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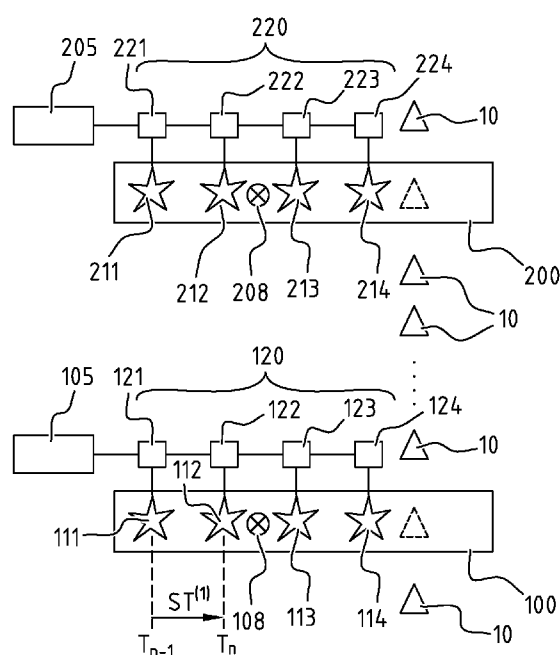
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(54) Title: SYSTEM AND METHOD FOR ACQUISITION OF SEISMIC DATA

**FIG. 1**

(57) Abstract: A seismic data acquisition system and method wherein multiple clusters (100, 200) of sources are employed that are time regulated with respect to each other ("concerted sources"). Only sources within the same cluster are time regulated with respect to each other while no time regulation is imposed between sources that do not belong to the same cluster. The concerted sources within each cluster are operated in slip-sweep mode. The slip time that is imposed between starting times of successively actuated concerted sources within a single cluster consists of a predetermined listening period of a fixed duration plus an additional variable delay time, which varies from shot to shot to introduce dither noise. The additional variable delay imposes a slip time dither. A common seismic receiver (10) is configured to measure seismic signals induced by the sources from multiple of said clusters.

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SYSTEM AND METHOD FOR ACQUISITION OF SEISMIC DATA

Field of the invention

The present invention relates to a system and method for acquisition of seismic data by recording seismic signals induced by a plurality of sources with a common seismic receiver.

5 Background of the invention

Seismic acquisition has been of vital importance for exploration of hydrocarbons, such as oil and/or natural gas, from subsurface earth formations, and it is becoming increasingly used in the context of monitoring the subsurface earth formations during production of these hydrocarbons as well.

10 The principle of seismic acquisition is that a seismic source is employed to induce seismic waves that propagate downwardly through the subsurface earth formation. The downwardly-propagating seismic waves are reflected by one or more geological structures within the subsurface earth formation, which act as partial reflectors for the seismic waves. It is possible to obtain information about the geological structure of the subsurface earth
15 formation from seismic waves that undergo reflection within the subsurface earth formation and is subsequently acquired by one or more seismic sensors (generally referred to as seismic "receivers"). Reflected seismic waves are typically recorded during a so-called listening time. Longer listening times allow recording of multiple reflection events and/or reflection events that occurred deeper under the earth surface.

20 Various specific methods for seismic acquisition have been described in the literature. One such method, disclosed in pre-grant patent application publication US 2010/0085836 A1, makes use of a so-called dithered slip-sweep vibroseis acquisition technique which uses both source dithering and slip sweep techniques to enhance the efficiency of the survey. The multiple sources are vibrators, employed to transmit seismic
25 energy into the ground. When actuated, the vibrators start emitting the seismic energy in the earth formation at a frequency that changes over time during a period of time. This is referred to as a frequency sweep, and the period of time is called sweep time.

The slip-sweep technique, first proposed by Justus Rozemond at the 66th annual SEG meeting, 1996, in Denver (AQC 3.2 pp. 64-67), allows for a reduction in the cycle time by
30 efficiently timing multiple sources. The source dithering technique is used to operate

sources so close in time that the corresponding seismic signals to interfere with each other for at least part of the record in the recorded time frequency space.

