one of claims 58 to 61, in which each of the derivatives is a first or second or third order derivative.

63. A method as claimed in claim 62, in which the interpolating filter is a sinc squared or sinc cubed or sinc to the power four interpolation filter.

5 64. A method as claimed in any one of claims 58 to 63, in which each derivative is formed from a measurement of difference.

65. A method as claimed in any one of claims 52 to 64, in which the or each receiver location is fixed.

10 66. A method as claimed in any one of claims 52 to 65, in which the or each receiver location comprises a receiver station disposed on or above the seabed, and/or in at least one cable on the seabed and/or orientated vertically in the water column.

67. A method as claimed in any one of claims 52 to 66, in which the or each receiver location comprises a receiver station deployed in a borehole on land or below the seabed.

15 68. A method as claimed in claim 67, in which the multicomponent measurement is used to measure a strain field.

69. A method as claimed in claim 68, in which a stress field is derived from the strain field.

20 70. A method as claimed in claim 69, in which the stress field is derived from the strain field by Hooke's law.

71. A method as claimed in any one of claims 52 to 70, further comprising measuring at least one non-seismic geophysical field.

25 72. A method as claimed in claim 71, in which the at least one non-seismic geophysical field comprises at least one of an electromagnetic field, a gravity field and a magnetic field.

73. A method of processing marine seismic data acquired by actuating a marine seismic source at a plurality of source locations in turn and, for each source location, performing a multicomponent seismic measurement at at least one receiver location, the method comprising applying a reconstructing and/or interpolating filter to the or
5 each multicomponent measurement to obtain pressure data and/or vertical particle velocity component related data corresponding to source locations additional to the source locations at which the source was actuated.

74. A method of acquiring marine seismic data for processing by a method as claimed in claim 73, comprising actuating a marine seismic source at a plurality of
10 source locations in turn and, for each source location, performing a multicomponent seismic measurement at at least one receiver location.

75. An apparatus for performing a method as claimed in claim 74, comprising at least one receiver station for performing a multicomponent seismic measurement.

76. An apparatus as claimed in claim 75, in which the or each receiver station
15 comprises multiple hydrophones to measure pressure and derive spatial derivatives (gradients) therefrom, and/ or multiple geophones to measure particle velocities and derive particle velocity derivatives (gradients) therefrom, and/or multiple accelerometers to measure accelerations and derive particle acceleration derivatives (gradients) therefrom, and/or sensors to measure rotational motions around an axis to
20 derive spatial derivatives of any physical fields.

1/6

FIG. 1(a)

