



- (51) **International Patent Classification:**
G01V 1/30 (2006.01)
- (21) **International Application Number:**
PCT/IB2015/002627
- (22) **International Filing Date:**
21 December 2015 (21.12.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
62/105,855 21 January 2015 (21.01.2015) US
- (71) **Applicant:** CGG SERVICES SA [FR/FR]; 27, Avenue Carnot, 91300 Massy (FR).
- (72) **Inventors:** HOEBER, Henning; C/O CGG Services SA, 27, Avenue Carnot, 91300 Massy (FR). KAHLIL, Adel; C/O CGG Services SA, 27, Avenue Carnot, 91300 Massy (FR).
- (74) **Agents:** PETIT, Maxime et al.; Ipsilon Brema-loyer, Le Centralis, 63 avenue du Général Leclerc, 92340 Bourg-laine (FR).
- (81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,

BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))
- of inventorship (Rule 4.17(iv))

[Continued on next page]

(54) **Title:** DECOMPOSITION INTO AMPLITUDE AND TIME ALIGNMENT EFFECTS

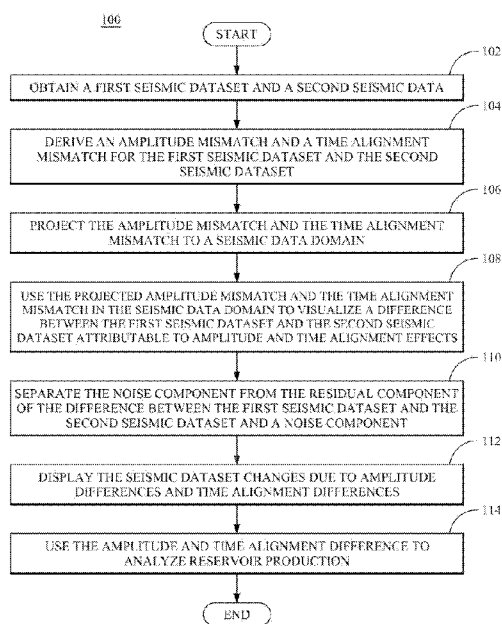


FIG. 1

(57) **Abstract:** 4D decomposition of seismic datasets into amplitude and time alignment effects (100) obtains a first seismic dataset and a later recorded second seismic dataset (102). An amplitude mismatch and a time alignment mismatch are derived (104) between the first and second seismic datasets, and the amplitude mismatch and the time alignment mismatch are projected to a seismic data domain (106). The projected amplitude mismatch and the time alignment mismatch are used in the seismic data domain to visualize a difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects (108).



Published:

— with international search report (Art. 21(3))

— before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

DECOMPOSITION INTO AMPLITUDE AND TIME ALIGNMENT EFFECTS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority and benefit from U.S. Provisional Patent Application No. 62/105,855, filed January 21, 2015, for “4D QC and 4D Denoise”, the entire content of which is incorporated herein by reference.

TECHNICAL FIELD

[0002] Embodiments of the subject matter disclosed herein generally relate to methods and systems for processing multi-vintage seismic data.

BACKGROUND

[0003] Four-Dimensional (4D) analysis involves time-lapse processing of seismic data and is used to analyze changes in the subsurface over time in order to monitor changes in subsurface structures such as reservoirs due to production from those reservoirs. Seismic datasets obtained at different times, i.e., vintages, are compared for these subsurface changes. A first vintage is taken by a base seismic survey before reservoir production and is referred to as a base vintage. Each subsequent vintage is taken during a monitor seismic survey and is referred to as a monitor vintage.

[0004] For two seismic datasets, a base vintage seismic dataset and a monitor vintage seismic dataset, each seismic dataset includes a multi-dimensional objects, i.e., a plurality of seismic traces recorded at a plurality of spatial locations. In addition, each seismic dataset is a function of time t . The result is a seismic dataset containing data in space and time. Each unique position in space and time is referred to as a sample. Therefore, the base seismic dataset and monitor seismic dataset each contain a plurality of samples.

[0005] Comparison using 4D analysis analyzes the samples in each seismic dataset vintage. In particular, the 4D analysis difference is determined on a sample by sample basis, i.e., the base seismic dataset and the monitor seismic dataset are subtracted from each other at every sample. A goal, therefore, of 4D processing is an optimal subtraction of the seismic datasets such that the difference is practically zero everywhere and only subsurface changes due to reservoir production are

visible. However, differences in the different vintages of seismic surveys, e.g., changes in acquisition geometry, used to acquire the seismic datasets produce non-zero differences in samples for subsurface locations other than the reservoir.

[0006] Therefore, systems and methods are desired that provide for 4D processing of multi-vintage seismic data that remove apparent changes, i.e., non-zero sample differences, that are not attributable to reservoir production. These system and methods would also be able to determine those changes attributable to amplitude effects and time alignment effects in the reservoir samples.

10 SUMMARY

[0007] Exemplary embodiments are directed to systems and methods four-dimensional (4D) signal processing. 4D projection operators are used to decompose a 4D difference into amplitude mismatch and time alignment mismatch components. Any residual 4D is further decomposed using 3D projections, which reduces residual leakage remaining after the 4D projection. A given 4D difference between a first or base seismic dataset and a second or monitor seismic dataset is decomposed into the dominant amplitude and time-shift related components in the seismic data domain. Using, for example, co-filtering methods, the original 4D difference is denoised to obtain a cleaner and more interpretable 4D difference. This 4D difference is a mixture of amplitude and time-shift changes and is used during seismic data processing for reservoir production analysis phase to disentangle the amplitude changes from the time-shift changes.

[0008] This method decomposes a given 4D difference between two seismic datasets acquired at two different times into the dominant amplitude and time-shift related components in the seismic domain. Using co-filtering methods, original 4D difference is denoised by correlating the original amplitude and time-shift related components, or their sum, back to the original 4D difference. This identifies any signal leakage that may have occurred. An improved 4D difference is obtained by adding the original components and their back projection components. Denoising can be done in any domain, e.g., x-t, f-x, f-k, tau-p, curvelet or wavelet and can be performed iteratively to improve the result.

[0009] An embodiment is directed to a method for decomposition of seismic datasets into amplitude and time alignment effects. The method includes obtaining a

first seismic dataset and a second seismic dataset recorded at a later time than the first seismic dataset, deriving an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset, projecting the amplitude mismatch and the time alignment mismatch to a seismic data domain and using the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects.

[0010] In one embodiment, deriving the amplitude mismatch and the time alignment mismatch includes defining the first seismic dataset as a function of the second seismic dataset, the amplitude mismatch and the time alignment mismatch and approximating the second seismic dataset as a sum of the second seismic dataset and a product of the time alignment mismatch and a derivative of the second seismic dataset. In one embodiment, the defined function of the first seismic dataset and the approximated second seismic dataset are used to express a difference between the first seismic dataset and the second seismic dataset. The expressed difference between the first seismic dataset and the second seismic dataset is inverted to derive the amplitude mismatch and the time alignment mismatch. Suitable inversions include a least squares inversion.

[0011] In one embodiment, projecting the amplitude mismatch and the time alignment mismatch further includes multiplying the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches and multiplying the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches. The seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches are displayed, and the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches the dataset are used to visualize the difference between the first seismic dataset and the second seismic attributable to amplitude effects and time alignment effects.

[0012] In one embodiment, the difference between the first seismic dataset and the second seismic dataset is a sum of the seismic dataset attributable to amplitude mismatches, the seismic dataset attributable to time alignment

mismatches and a residual term. The residual term is a residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component. In addition, the method includes separating the noise component from the residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component. In one embodiment, separating the noise component from the residual component of the difference includes determining a residual seismic dataset attributable to amplitude mismatches, determining a residual seismic dataset attributable to time alignment mismatches and subtracting the residual seismic dataset attributable to amplitude mismatches and the residual seismic dataset attributable to time alignment mismatches from the residual term to generate the noise component.