In the dithered slip-sweep method of US 2003/0210609 A1, the vibrators are grouped in vibrator groups. Two levels of time regulation between the vibrators are employed. The timing of the vibrators within each of the groups is regulated in slip-sweep condition. In addition, the timing of the sweeps of each group is regulated, such that consecutive sweep firings of each group are spaced apart by a time substantially less than the slip time. Since these consecutive firings are spaced apart by a relatively small amount of time (substantially less than the slip time), a higher data acquisition rate is possible in theory. However, the dithered slip-sweep method appears to be difficult to operate in practice to its full potential.

Summary of the invention

In accordance with a first aspect of the present invention, there is provided a system for acquisition of seismic data by recording seismic signals induced by a plurality of sources with a common seismic receiver, comprising:

- a first plurality of concerted sources that are time regulated with respect to each other to operate in a first slip-sweep mode, whereby all concerted sources that are time regulated with respect to each other are grouped in a first cluster;
- a first actuator system arranged to actuate each of the concerted sources from the first cluster according to said first slip-sweep mode, whereby each concerted source within the first plurality is induced to perform a frequency sweep lasting for the predetermined first sweep period $SP^{(1)}$ and wherein a regulated first slip time $ST^{(1)}$ is imposed between starting times of successively actuated concerted sources of the first plurality, wherein $ST^{(1)} = ST^{(1)}_{\min} + \Delta ST^{(1)}$, wherein $ST^{(1)}_{\min}$ is a predetermined fixed minimum first amount of slip time which is the same for each sweep in the first cluster whereby $L^{(1)} < ST^{(1)}_{\min} < L^{(1)} + SP^{(1)}$, wherein $L^{(1)}$ is a predetermined first listening period and wherein $\Delta ST^{(1)}$ represents a first slip time dither;
- a second plurality of concerted sources that are time regulated with respect to each other to operate in a second slip-sweep mode, whereby all concerted sources that are time regulated with respect to each other are grouped in a second cluster;
- a second actuator system arranged to actuate each of the concerted sources from the second cluster according to said second slip-sweep mode, whereby each concerted source

within the second plurality is induced to perform a frequency sweep lasting for the predetermined second sweep period $SP^{(2)}$ and wherein a regulated second slip time $ST^{(2)}$ is imposed between starting times of successively actuated concerted sources of the second plurality wherein $ST^{(2)} = ST^{(2)}_{\min} + \Delta ST^{(2)}$, wherein $ST^{(2)}_{\min}$ is a predetermined fixed minimum second amount of slip time which is the same for each sweep in the second cluster whereby $L^{(2)} < ST^{(2)}_{\min} < L^{(2)} + SP^{(2)}$, wherein $L^{(2)}$ is a predetermined second listening period and wherein $\Delta ST^{(2)}$ represents a second slip time dither; and

- a common seismic receiver configured to measure seismic signals induced by said first plurality of concerted sources of the first cluster and seismic signals induced by said second plurality of concerted sources of the second cluster;

wherein the second cluster is independent from the first cluster whereby no time regulation is imposed between sources that do not belong to the same cluster.

In accordance with a second aspect of the invention, there is provided a method for acquisition of seismic data by recording seismic signals induced by a plurality of sources with a common seismic receiver, comprising:

- operating a first plurality of concerted sources in a first slip-sweep mode, comprising inducing each concerted source within the first plurality to perform a frequency sweep lasting for the predetermined first sweep period $SP^{(1)}$ and imposing a regulated first slip time $ST^{(1)}$ between starting times of successively actuated concerted sources of the first plurality, wherein all concerted sources that are time regulated with respect to each other are grouped in a first cluster, and wherein $ST^{(1)} = ST^{(1)}_{\min} + \Delta ST^{(1)}$, wherein $ST^{(1)}_{\min}$ is a predetermined fixed minimum first amount of slip time which is the same for each sweep in the first cluster whereby $L^{(1)} < ST^{(1)}_{\min} < L^{(1)} + SP^{(1)}$, wherein $L^{(1)}$ is a predetermined first listening period and wherein $\Delta ST^{(1)}$ represents a first slip time dither;
- operating a second plurality of concerted sources in a second slip-sweep mode, comprising inducing each concerted source within the second plurality to perform a frequency sweep lasting for the predetermined second sweep period $SP^{(2)}$ and imposing a regulated second slip time $ST^{(2)}$ between starting times of successively actuated concerted sources of the second plurality, wherein all concerted sources that are time regulated with respect to each other are grouped in a second cluster, and wherein $ST^{(2)} = ST^{(2)}_{\min} +$