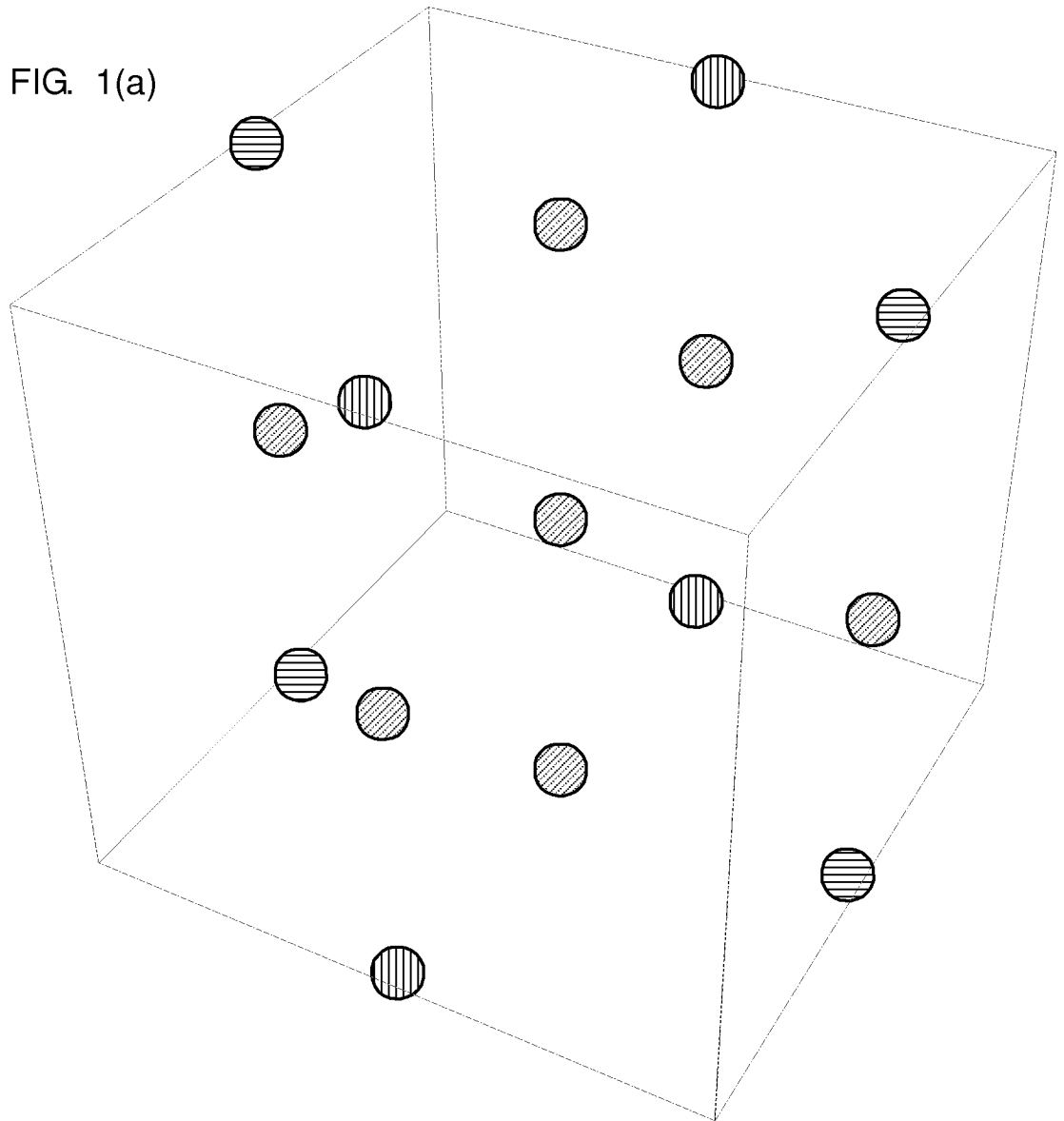
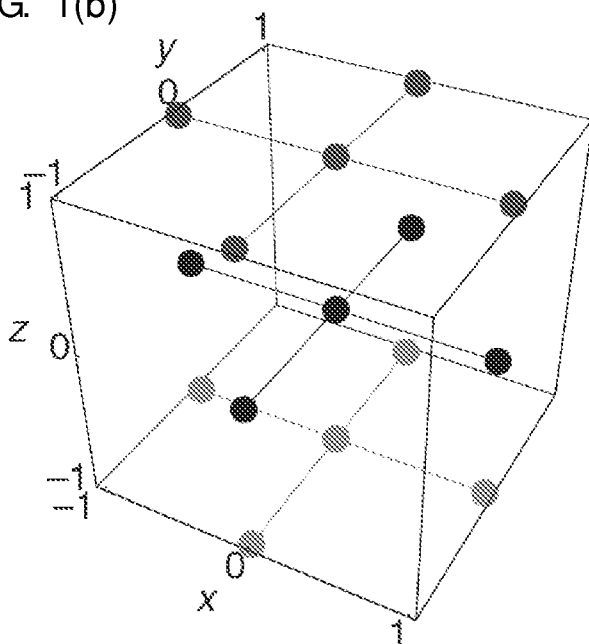


FIG. 1(b)