[0013] In one embodiment, the residual seismic dataset attributable to amplitude mismatches is to the seismic dataset attributable to amplitude changes to generate an improved seismic dataset attributable to amplitude changes. In addition, the residual seismic dataset attributable to time alignment mismatches is added to the seismic dataset attributable to time alignment mismatches to generate an improved seismic dataset attributable to time alignment mismatches.

[0014] An embodiment is directed to a computer-readable medium containing a computer-executable code that when read by a computer causes the computer to perform a method for 4D decomposition of seismic datasets into amplitude and time alignment effects. This method includes obtaining a first seismic dataset and a second seismic dataset recorded at a later time than the first seismic dataset, deriving an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset, projecting the amplitude mismatch and the time alignment mismatch to a seismic data domain and using the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects.

[0015] In one embodiment, deriving the amplitude mismatch and the time alignment mismatch includes defining the first seismic dataset as a function of the second seismic dataset, the amplitude mismatch and the time alignment mismatch and approximating the second seismic dataset as a sum of the second seismic dataset and a product of the time alignment mismatch and a derivative of the second

seismic dataset. In one embodiment, the defined function of the first seismic dataset and the approximated second seismic dataset are used to express a difference between the first seismic dataset and the second seismic dataset. The expressed difference between the first seismic dataset and the second seismic dataset is inverted to derive the amplitude mismatch and the time alignment mismatch. Suitable inversions include a least squares inversion.

[0016] In one embodiment, projecting the amplitude mismatch and the time alignment mismatch further includes multiplying the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches and multiplying the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches. The seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches are displayed, and the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches the dataset are used to visualize the difference between the first seismic dataset and the second seismic attributable to amplitude effects and time alignment effects.

[0017] In one embodiment, the difference between the first seismic dataset and the second seismic dataset is a sum of the seismic dataset attributable to amplitude mismatches, the seismic dataset attributable to time alignment mismatches and a residual term. The residual term is a residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component. In addition, the method includes separating the noise component from the residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component. In one embodiment, separating the noise component from the residual component of the difference includes determining a residual seismic dataset attributable to amplitude mismatches, determining a residual seismic dataset attributable to time alignment mismatches and subtracting the residual seismic dataset attributable to amplitude mismatches and the residual seismic dataset attributable to time alignment mismatches from the residual term to generate the noise component.

[0018] In one embodiment, the residual seismic dataset attributable to amplitude mismatches is to the seismic dataset attributable to amplitude changes to

generate an improved seismic dataset attributable to amplitude changes. In addition, the residual seismic dataset attributable to time alignment mismatches is added to the seismic dataset attributable to time alignment mismatches to generate an improved seismic dataset attributable to time alignment mismatches.

5 **[0019]** An embodiment is directed to a computing system for 4D decomposition of seismic datasets into amplitude and time alignment effects. The computing system includes a storage device storing a first seismic dataset and a second seismic dataset recorded at a later time than the first seismic dataset. In addition, a processor is provided in communication with the storage device. The
10 processor is configured to derive an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset, project the amplitude mismatch and the time alignment mismatch to a seismic data domain and use the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and
15 the second seismic dataset attributable to amplitude effects and time alignment effects.

[0020] In one embodiment, the processor is further configured to multiply the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches, multiply the time alignment mismatch by a
20 derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches, display the seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches and use the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches the dataset visualize the
25 difference between the first seismic dataset and the second seismic attributable to amplitude effects and time alignment effects.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The accompanying drawings, which are incorporated in and constitute
30 a part of the specification, illustrate one or more embodiments and, together with the description, explain these embodiments. In the drawings:

[0022] Figure 1 is a flow chart of an embodiment of a method for 4D decomposition of seismic datasets into amplitude and time alignment effects;

[0023] Figure 2 is a flow chart of an embodiment of a method for deriving the amplitude mismatch and the time alignment mismatch;

[0024] Figure 3 is a set of graphs illustrating an embodiment of the visualization of the seismic dataset attributable to amplitude mismatch and the seismic dataset attributable to time alignment mismatch;

[0025] Figure 4 is a set of graphs illustrating another embodiment of the visualization of the seismic dataset attributable to amplitude mismatch and the seismic dataset attributable to time alignment mismatch;

[0026] Figure 5 is a set of graphs illustrating residual signal and noise; and

[0027] Figure 6 is a schematic representation of an embodiment of a computing system for use in executing a method for 4D decomposition of seismic datasets into amplitude and time alignment effects.

DETAILED DESCRIPTION

[0028] 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. Some of the following embodiments are discussed, for simplicity, with regard to local activity taking place within the area of a seismic survey. However, the embodiments to be discussed next are not limited to this configuration, but may be extended to other arrangements that include regional activity, conventional seismic surveys, etc.

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

[0030] Referring to Figure 1, embodiments are directed to a method for 4D decomposition of seismic datasets into amplitude and time alignment effects 100. A first dataset and a second seismic dataset are obtained. The seismic datasets represent the results of seismic surveys over a given subsurface conducted using any

type of seismic survey acquisition system known and available in the art. In one embodiment, the seismic surveys are a base seismic survey conducted at a first time and a monitor seismic survey taken second time, later than the first time. The first seismic dataset corresponds to the base seismic survey, and the second seismic dataset corresponds to the monitor seismic survey. Therefore, the second seismic dataset was recorded at a later time than the first seismic dataset. This difference in time facilitates the use of the first and second seismic datasets for time-lapse or 4D processing.

[0031] Each one of the first and second datasets contains a plurality of seismic traces. The seismic traces in the plurality of seismic traces are recorded at a plurality of spatial locations and, therefore, are a function of space. In addition, the seismic datasets are also a function of time. Therefore, each seismic dataset is a function of space and time, and any given position within space and time for the seismic dataset is a sample.

[0032] Seismic datasets recorded at two different times are used in order to analyze changes that occur overtime in the subsurface, and in particular to reservoirs in the subsurface, that are attributable to production from those reservoirs. Looking at changes between the first and second datasets in 4D processing includes subtracting the one dataset from the other dataset, for example, on a sample by sample basis. This difference is illustrated in the following equation:

$$4D = b(t) - m(t) \quad (1)$$

where $4D$ is the 4D difference between the first and second seismic datasets, $b(t)$ is the first or base seismic dataset, and $m(t)$ is the second or monitor seismic dataset. As illustrated, the first and second seismic datasets are a function of time only, as the spatial indexing portion of the seismic datasets has been dropped.

[0033] To better analyze any non-zero signals indicated by the 4D difference in equation (1), the 4D difference being data, an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset are derived 104. Referring to Figure 2, an embodiment of deriving the amplitude mismatch and the time alignment mismatch 200 is illustrated. Assuming, in general, that the data are mismatched in amplitude and time, the first seismic dataset is defined as a function of the second seismic dataset, the amplitude mismatch and the time alignment mismatch 202. This function is illustrated in the following equation:

$$b(t) = A(t)m(t + \tau(t)) \quad (2)$$

where $A(t)$ is a function describing the amplitude mismatch, and $\tau(t)$ is a function describing the time alignment mismatch between the first and second datasets. These mismatch functions are also referred to as attributes, since they are derived from the seismic data. Both the amplitude and time attributes have the same dimensionality as the first and second seismic datasets as they are defined at every sample within the first and second seismic datasets. That is the first and second seismic datasets have a dimensionality equal to the number of samples, and comparing the first and second seismic datasets involves pairwise comparison of all of the samples in the first and second seismic datasets.

