[0014] Embodiments of the invention have been made with these points in mind.

[0015] Before proceeding to a detailed description, however, it should be noted and remembered that the description which follows, together with the accompanying drawings, should not be construed as being limited to the examples (or embodiments) shown and described. This is so because those skilled in the art will be able to devise other variations within the ambit of the appended claims.

SUMMARY

[0016] According to a first aspect, there is provided a method for use in seismic exploration of a region of the subsurface of the earth, wherein is provided a plurality of continuously recorded seismic traces collected in a seismic survey conducted proximate to the region of the subsurface of the earth, each of said traces being recorded by a receiver having a clock, the method comprising the steps of:

(a) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver, wherein the second receiver is proximate to the first receiver if it records signals from the same seismic event;

(b) for each of said proximate trace pairs, determining a relative time shift between said first trace and said second trace;

(c) inverting said relative time shifts determined in step (b) to obtain a clock drift estimate for each of the clocks of said first and second receivers by solving the equation:

$$\begin{bmatrix} 1 & -1 & \dots & 0 & 0 \\ 1 & 0 & -1 & \dots & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & \dots & 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \vdots \\ \Delta t_N \end{bmatrix} = \begin{bmatrix} \Delta_{1,2} \\ \Delta_{1,3} \\ \vdots \\ \Delta_{N-1,N} \end{bmatrix}$$

for Δt_i , $i = 1, N$,

where Δt_i is said clock drift estimate associated with an *ith* one of said clocks of said first and second receivers,

where N is a number of said clocks of said first and second receivers, and,

where Δ_{kj} is said relative time shift between a *kth* one of said first traces and a jth one of said second traces; and

(d) using said clock drift estimates obtained in step (c) to time correct the first and second traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth.

[0017] A seismic trace is the data recorded by a seismic recorder. By continuously recorded seismic trace, it is meant a single seismic trace which records the reflections from several seismic source activations. The recorder may record data for long durations of a survey, possibly the whole survey. In other words, the recorders are not switched on and off to coincide with individual seismic source activations.

[0018] By proximate to said first receiver, it is meant that the second receiver was located proximate to the first receiver during the seismic survey which gathered the continuously recorded seismic traces. This is discussed in more detail below.

[0019] Step (c) therefore produces a clock drift estimate for each clock being corrected. The clock drift estimate is an absolute value which can be applied to the trace recorded by the corresponding receiver.

[0020] The inventors have recognized that embodiments of the present invention permit the removal of the requirement for an accurate clock in the receiver, which can significantly reduce the manufacturing cost, size and weight of a seismic receiver. Instead, embodiments of the invention are used to correct the clock drift of a relatively inaccurate clock in a seismic receiver. By inaccurate clock, it is meant one which drifts by more than one sample over the course of the survey. It will be understood by the skilled reader that one sample over the course of the survey equates to an amount of drift per day which depends on the length of the survey and the sample rate. For example, for a 30 day survey using receivers which sample every 4ms, a clock which drifts by more than about 0.00013 seconds per day could be said to be inaccurate. As another example, for a 60 day survey using receivers which sample every 2ms, a clock which drifts by more than about 3.3×10^{-5} seconds per day would be deemed to be an inaccurate clock for the survey.

[0021] According to one embodiment seismic data that is recorded by the receivers as part of the seismic acquisition survey will be used to estimate and remove the clock drift in each receiver. Since seismic data are not random, and contain coherent events that are recorded by all receivers in a local area, according to one embodiment it is possible to compare the arrival times of these events, which should be locally coherent, to estimate how a clock is drifting compared to other clocks in other receivers in the area. For example, the relative time shift in step (b) may comprise calculating a cross correlation between said first and second traces. The maxima of those cross correlations are then used to estimate the drift difference of the clock in the selected receiver from true time. As an alternative to cross correlation, other techniques for identifying the same signal in two different traces, and particularly for identifying what shift in two traces would achieve maximum similarity between the two

traces, may be used. For example, dynamic image warping, a correlated leakage method or the Monte Carlo method may be used to identify what shift would achieve maximum similarity between two traces, thereby generating an estimate of the relative time shift between the two traces. These techniques are known generally, and also within the seismic industry, for example as applied to assessing 4D time shifts.