2/6

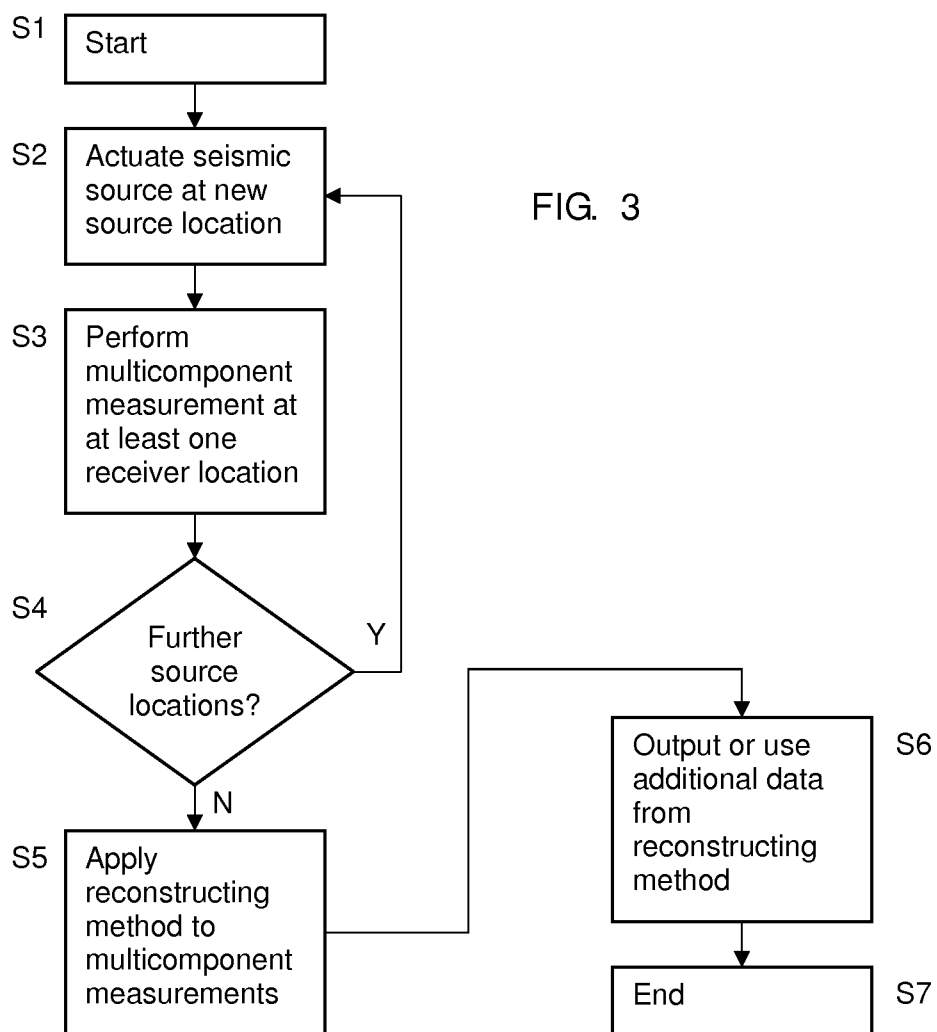


FIG. 4(a)