[0034] Having defined the function between the first and second seismic datasets, the second seismic dataset is approximated as a sum of the second seismic dataset and a product of the time alignment mismatch and a derivative of the second seismic dataset 204. This approximation is illustrated as follows:

$$m(t + \tau(t)) = m(t) + \tau(t)m'(t) \quad (3)$$

where $m(t)$ represents the second seismic dataset and $m'(t)$ denotes a derivative, i.e., a first derivative, of the data with respect to time t . Second and higher order derivatives are excluded from this approximation.

[0035] The defined function of the first seismic dataset and the approximated second seismic dataset are used to express a difference between the first seismic dataset and the second seismic dataset 206. Therefore, the defined function of the first seismic dataset as given in equation (2) and the approximation of the second seismic dataset as given in equation (3) are substituted into equation (1) to yield:

$$b(t) - m(t) \approx m(t) (A(t) - 1) + A(t)\tau(t)m'(t) \quad (4)$$

[0036] The expressed difference between the first seismic dataset and the second seismic dataset is inverted to derive the amplitude mismatch and the time alignment mismatch 208. Suitable inversions include, but are not limited to, a least squares inversion. More sophisticated inversion schemes can also be used for these two attributes. Least-squares solutions can be formulated to obtain the attributes or functions $A(t)$ and $\tau(t)$. In the simplest form, for example, these functions are given by:

$$A(t) = \frac{\sum_i m_i(b_i - m_i)}{\sum_i m_i m_i} \quad (5)$$

$$\tau(t) = \frac{\sum_i m'_i (b_i - m_i)}{\sum_i m'_i m'_i} \quad (6)$$

Summation over discrete indices i in time and space is implied.

[0037] Returning to Figure 1, having generated the amplitude mismatch, equation (5), and the time alignment mismatch, equation (6), through inversion, the amplitude mismatch and the time alignment mismatch are projected to a seismic data domain 106. As the inversion of the equation (4) produces the desired seismic attributes, these attributes and the information encoded in the attributes $A(t)$ and $\tau(t)$ are projected back onto the seismic data domain itself. Projecting the amplitude mismatch and the time alignment mismatch to the seismic data domain includes multiplying the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches and multiplying the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches. With the seismic dataset attributable to amplitude mismatch given by P_A and the seismic dataset attributable to time alignment mismatches given by P_τ , the projections are acquired by:

$$P_A = A(t) \cdot y(t) \quad (7)$$

$$P_\tau = \tau(t) \cdot y'(t) \quad (8)$$

where $y(t)$ is the second seismic dataset and $y'(t)$ is the derivative of the second seismic dataset, i.e., the first derivative.

[0038] Mapping the amplitude and time alignments back to the seismic domain facilitates a visual comparison of the 4D changes related to either only amplitude changes, or only time-shift changes. Referring to Figure 3, a set of graphs illustrating the different visualizations for a given slice through the seismic data samples is illustrated. A given 4D difference between the first and second seismic datasets is illustrated without noise, and with noise. This given 4D difference is only due to an amplitude change. The resulting attributes are illustrated for the amplitude mismatch and the time alignment mismatch. As illustrated, the portions of the 4D difference attributable to the amplitude and time differences cannot be visualized from the attributes or mismatch functions. However, when the attributes are projected back into the seismic data domain, the resulting amplitude mismatch projections and time alignment mismatch projection provide a clear visualization that the 4D difference is attributable to the amplitude change, as expected. Combining the resulting projections yields the same visualization as the original 4D difference.

[0039] Referring to Figure 4, a set of graphs 400 illustrating the different visualizations for a given slice through the seismic data samples is illustrated. A given 4D difference 402 between the first and second seismic datasets is illustrated without noise, and with noise 404. This given 4D difference is only due to a time shift change.

5 The resulting attributes are illustrated for the amplitude mismatch 411 and the time alignment mismatch 412. As illustrated, the portions of the 4D difference attributable to the amplitude and time differences cannot be visualized from the attributes or mismatch functions. However, when the attributes are projected back into the seismic data domain, the resulting amplitude mismatch projections 406 and time alignment mismatch projection 408 provide a clear visualization that the 4D difference is
10 attributable to the time shift change, as expected. Combining the resulting projections 410 yields the same visualization as the original 4D difference 402.

[0040] Returning to Figure 1, therefore, the projected amplitude mismatch and the time alignment mismatch in the seismic data domain are used to visualize a
15 difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects 108. The seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches are displayed, for example as illustrated in Figures 3 and 4. The display of the seismic dataset attributable to amplitude mismatches and the seismic dataset
20 attributable to time alignment mismatches are used to visualize the difference between the first seismic dataset and the second seismic attributable to amplitude effects and time alignment effects.

[0041] Since the approximation of the second seismic dataset as given in equation (3) is truncated at the first derivative, the resulting projections of the amplitude
25 and time alignment differences in the seismic data domain do not capture the entire seismic signal. In one embodiment, about 90% of the seismic signal is captured, leaving a residual of about 10%. In addition to this residual, the process of projecting the amplitude and time attributes back into the seismic data domain effectively removes noise, for example, as illustrated in Figures 3 and 4, since the attributes can be noisy,
30 particularly in areas of low amplitudes on the seismic data. Referring to Figure 5, a set of graphs 500 are provided illustrating this residual signal and noise. For the input 4D difference 502, the seismic dataset attributable to amplitude mismatch is given by P_A and the seismic dataset attributable to time alignment mismatches given by P_τ are

combined and displayed. This combination is subtracted from the original input 4D difference, and the result 504 is combination of noise and some leakage or residual 4D signal 508.

[0042] The combination of the attributes projected back into the seismic data domain along with the data residual and noise is illustrated by the following equation:

$$b(t) - m(t) = P_A(t) + P_r(t) + \text{residual 4D signal and noise} \quad (9)$$

where again the spatial indices are not carried.

[0043] Returning again to Figure 1, the difference between the first seismic dataset and the second seismic dataset is a sum of the seismic dataset attributable to amplitude mismatches, the seismic dataset attributable to time alignment mismatches and a residual term, the residual term containing a residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component. Therefore, 4D decomposition of seismic datasets into amplitude and time alignment effects also includes separating the noise component from the residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component 110. In one embodiment, a residual seismic dataset attributable to amplitude mismatches is determined, and a residual seismic dataset attributable to time alignment mismatches is determined. The residual seismic dataset attributable to amplitude mismatches and the residual seismic dataset attributable to time alignment mismatches are subtracted from the residual term to generate the noise component.

[0044] The seismic datasets due to amplitude changes and time alignment differences can then be displayed 112. In addition, the amplitude and time alignment differences can be used to analyze reservoir production 114. When residual signal is recaptured and subtracted from signal noise, the residual seismic dataset attributable to amplitude mismatches is added to the seismic dataset attributable to amplitude changes to generate an improved seismic dataset attributable to amplitude changes. Similarly, the residual seismic dataset attributable to time alignment mismatches is added to the seismic dataset attributable to time alignment mismatches to generate an improved seismic dataset attributable to time alignment mismatches. These improved mismatches are then displayed and used to analyze reservoir production.

[0045] In one embodiment, the residual signal is separated from the noise using a 4D co-denoise technique. Given the decomposition of seismic data into two

components, signal and noise, several samples of each of these two data components, i.e., signal estimation and noise estimation, are collected into a vector. A check for a perfect denoise is performed by verifying that the signal and noise vectors are perpendicular. In one embodiment, this check uses a cross-product of the two vectors.