[0022] This approach allows seismic data to be collected by many independent seismic receivers with independent and potentially inaccurate clocks and allows the data recorded by each receiver to subsequently be time shifted to correct for the differing clock drift of the receiver that recorded it. The method makes use of the data recorded by the receivers as part of the seismic acquisition survey and no separate, specific timing signals are needed. This approach can potentially accommodate a different time-variable correction for each receiver.

[0023] Typically, techniques taught herein will be applied to continuously recorded data and so can be useful in a passive seismic survey, such as where seismic signals from other operations in the area (drilling, production, fracking activities etc) or from background noise (waves, earthquakes etc) are recorded, or a simultaneous source survey such as that described in WO 2008/025986, etc. In this embodiment, relatively long data recordings (e.g., several hours per receiver) will be used to estimate relative time shifts between nearby traces, preferably using cross correlation.

[0024] The relative time shifts can be used to estimate the residual, absolute time shift which will be an estimate of the unique constant clock drift associated with each receiver, preferably by solution of a least squares over determined system of equations. To assist, a least squares solver can be used. In some cases the system of equations might be augmented by constraints on the solution.

[0025] Optionally, step (a) can comprise the steps of:

(a1) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver;

(a2) for the clock in each of said first and second receivers, selecting a shooting time window;

(a3) calculating a linear estimate of a drift correction for each of said clocks during said shooting time window; and

(a4) adjusting said first and second traces in time according to the calculated linear estimate of said drift correction for the corresponding clock.

[0026] Here, it will be understood that references to the first and second traces in steps (b) and (d) refer to the trace as adjusted by step (a4).

[0027] The shooting time window for a given clock can be selected by identifying a receiver clock first time and a receiver clock second time corresponding to known accurate first and

second times. The known accurate first and second times can be times when a comparison of two times as recorded by the clock can be made with the corresponding true times. For example, the clocks may at times be synchronised to an accurate time source, such as a GPS receiver. The shooting time window can span substantially all of the seismic survey, though a shorter time window could alternatively be selected.

[0028] The skilled reader will understand that step (a1) may be performed after steps (a2) to (a4) i.e. the traces may have a linear correction applied to them before the trace pairs are established.

[0029] Accordingly, given the linear drift estimate for each receiver and the residual, absolute shift as calculated in step (b), the traces for each receiver can be corrected.

[0030] In embodiments, the method may comprise identifying at least two trace sections for each of said first and second traces, and performing steps (a) to (d) separately for each of the trace sections, thereby forming a plurality of time-corrected traces representative of the subsurface of the earth wherein each time-corrected trace comprises at least two sections of time-corrected trace corrected using the clock drift estimate obtained for the respective section of trace.

[0031] In other words:

step (a) may comprise the steps of:

(ai) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver; and

(aii) for each of the first traces and second traces, identifying a first trace section and at least one subsequent trace section;

step (b) may comprise determining, for each of said proximate trace pairs, a relative time shift between said first trace section of said first trace and said first trace section of said second trace, and determining, for each of said proximate trace pairs, a relative time shift between said subsequent trace sections of said first trace and said subsequent trace sections of said second trace;

step (c) may comprise, for each trace section, inverting the relative time shifts determined in step (b) to obtain a clock drift estimate for the clocks of the first and second receivers; and

step (d) may comprise using the clock drift estimates obtained in step (c) to time correct the corresponding sections of the first and second traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth, each of which comprises at least two sections of time-corrected seismic trace.

[0032] Again, it will be understood that step (ai) may be performed after the trace sections have been identified.

[0033] Typically, the trace sections may be multiple hours in length, e.g. sections up to about 6 hours, such as between 1 and 4 or 1 and 3 hours. In certain conditions, though, trace sections of at least one day, or multiple days, such as up to 2 to 3 days, may be appropriate, as discussed in more detail below.

[0034] In embodiments, the relative time shift between said first trace and said second trace may be determined in step (b) by determining the relative time shifts between a plurality of shot records comprised in said first trace and corresponding shot records in said second trace, and determining the average of said relative time shifts between said corresponding shot records.

[0035] By shot record, it is meant a segment of seismic trace comprising the recorded reflections resulting from a particular seismic source activation. In general, the exact time of the source activation will be known, and so the segment of seismic trace which will comprise the recorded signals/reflections can be known, despite the drift in the clock, with enough accuracy as to identify the appropriate segment.