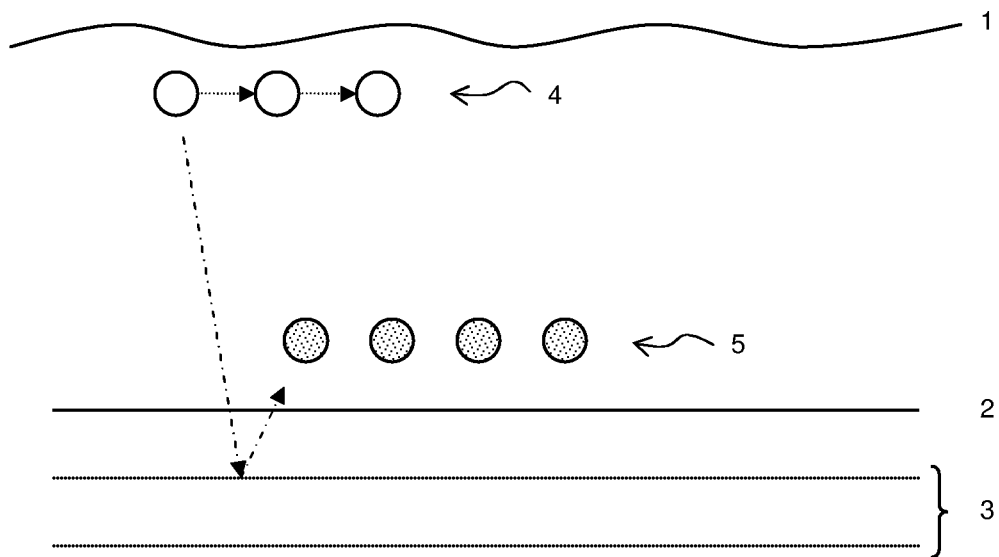
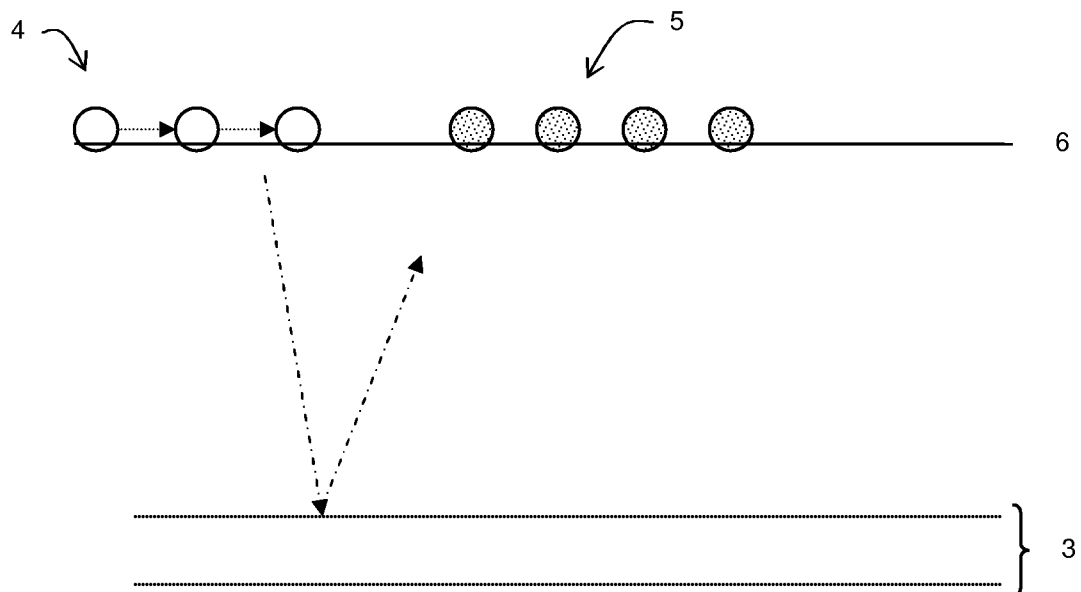