- 5 If signal and noise vectors are not perpendicular, then the leakage of the signal into the noise can also be calculated by projecting the noise onto the signal.

[0046] The 4D co-denoise method uses this scheme to improve upon the estimates of P_A and P_τ , in order to minimize the signal leakage in equation (9) and to obtain improved estimates $\tilde{P}_A$ and $\tilde{P}_\tau$ such that:

$$10 \quad b(t) - m(t) = \tilde{P}_A(t) + \tilde{P}_\tau(t) + \text{residual 4D noise} \quad (10)$$

[0047] The improved estimates $\tilde{P}_A$ and $\tilde{P}_\tau$ are obtained by back-projecting into the seismic data domain as described the original estimates onto the original 4D estimates. Many different kinds of back projections in many different seismic domains can be used.

- 15 **[0048]** In another embodiment for separating the residual signal from the noise, the 4D difference equation is given as:

$$4D = a(t)y(t) + b(t)y'(t) \quad (11)$$

and is solved for $a(t)$ and $b(t)$ using a regularized inversion scheme.

[0049] Using simple least squares as the regularized inversion scheme:

$$20 \quad \begin{pmatrix} b_1(t) - m_1(t) \\ \dots \\ b_N(t) - m_N(t) \end{pmatrix} = \begin{pmatrix} m_1(t) & m'_1(t) \\ \dots & \dots \\ m_N(t) & m'_N(t) \end{pmatrix} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \quad (12)$$

[0050] The indices are for adjacent samples around the sample being investigated. This is solved for a and b at each sample and then:

$$A(t) = a(t) + 1 \quad (13)$$

$$\tau(t) = b(t)A(t) \quad (14)$$

- 25 and the clean 4D is built as before, as are the two projections.

[0051] In another embodiment for separating residual signal from noise:

$$\begin{pmatrix} b - m \\ b + m \end{pmatrix} = \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} b \\ m \end{pmatrix} \quad (15)$$

and set up the system such that:

$$\begin{pmatrix} b_1 - m_1 \\ \dots \\ b_N - m_N \\ b_1 + m_1 \\ \dots \\ b_N + m_N \end{pmatrix} = \begin{pmatrix} m_1 & m'_1 & 0 & 0 \\ \dots & \dots & \dots & \dots \\ m_N & m'_N & 0 & 0 \\ 0 & 0 & m_1 & m'_1 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & m_N & m'_N \end{pmatrix} \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} \quad (16)$$

[0052] Indexing is for fixed time t but for summation over adjacent samples around the sample of consideration. This yields:

$$a = A - 1 \quad (17)$$

$$c = A + 1 \quad (18)$$

$$b = d = A\tau \quad (19)$$

[0053] Therefore, the matrix system above can be augmented by two equations:

$$a - c - 2 = 0 \quad (20)$$

$$b - d = 0 \quad (21)$$

[0054] These equations are solved for a, b, c and d with the two constraints followed by rotating back, resulting in:

$$\begin{pmatrix} b \\ m \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} b - m \\ b + m \end{pmatrix} \quad (22)$$

to obtain the clean data and clean 4D estimate.

[0055] Referring now to Figure 6, exemplary embodiments are directed to a computing system 600 for decomposition of seismic datasets into amplitude and time alignment effects, a computing device for performing the calculations as set forth in the above-described embodiments may be any type of computing device capable of obtaining, processing and communicating acquired seismic data from marine surveys. The computing system 600 includes a computer or server 602 having one or more central processing units 604 in communication with a communication module 606, one or more input/output devices 610 and at least one storage device 608.

[0056] The communication module is used to obtain seismic datasets that from multiple vintages and that include a plurality of seismic traces. These seismic datasets can be obtained, for example, through the input/output devices. The acquired seismic data containing a first seismic dataset and a second seismic dataset, the second seismic dataset recorded at a later time than the first seismic dataset, are stored in the storage device. The input/output device can also be used to communicate or display the seismic dataset attributable to amplitude mismatch is given by P_A and the seismic

dataset attributable to time alignment mismatches given by P_t and any images or models generated for the subsurface or seismic survey, for example, to a user of the computing system.

[0057] The processor is in communication with the communication module and storage device and is configured to derive an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset, project the amplitude mismatch and the time alignment mismatch to a seismic data domain and use the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects.

[0058] In one embodiment, the processor is configured to multiply the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches, multiply the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches, display the seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches and use the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches the dataset visualize the difference between the first seismic dataset and the second seismic attributable to amplitude effects and time alignment effects.

[0059] Suitable embodiments for the various components of the computing system are known to those of ordinary skill in the art, and this description includes all known and future variants of these types of devices. The communication module provides for communication with other computing systems, databases and data acquisition systems across one or more local or wide area networks 612. This includes both wired and wireless communication. Suitable input/output devices include keyboards, point and click type devices, audio devices, optical media devices and visual displays.

[0060] Suitable storage devices include magnetic media such as a hard disk drive (HDD), solid state memory devices including flash drives, ROM and RAM and optical media. The storage device can contain data as well as software code for executing the functions of the computing system and the functions in accordance with the methods described herein. Therefore, the computing system 600 can be used to

implement the methods described above associated with 4D decomposition of seismic datasets into amplitude and time alignment effects. Hardware, firmware, software or a combination thereof may be used to perform the various steps and operations described herein.

5 **[0061]** Methods and systems in accordance with exemplary embodiments can be hardware embodiments, software embodiments or a combination of hardware and software embodiments. In one embodiment, the methods described herein are implemented as software. Suitable software embodiments include, but are not limited to, firmware, resident software and microcode. In addition, exemplary methods and
10 systems can take the form of a computer program product accessible from a computer-usable or computer-readable medium providing program code for use by or in connection with a computer, logical processing unit or any instruction execution system. In one embodiment, a machine-readable or computer-readable medium contains a machine-executable or computer-executable code that when read by a
15 machine or computer causes the machine or computer to perform a method for decomposition of seismic datasets into amplitude and time alignment effects and to the computer-executable code itself. The machine-readable or computer-readable code can be any type of code or language capable of being read and executed by the machine or computer and can be expressed in any suitable language or syntax known
20 and available in the art including machine languages, assembler languages, higher level languages, object oriented languages and scripting languages.

[0062] As used herein, a computer-usable or computer-readable medium can be any apparatus that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus,
25 or device. Suitable computer-usable or computer readable mediums include, but are not limited to, electronic, magnetic, optical, electromagnetic, infrared, or semiconductor systems (or apparatuses or devices) or propagation mediums and include non-transitory computer-readable mediums. Suitable computer-readable mediums include, but are not limited to, a semiconductor or solid state memory, magnetic tape, a
30 removable computer diskette, a random access memory (RAM), a read-only memory (ROM), a rigid magnetic disk and an optical disk. Suitable optical disks include, but are not limited to, a compact disk - read only memory (CD-ROM), a compact disk - read/write (CD-R/W) and DVD.

[0063] The disclosed exemplary embodiments provide a computing device, software and method for method for decomposition of seismic datasets into amplitude and time alignment effects. It should be understood that this description is not intended to limit the invention. On the contrary, the exemplary embodiments are intended to
5 cover alternatives, modifications and equivalents, which are included in the spirit and scope of the invention. Further, in the detailed description of the embodiments, numerous specific details are set forth in order to provide a comprehensive understanding of the invention. However, one skilled in the art would understand that various embodiments may be practiced without such specific details.

[0064] Although the features and elements of the present embodiments are described in the embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the embodiments or in various combinations with or without other features and elements disclosed herein. The methods or flowcharts provided in the present application may be implemented in
15 a computer program, software, or firmware tangibly embodied in a computer-readable storage medium for execution by a geophysics dedicated computer or a processor.