$\Delta ST^{(2)}$, wherein $ST^{(2)}_{\min}$ is a predetermined fixed minimum second amount of slip time which is the same for each sweep in the second cluster whereby $L^{(2)} < ST^{(2)}_{\min} < L^{(2)} + SP^{(2)}$, wherein $L^{(2)}$ is a predetermined second listening period and wherein $\Delta ST^{(2)}$ represents a second slip time dither

- 5 - recording seismic signals induced by said first plurality of concerted sources of the first cluster and seismic signals induced by said second plurality of concerted sources of the second cluster as measured in a common receiver;
wherein the second cluster is operated independently from the first cluster whereby no time regulation is imposed between sources that do not belong to the same cluster.

10 The invention will be further illustrated hereinafter by way of example only, and with reference to the non-limiting drawing.

Brief description of the drawings

Fig. 1 shows a schematic example of a seismic acquisition system and method; and

Fig. 2 shows a schematic graph of concerted sources with dithered slip time.

- 15 These figures are not to scale. Identical reference numbers used in different figures refer to similar components. The person skilled in the art will readily understand that, while the invention is illustrated making reference to one or more specific combinations of features and measures, many of those features and measures are functionally independent from other features and measures such that they can be equally or similarly applied
20 independently in other embodiments or combinations.

Detailed description of the embodiments

- A system and method are proposed for acquisition of seismic data, which employ multiple clusters of sources that are time regulated with respect to each other (which are referred to with the term “concerted sources”) whereby only sources within the same
25 cluster are time regulated with respect to each other while no time regulation is imposed between sources that do not belong to the same cluster. The concerted sources within each cluster are operated in slip-sweep mode. However, the slip time that is imposed between starting times of successively actuated concerted sources within a single cluster consists of a predetermined listening period of a fixed duration plus an additional variable delay time,
30 which varies from shot to shot to introduce dither noise. The additional variable delay is referred to as “slip time dither.” A common seismic receiver is configured to measure seismic signals induced by the sources from multiple of said clusters.

One advantage of this proposed acquisition system and method over the so-called dithered slip-sweep method described in US 2003/0210609 A1 is that only a slip-sweep regulation needs to be imposed where the dithered slip-sweep method requires both a slip-sweep time regulation as well as a source dithering time regulation between dither pairs.

5 While with source dithering a higher data acquisition rate is possible on paper, it is presently considered that the higher acquisition rate is difficult to achieve in practice, because both sources in a dithered pair need to be lined up and ready for firing before the sources can be fired. Thus, a delay in one of sources from the dithered pair in getting ready for firing (e.g. because it had to overcome an obstacle while moving up to its next shooting
10 location) causes a delay not only to that one source, but to two sources. With the proposed method and system, any delay in firing one of the sources in one cluster does not cause a knock-on effect in other clusters.

Moreover, various clusters can operate at large distances from each other. An inter-cluster spacing of several kilometers is not an exception. The presently proposed method
15 and system avoid the need for regulating source timing across clusters and allow these clusters to operate independently from each other.

Furthermore, as successive clusters are operated independently from each other with the presently proposed system and method, the frequency sweep parameters do not have to be identical for each cluster (although they can be identical if desired). An example of
20 employing clusters having mutually different sweep parameters is where the respective ranges of the frequency sweeps employed in first and second clusters may be different. Particularly, one may be covering lower frequencies than the other.