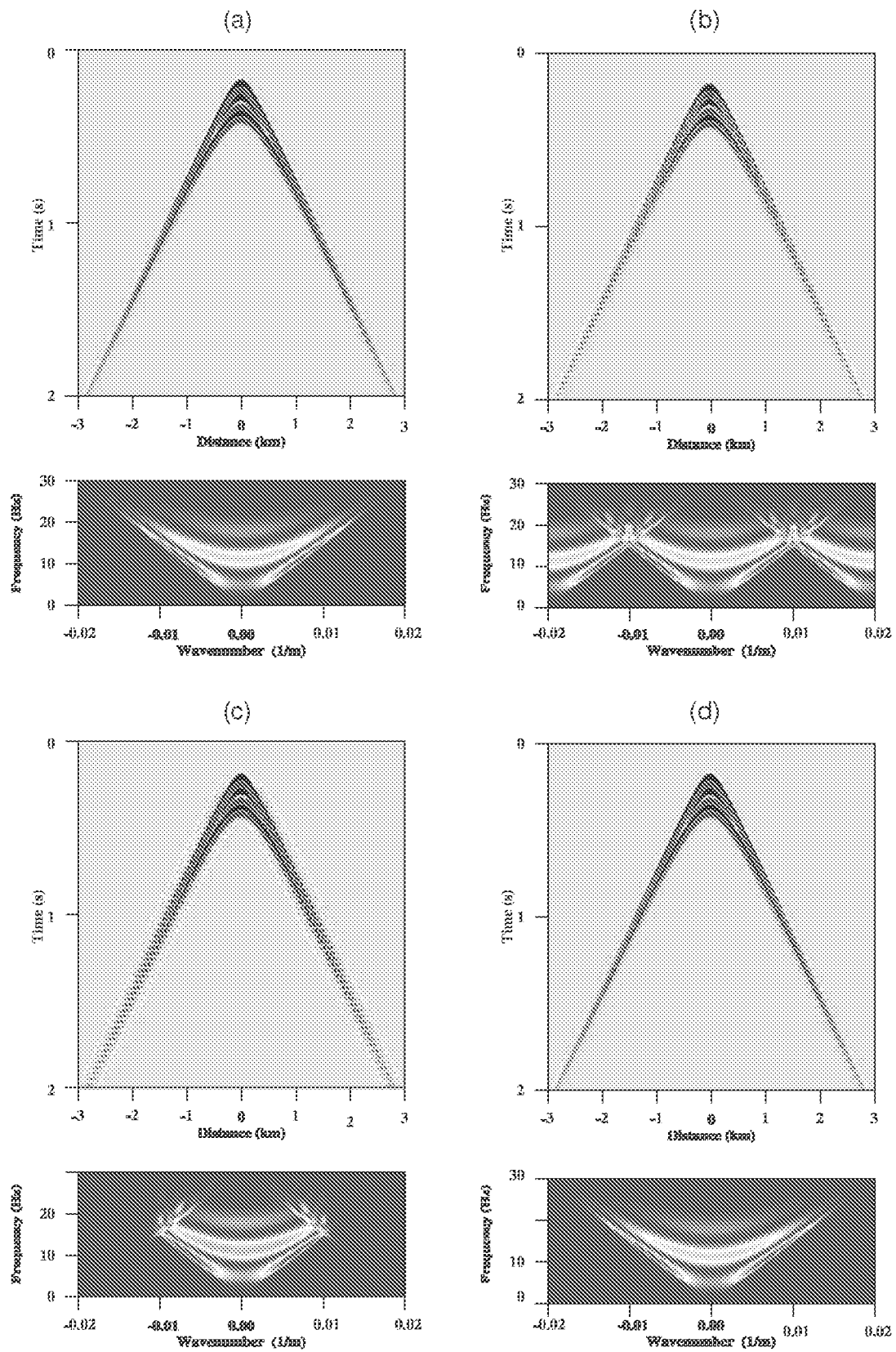