[0065] This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable
20 scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

WHAT IS CLAIMED IS:

1. A method for decomposition of seismic datasets into amplitude and time alignment effects (100), the method comprising:

obtaining a first seismic dataset and a second seismic dataset (102), the second seismic dataset recorded at a later time than the first seismic dataset;

deriving an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset (104);

projecting the amplitude mismatch and the time alignment mismatch to a seismic data domain (106); and

using the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects (108).

2. The method of claim 1, wherein deriving the amplitude mismatch and the time alignment mismatch further comprises:

defining the first seismic dataset as a function of the second seismic dataset, the amplitude mismatch and the time alignment mismatch; and

approximating the second seismic dataset as a sum of the second seismic dataset and a product of the time alignment mismatch and a derivative of the second seismic dataset.

3. The method of claim 2, wherein deriving the amplitude mismatch and the time alignment mismatch further comprises using the defined function of the first seismic dataset and the approximated second seismic dataset to express a difference between the first seismic dataset and the second seismic dataset.

4. The method of claim 3, wherein deriving the amplitude mismatch and the time alignment mismatch further comprises inverting the expressed difference between the first seismic dataset and the second seismic dataset to derive the amplitude mismatch and the time alignment mismatch.

5. The method of claim 4, wherein inverting the expressed difference comprises using a least squares inversion.

6. The method of claim 1, wherein projecting the amplitude mismatch and the time alignment mismatch further comprises:

multiplying the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches; and

multiplying the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches.

7. The method of claim 6, wherein the method further comprises displaying the seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches; and

using the projected amplitude mismatch and the time alignment mismatch to visualize the difference between the first seismic dataset and the second seismic dataset further comprises using the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches to visualize the difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects.

8. The method of claim 6, wherein:

the difference between the first seismic dataset and the second seismic dataset comprises a sum of the seismic dataset attributable to amplitude mismatches, the seismic dataset attributable to time alignment mismatches and a residual term, the residual term comprising a residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component; and

the method further comprises separating the noise component from the residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component.

9. The method of claim 8, wherein separating the noise component from the residual component of the difference comprises:

determining a residual seismic dataset attributable to amplitude mismatches;
determining a residual seismic dataset attributable to time alignment mismatches; and

subtracting the residual seismic dataset attributable to amplitude mismatches
5 and the residual seismic dataset attributable to time alignment mismatches from the residual term to generate the noise component.

10. The method of claim 9, wherein the method further comprises:

adding the residual seismic dataset attributable to amplitude mismatches to
10 the seismic dataset attributable to amplitude changes to generate an improved seismic dataset attributable to amplitude changes; and

adding the residual seismic dataset attributable to time alignment mismatches to the seismic dataset attributable to time alignment mismatches to generate an improved seismic dataset attributable to time alignment mismatches.

15

11. A computer-readable medium containing a computer-executable code that when read by a computer causes the computer to perform a method for 4D decomposition of seismic datasets into amplitude and time alignment effects (100), the method comprising:

20 obtaining a first seismic dataset and a second seismic dataset (102), the second seismic dataset recorded at a later time than the first seismic dataset;

deriving an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset (104);

projecting the amplitude mismatch and the time alignment mismatch to a
25 seismic data domain (106); and

using the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects (108).

30

12. The computer-readable medium of claim 11, wherein deriving the amplitude mismatch and the time alignment mismatch further comprises:

defining the first seismic dataset as a function of the second seismic dataset, the amplitude mismatch and the time alignment mismatch; and

approximating the second seismic dataset as a sum of the second seismic dataset and a product of the time alignment mismatch and a derivative of the second seismic dataset.

13. The computer-readable medium of claim 12, wherein deriving the amplitude mismatch and the time alignment mismatch further comprises using the defined function of the first seismic dataset and the approximated second seismic dataset to express a difference between the first seismic dataset and the second seismic dataset.

14. The computer-readable medium of claim 13, wherein deriving the amplitude mismatch and the time alignment mismatch further comprises inverting the expressed difference between the first seismic dataset and the second seismic dataset to derive the amplitude mismatch and the time alignment mismatch.

15. The computer-readable medium of claim 11, wherein projecting the amplitude mismatch and the time alignment mismatch further comprises:

multiplying the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches; and

multiplying the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches.

16. The computer-readable medium of claim 15, wherein the method further comprises displaying the seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches; and using the projected amplitude mismatch and the time alignment mismatch to visualize the difference between the first seismic dataset and the second seismic dataset further comprises using the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches to visualize the difference between the first seismic dataset and the second seismic dataset attributable to amplitude effects and time alignment effects.

17. The computer-readable medium of claim 15, wherein:

the difference between the first seismic dataset and the second seismic dataset comprises a sum of the seismic dataset attributable to amplitude mismatches, the seismic dataset attributable to time alignment mismatches and a residual term, the residual term comprising a residual component of the difference between the first seismic dataset and the second seismic dataset and a noise component; and

the method further comprises separating the noise component from the residual component of the difference.

18. The computer-readable medium of claim 17, wherein separating the noise component from the residual component of the difference comprises:

determining a residual seismic dataset attributable to amplitude mismatches;

determining a residual seismic dataset attributable to time alignment mismatches; and

subtracting the residual seismic dataset attributable to amplitude mismatches and the residual seismic dataset attributable to time alignment mismatches from the residual term to generate the noise component.

19. A computing system (600) for 4D decomposition of seismic datasets into amplitude and time alignment effects, the computing system comprising:

a storage device (608) comprising a first seismic dataset and a second seismic dataset, the second seismic dataset recorded at a later time than the first seismic dataset (102); and

a processor (604) in communication with the storage device and configured to:

derive an amplitude mismatch and a time alignment mismatch between the first seismic dataset and the second seismic dataset (104);

project the amplitude mismatch and the time alignment mismatch to a seismic data domain (106); and

use the projected amplitude mismatch and the time alignment mismatch in the seismic data domain to visualize a difference between the first seismic dataset and

the second seismic dataset attributable to amplitude effects and time alignment effects (108).

20. The computing system of claim 19, wherein the processor is further
5 configured to:

multiply the amplitude mismatch by the second seismic dataset to generate a seismic dataset attributable to amplitude mismatches;

multiply the time alignment mismatch by a derivative of the second seismic dataset to generate a seismic dataset attributable to time alignment mismatches;

10 display the seismic dataset attributable to amplitude mismatches and the seismic dataset attributable to time alignment mismatches; and

use the displayed seismic dataset attributable to amplitude mismatches and seismic dataset attributable to time alignment mismatches the dataset visualize the difference between the first seismic dataset and the second seismic attributable to
15 amplitude effects and time alignment effects.