[0036] The average of said relative time shifts between said corresponding shot records is determined so as to give a single, representative value for the relative time shift between said first trace and said second trace. The average of said relative time shifts may be determined by stacking. The process of stacking is well known to the skilled reader and refers to summing a plurality of signals. Averaging the relative time shifts in this way can be helpful since an individual time shift estimate corresponding to a single proximate trace pair will likely contain errors; however, the error will generally be averaged out to zero if several time shifts are averaged/stacked.

[0037] Although determining relative time shifts in this "shot by shot" manner is possible, it is not necessary. Instead, relative time shifts may be determined in respect of longer periods of time, such as in respect of trace sections as described above.

[0038] A kinematic correction may be applied, for each proximate trace pair, to remove the effect of differential arrival times (i.e. event moveout or velocity) between the first and second receivers associated with said proximate trace pair. The kinematic correction may be applied before or after step (b). The kinematic correction will typically be applied before step (c). The kinematic correction can be an NMO (normal moveout) correction or an LMO (linear moveout) correction. The use of NMO or LMO is particularly applicable where the kinematic correction is applied before step (b).

[0039] In embodiments, the method may further comprise identifying a trend in the clock drift estimates obtained in step (c) for each of the clocks of said first and second receivers and removing said trend from said clock drift estimates, thereby forming de-trended clock drift estimates for each of the clocks of the first and second receivers. In this case, step (d) comprises using said de-trended clock drift estimates to time correct the first and second

traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth. The trend may be identified and removed using a de-trending algorithm or using a smoothing filter to identify the trend which can then be removed. De-trending algorithms and smoothing filters are well known and readily available. Removing this trend can be useful to reduce inaccuracies due to moveout.

[0040] It is possible to provide at least one of said receivers with a clock which is an accurate clock. For example, up to 5%, or between 1% and 5%, such as between 1% and 3%, of the total number of clocks may be accurate clocks. Use of at least on accurate clock can improve the accuracy of the method in the vicinity of the accurate clock(s).

[0041] In embodiments, the proximate trace pairs are identified in step (a) such that each proximate trace pair is associated with at least one other proximate trace pair.

[0042] A first proximate trace pair can be directly associated with a second proximate trace pair if either the first or second trace of the first proximate trace pair is also the first or second trace of the second proximate trace pair. A proximate trace pair can also be indirectly associated with another proximate trace pair through a chain of directly associated trace pairs. In an example, each proximate trace pair is associated, either directly or indirectly, with all the other proximate trace pairs identified in step (a). In this way, a "network" of proximate trace pairs is established.

[0043] The above methods may further comprise the steps of

(e) using said plurality of time-corrected seismic traces to image at least a portion of said region of the subsurface of the earth; and

(f) using said imaged region of the subsurface of the earth in exploration for hydrocarbons within the region of the subsurface of the earth.

[0044] In another aspect, there is a method of seismic exploration of a region of the subsurface of the earth, wherein is provided a plurality of continuously recorded seismic traces collected in a seismic survey conducted proximate to the region of the subsurface of the earth, each of said traces being recorded by a receiver having a clock. The method comprises the steps of:

(a) accessing a plurality of time-corrected traces created by a method comprising the steps of:

(i) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver, wherein the second receiver is proximate to the first receiver if it records signals from the same seismic event;

(ii) for each of said proximate trace pairs, determining a relative time shift between said first trace and said second trace;

(iii) inverting the relative time shifts determined in step (ii) to obtain a clock drift estimate for the clocks of the first and second receivers, by solving the equation:

$$\begin{bmatrix} 1 & -1 & \dots & 0 & 0 \\ 1 & 0 & -1 & \dots & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & \dots & 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \vdots \\ \Delta t_N \end{bmatrix} = \begin{bmatrix} \Delta_{1,2} \\ \Delta_{1,3} \\ \vdots \\ \Delta_{N-1,N} \end{bmatrix}$$

for Δt_i , $i = 1, N$,

where Δt_i is said clock drift estimate associated with an *ith* one of said clocks of said first and second receivers,

where N is a number of said clocks of said first and second receivers, and,

where Δ_{kj} is said relative time shift between a *kth* one of said first traces and a jth one of said second traces; and

(iv) using the clock drift estimates obtained in step (iii) to time correct the first and second traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth;

(b) using said accessed time-corrected seismic traces to image at least a portion of said region of the subsurface of the earth; and

(c) using said imaged at least a portion of the subsurface of the earth in exploration for hydrocarbons within the region of the subsurface of the earth.