FIG. 4(b)



4/6

FIG. 2



5/6

FIG. 5

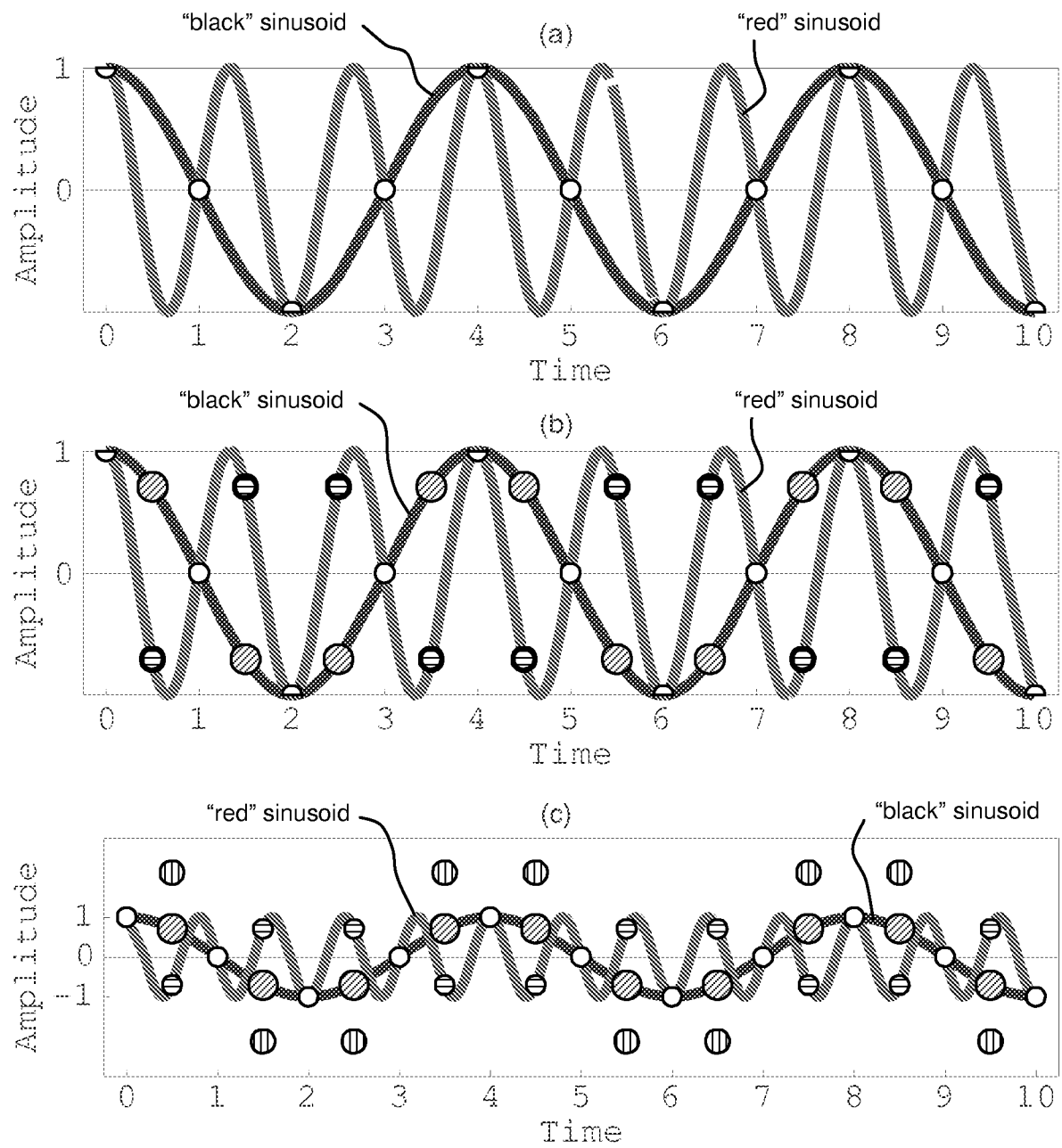
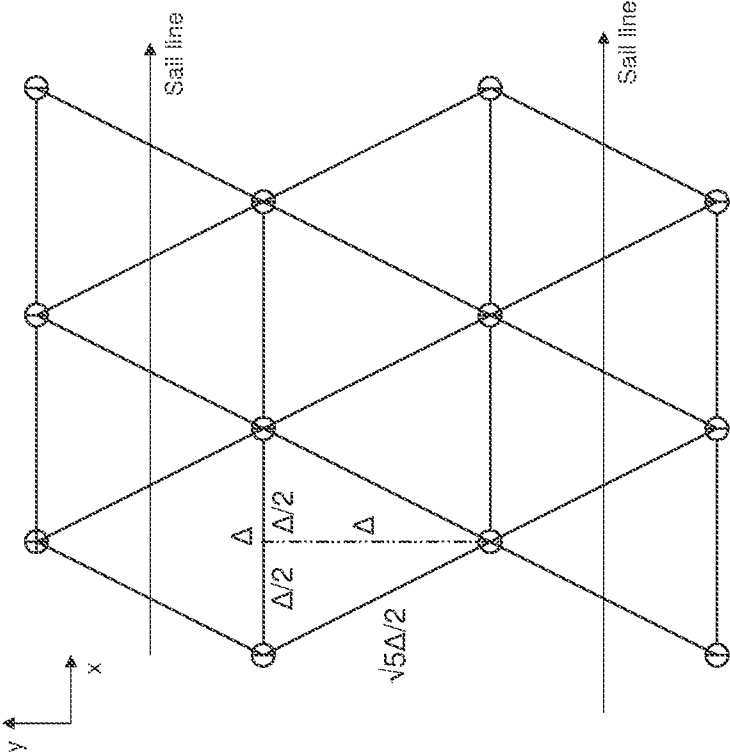


FIG. 6

(a)



(b)