1 of 6

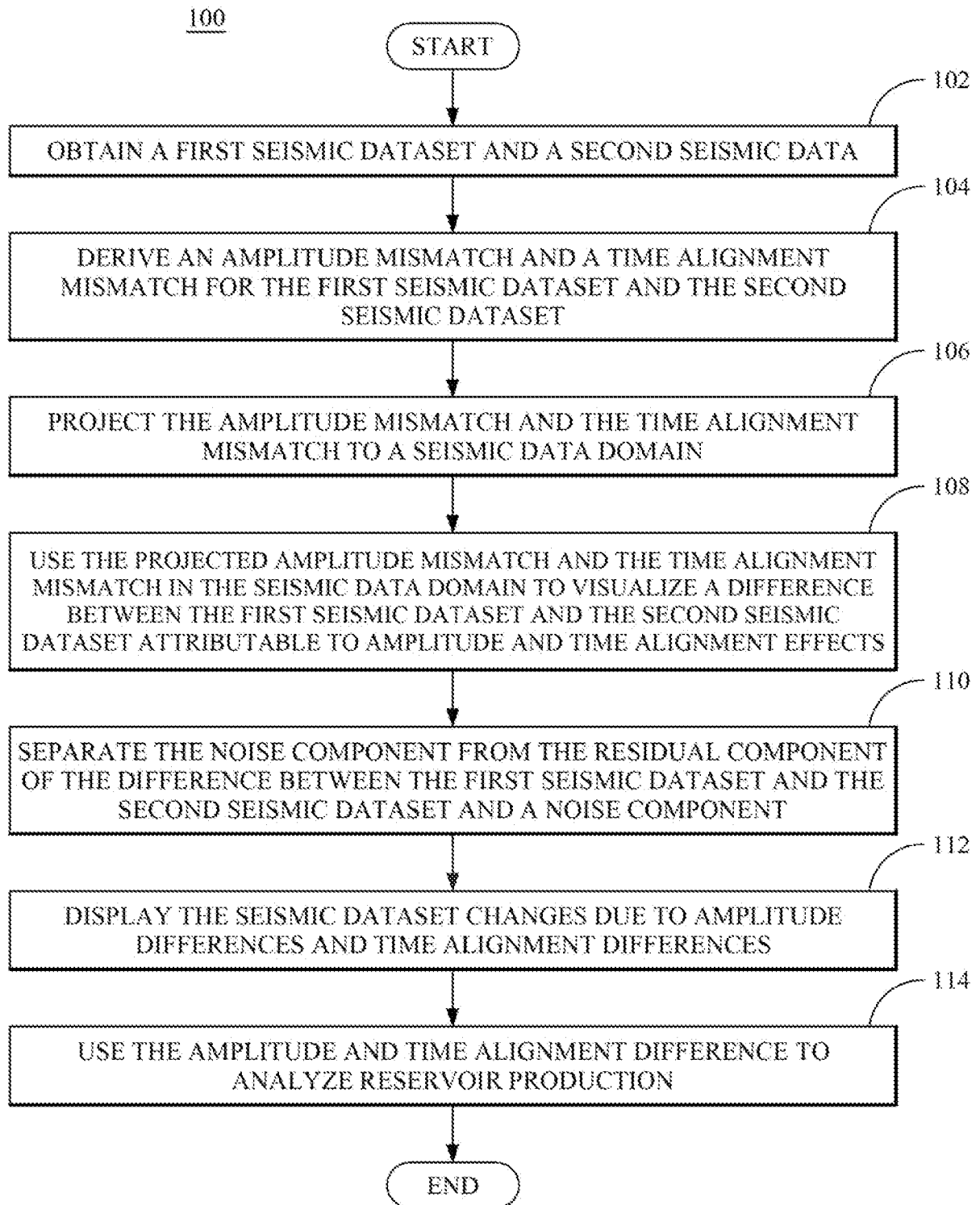


FIG. 1

2 of 6

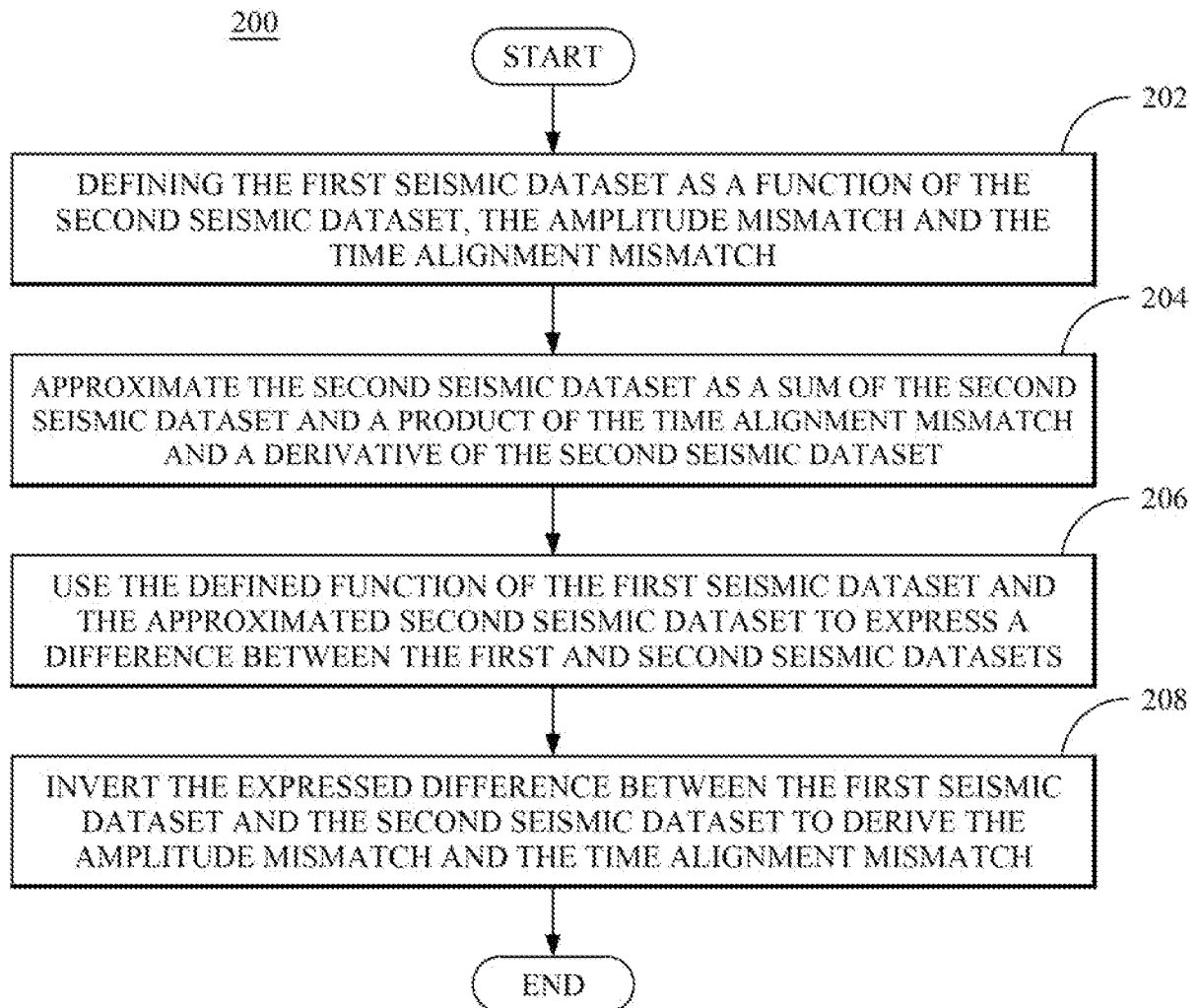


FIG. 2

300

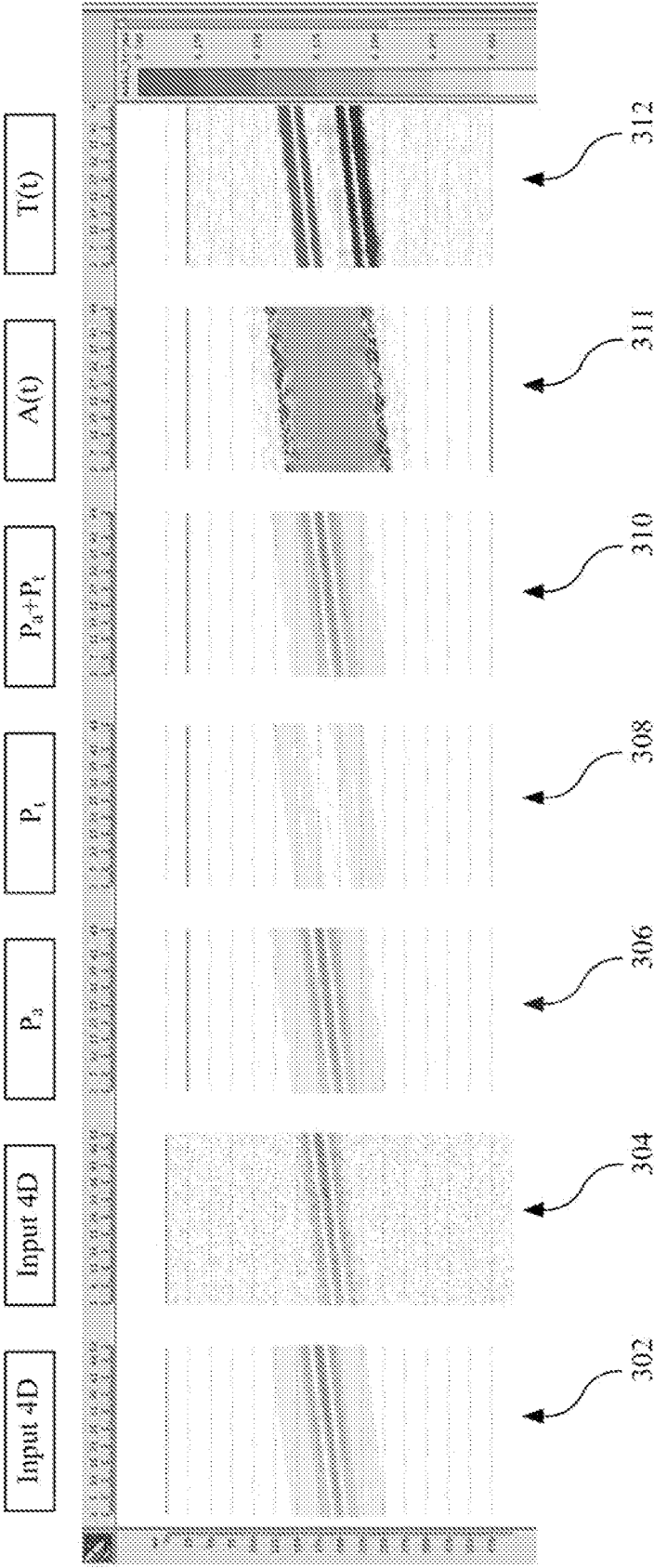


FIG. 3

400

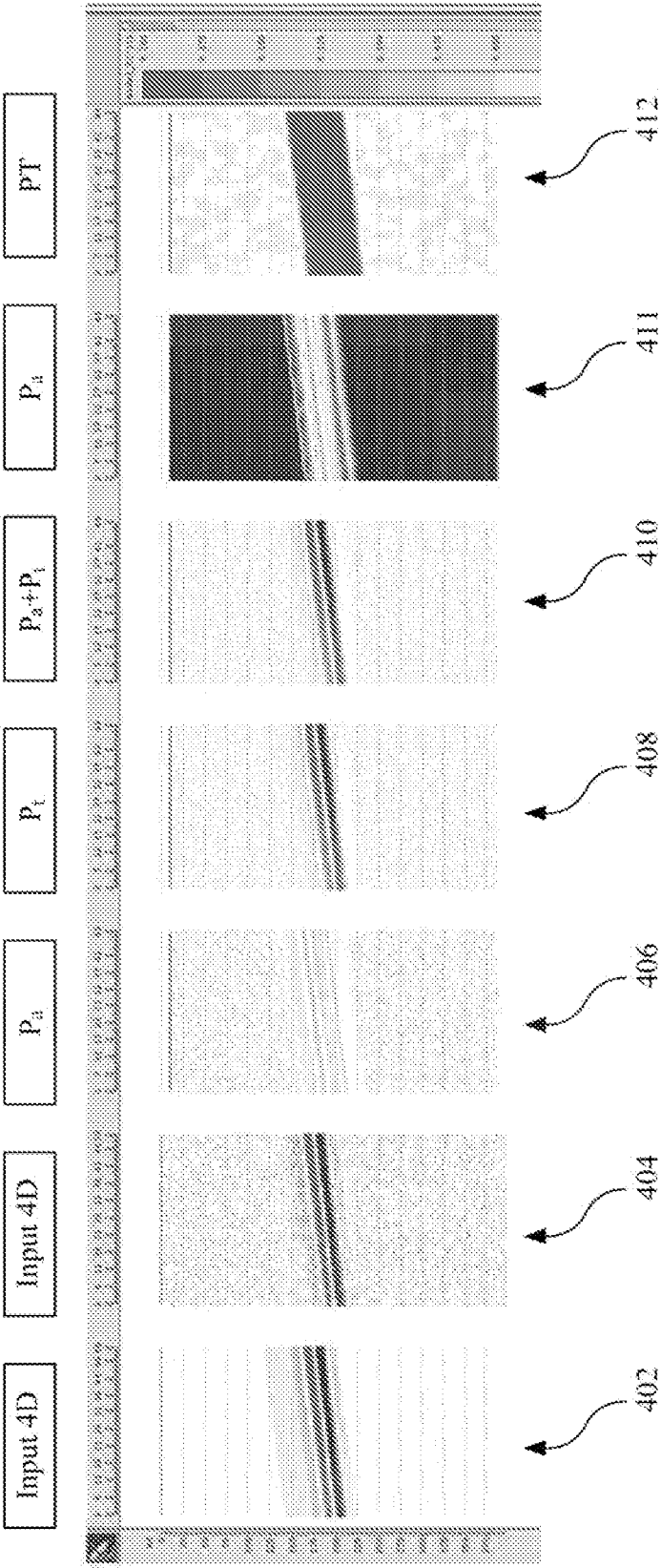


FIG. 4

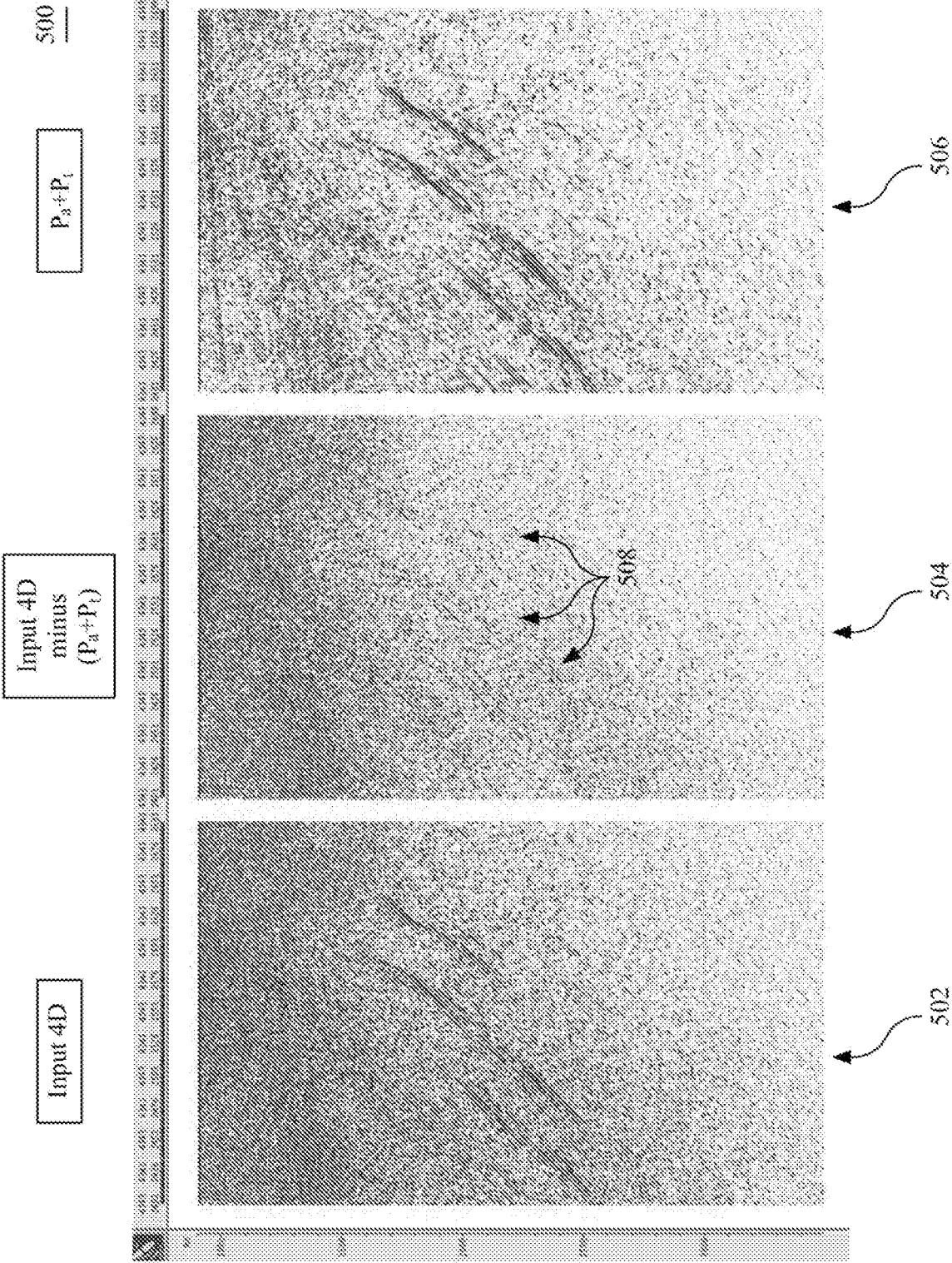


FIG. 5

6 of 6

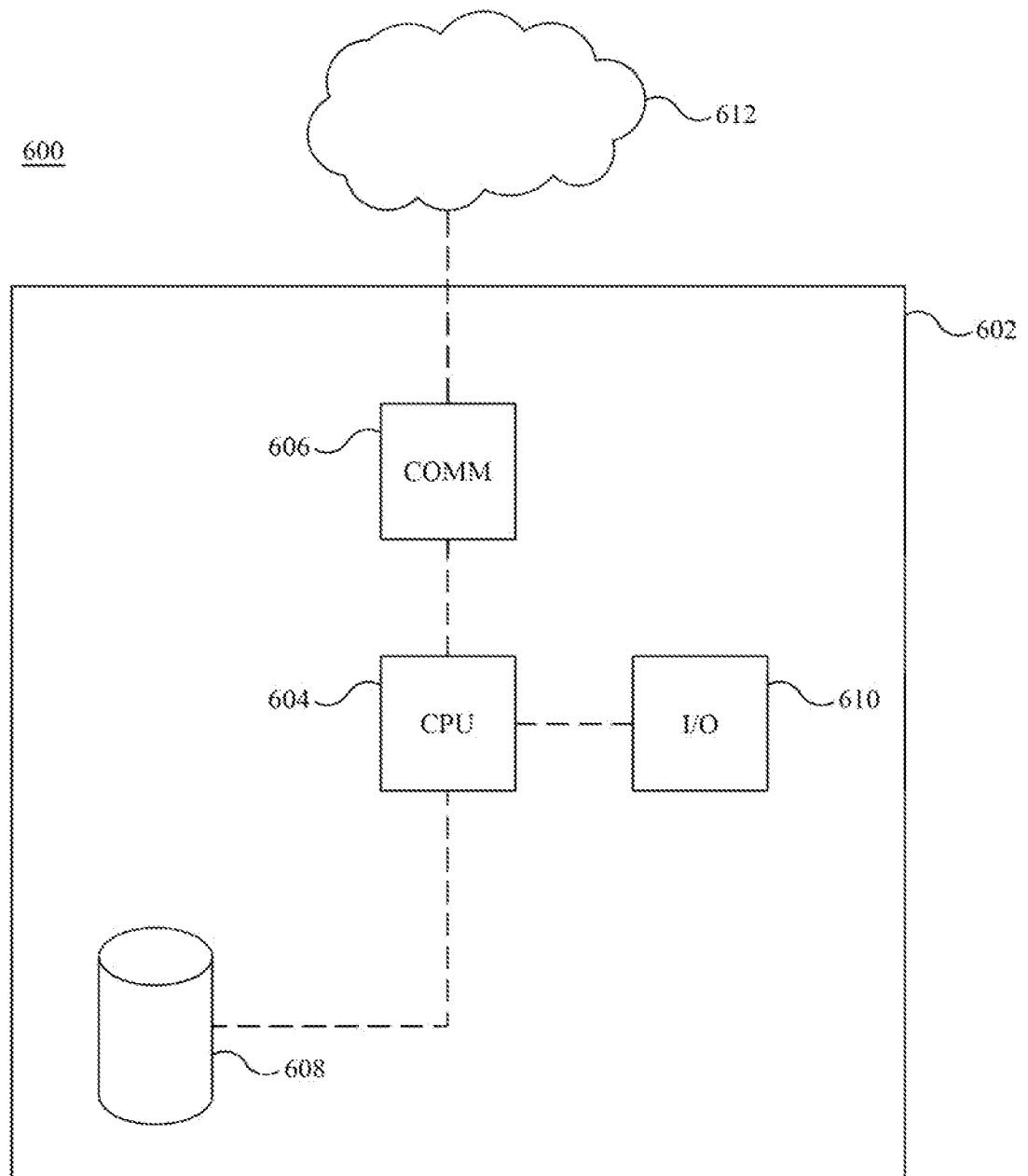


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/002627

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V1/30
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2003/043693 A1 (EASTWOOD JOHN E [US] ET AL) 6 March 2003 (2003-03-06) paragraphs [0014] - [0016], [0034], [0038] - [0040], [0058] - [0064]; figures 2,5-10	1,11,19