[0045] In any of the embodiments above, the method may be repeated, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth. The method may be repeated iteratively. Repetition in this way can improve the accuracy of the time correction.

[0046] Other embodiments and variations are certainly possible within the scope of the instant disclosure and can readily be formulated by those of ordinary skill in the art based on the disclosure herein.

[0047] The foregoing has outlined in broad terms the more important features of the instant disclosure so that the detailed description that follows may be more clearly understood, and so that the contribution of the instant inventors to the art may be better appreciated. The instant disclosure is not to be limited in its application to the details of the construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. Rather, the methods and apparatus disclosed herein are capable of other embodiments and of being practiced and carried out in various other ways not specifically enumerated herein. Finally, it should be understood that the phraseology and terminology

employed herein are for the purpose of description and should not be regarded as limiting, unless the specification specifically so limits the text and claims that follows.

BRIEF DESCRIPTION OF THE DRAWINSG

[0048] Other embodiments and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0049] Figure **1** illustrates a general seismic processing environment suitable for use with the instant disclosure.

[0050] Figure 2 illustrates in a general way that receiver clocks are inaccurate, and might be influenced by temp, age, and variation in natural clock-rate inherent to each oscillator at manufacture.

[0051] Figure **3** illustrates in a general way that the drift in receiver clocks may not be exactly linear over time and when a linear trend is removed, inaccuacies might remain.

[0052] Figure **4** contains a schematic illustration of one approach to an embodiment that uses a section of the trace so that the residual clock drift is quasi-static during that time period.

[0053] Figure **5** illustrates seismic arrivals that may be recorded by each receiver and therefore may be used in this embodiment to correct each receiver for clock drift.

[0054] Figure 6 illustrates an embodiment where the receivers r_1 and r_2 that are cross correlated are chosen to be proximate to each other.

[0055] Figure **7** illustrates an operating logic suitable for use with an embodiment.

[0056] Figure 8 shows derived clock drift estimates compared with actual clock drifts for a synthetic data example.

[0057] Figure 9 shows de-trended clock drift estimates compared with actual clock drifts.

[0058] Figure 10 is a difference plot showing the difference between the de-trended clock drift estimates and the actual clock drifts of Figure 9.

[0059] Figure 11 shows synthetic seismic data before drift correction.

[0060] Figure 12 shows synthetic seismic data after drift correction in accordance with an embodiment.

[0061] Figures 13a to 13c show synthetic seismic data with random clock drift applied to the data (Fig. 13a); synthetic seismic data of Fig. 13a after application of the method according to an embodiment (Fig. 13b); and synthetic seismic data of Fig. 13a after removal of actual clock error (Fig. 13c).

Detailed Description

[0062] While this invention is susceptible of embodiment in many different forms, there is shown in the drawings, and will be described hereinafter in detail, some specific

CLAIMS

1. A method for use in seismic exploration of a region of the subsurface of the earth, wherein is provided a plurality of continuously recorded seismic traces collected in a seismic survey conducted proximate to the region of the subsurface of the earth, each of said traces being recorded by a receiver having a clock, the method comprising the steps of:

(a) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver, wherein the second receiver is proximate to the first receiver if it records signals from the same seismic event;

(b) for each of said proximate trace pairs, determining a relative time shift between said first trace and said second trace;

(c) inverting said relative time shifts determined in step (b) to obtain a clock drift estimate for each of the clocks of said first and second receivers by solving the equation:

$$\begin{bmatrix} 1 & -1 & \dots & 0 & 0 \\ 1 & 0 & -1 & \dots & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & \dots & 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \vdots \\ \Delta t_N \end{bmatrix} = \begin{bmatrix} \Delta_{1,2} \\ \Delta_{1,3} \\ \vdots \\ \Delta_{N-1,N} \end{bmatrix}$$

for Δt_i , $i = 1, N$,

where Δt_i is said clock drift estimate associated with an *ith* one of said clocks of said first and second receivers,

where N is a number of said clocks of said first and second receivers, and,

where Δ_{kj} is said relative time shift between a *kth* one of said first traces and a jth one of said second traces; and

(d) using said clock drift estimates obtained in step (c) to time correct the first and second traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth.

2. The method according to claim 1, wherein step (a) comprises the steps of:

(a1) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver;

(a2) for the clock in each of said first and second receivers, selecting a shooting time window;

(a3) calculating a linear estimate of a drift correction for each of said clocks during said shooting time window; and

(a4) adjusting said first and second traces in time according to the calculated linear estimate of said drift correction for the corresponding clock.