X	US 2012/140593 A1 (STOFFA PAUL L [US] ET AL) 7 June 2012 (2012-06-07)	1-3, 6-13, 15-20
Y	paragraphs [0003], [0010], [0027] - [0036], [0047] - [0061], [0070] - [0084]; figure 5 ----- -/-	4,5,14



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

"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

15 June 2016

Date of mailing of the international search report

22/06/2016

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

Vollmer, Thorsten

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2015/002627

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 041 018 A (ROCHE STEVEN L [US]) 21 March 2000 (2000-03-21) column 1, line 10 - line 15; figure 5 column 3, line 37 - column 4, line 8 column 6, line 63 - column 5, line 30 column 10, line 40 - line 63 -----	1,11,19
Y	Y LAFET ET AL: "Eleventh International Congress of the Brazilian Geophysical Society Global 4-D seismic inversion and time-lapse fluid prediction", 11TH INTERNATIONAL CONGRESS OF THE BRAZILIAN GEOPHYSICAL SOCIETY, 24 August 2009 (2009-08-24), pages 1-4, XP055193941, the whole document -----	4,5,14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2015/002627

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2003043693	A1	06-03-2003	NONE
US 2012140593	A1	07-06-2012	US 2012140593 A1 07-06-2012
		WO 2011034870 A1	24-03-2011
US 6041018	A	21-03-2000	NONE