3. The method according to claim 1 or claim 2, further comprising identifying at least two trace sections for each of said first and second traces, and performing steps (a) to (d) separately for each of the trace sections, thereby forming a plurality of time-corrected traces representative of the subsurface of the earth wherein each time-corrected trace comprises at least two sections of time-corrected trace using the clock drift estimate obtained for the respective section of trace.

4. The method according to any one of the preceding claims, wherein the relative time shift between said first trace and said second trace is determined in step (b) by determining the relative time shifts between a plurality of shot records comprised in said first trace and corresponding shot records in said second trace, and determining the average of said relative time shifts between said corresponding shot records.

5. The method according to any one of the preceding claims, further comprising the step of, for each proximate trace pair, applying a kinematic correction to remove the effect of differential arrival times between the first and second receivers associated with said proximate trace pair.

6. The method according to claim 5, wherein said kinematic correction is an NMO correction or an LMO correction.

7. The method according to any one of the preceding claims, wherein determining said relative time shift in step (b) comprises calculating a cross-correlation between said first and second traces.

8. The method according to any one of the preceding claims, whereby at least one of said receivers has a clock which is an accurate clock, and wherein step (c) further comprises setting the clock drift estimate associated with said accurate clock to zero in the equation.

9. The method according to any one of the preceding claims, wherein the proximate trace pairs are identified in step (a) such that each proximate trace pair is associated with at least one other proximate trace pair.

10. The method according to any one of the preceding claims, further comprising the steps of:

(e) using said plurality of time-corrected seismic traces to image at least a portion of said region of the subsurface of the earth; and

(f) using said imaged region of the subsurface of the earth in exploration for hydrocarbons within the region of the subsurface of the earth.

11. The method of any one of the preceding claims, wherein step (c) further comprises identifying a trend in the clock drift estimates for each of the clocks of said first and second receivers and removing said trend from said clock drift estimates, thereby forming de-trended clock drift estimates for each of the clocks of the first and second receivers;

and wherein step (d) comprises using said de-trended clock drift estimates obtained in step (c) to time correct the first and second traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth.

12. The method of any one of the preceding claims, wherein the plurality of proximate trace pairs includes line trace pairs and/or non-line trace pairs.

13. A method of seismic exploration of a region of the subsurface of the earth, wherein is provided a plurality of continuously recorded seismic traces collected in a seismic survey

conducted proximate to the region of the subsurface of the earth, each of said traces being recorded by a receiver having a clock, the method comprising the steps of:

(a) accessing a plurality of time-corrected traces created by a method comprising the steps of:

(i) identifying a plurality of proximate trace pairs, each proximate trace pair comprising a first trace recorded by a first receiver and a second trace recorded by a second receiver proximate to said first receiver, wherein the second receiver is proximate to the first receiver if it records signals from the same seismic event;

(ii) for each of said proximate trace pairs, determining a relative time shift between said first trace and said second trace;

(iii) inverting the relative time shifts determined in step (ii) to obtain a clock drift estimate for the clocks of the first and second receivers, by solving the equation:

$$\begin{bmatrix} 1 & -1 & \dots & 0 & 0 \\ 1 & 0 & -1 & \dots & 0 \\ \vdots & & & & \vdots \\ 0 & 0 & \dots & 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \vdots \\ \Delta t_N \end{bmatrix} = \begin{bmatrix} \Delta_{1,2} \\ \Delta_{1,3} \\ \vdots \\ \Delta_{N-1,N} \end{bmatrix}$$

for Δt_i , $i = 1, N$,

where Δt_i is said clock drift estimate associated with an *ith* one of said clocks of said first and second receivers,

where N is a number of said clocks of said first and second receivers, and,

where Δ_{kj} is said relative time shift between a *kth* one of said first traces and a jth one of said second traces; and

(iv) using the clock drift estimates obtained in step (iii) to time correct the first and second traces of each proximate trace pair, thereby forming a plurality of time-corrected seismic traces representative of the subsurface of the earth;

(b) using said accessed time-corrected seismic traces to image at least a portion of said region of the subsurface of the earth; and

(c) using said imaged at least a portion of the subsurface of the earth in exploration for hydrocarbons within the region of the subsurface of the earth.