The slip time employed within a single cluster thus comprises a predetermined fixed minimum period supplemented with a variable slip time, referred to as slip time
25 dither, which preferably adds a relatively small amount of time to the predetermined fixed minimum period. The slip time dither is suitably a relatively small amount of additional slip time compared to predetermined fixed minimum first amount of slip time. The predetermined fixed minimum first amount of slip time is suitably selected longer than the listening time and shorter than the listening time plus the sweep period of the concerted
30 sources within the cluster. The relatively small amount of variable slip time may for instance be in a range of from 0 to 0.10 times the predetermined fixed minimum first amount of slip time.

In the context of this disclosure, the term “dither” refers to an intentionally applied temporal noise which helps to subsequently deblend seismic responses and isolate seismic events arising from seismic waves induced by individual sources from the total seismic signal.

5 The term “common” in “common receiver” in the context of this disclosure means “shared”. The signals from multiple sources are measured by the shared receiver, and recorded. Recording can be done in the receiver, or at a central location for a plurality of common receivers.

10 The term “listening time” or “listening period” is used to characterize a user-defined amount of time which determines the maximum record length that will be available for the seismic traces, after data processing. A desired (maximum) record length may be determined by the amount of time after completing of a frequency sweep that useful seismic information is measurable by the seismic receiver. The desired maximum record length may already be taken into account during the acquisition of the seismic data, by
15 ensuring that the slip time imposed between concerted sources is never shorter than the listening time.

By applying the dithered slip time in accordance with the present disclosure, it may be possible to concurrently measure and record signal from one or more additional clusters of concerted sources using the common receiver, in addition to the first cluster of concerted
20 sources described above. Hence the number of clusters is not limited and they can be relatively far away from each other.

In the context of the present disclosure, the term “concurrent” is used when at least two seismic sources are induced to start close enough in time that there is overlap in their respective listening periods in time-frequency domain, which is accompanied by wave
25 field interference in the earth. Only interference of the fundamental frequency is considered. Wave interference involving harmonics is disregarded for the purpose of whether sources are concurrent.

The first cluster comprises no other source than said concerted sources that are time regulated with respect to each other and the second cluster comprises no other source than
30 said concerted sources that are time regulated with respect to each other. All concerted sources within a single cluster may be programmed to perform the identical frequency sweep parameters, including sweeping for the same length of time, with the same sweep waveform, at the same sweep rate and over the same frequency range, and with the same

phase. Comparing one cluster to another cluster, on the other hand, the frequency sweep parameters may be identical or different. An example of employing clusters having mutually different sweep parameters is where the respective ranges of the frequency sweeps employed in first and second clusters may be different. Particularly, one may be
5 covering lower frequencies than the other.

Figure 1 schematically illustrates a system and method for acquisition of seismic data. The system is set up to record seismic signals induced by a plurality of sources, operated in a plurality of time regulated clusters, with a common seismic receiver 10. Figure 1 schematically depicts two of such clusters, a first cluster 100 and a second cluster
10 200, each comprising concerted groups of concerted sources 111,112,113,114 and 211,212,213,214 respectively. Concerted, in this context, means that the sources are actuated in a time-regulated dependence of each other. Additional clusters, beyond two, are optional.

Each concerted source 111,112,113,114 in first cluster 100 is laterally separated from
15 each other concerted source in the first cluster 100, and each concerted source 211,212,213,214 in the second cluster 200 is laterally separated from each other concerted source in the second cluster.

The second cluster 200 can be operated fully independently from the first cluster 100. This means that no concerted inter-cluster source actuation is necessary between sources in
20 the first cluster and sources in the second cluster. This is useful, as clusters can be operated at large distances from each other. The second cluster 200 may be identical to the first cluster 100, although different numbers of concerted groups and different numbers of concerted sources may be provided.

The sources may be vibrators, which are actuated to perform a frequency sweep over
25 a sweep period. The frequency sweep traditionally starts at a lower frequency and ends at an upper frequency. For typical vibrators, the lower frequency may for instance be 5 Hz and the upper frequency may for instance be 80 Hz.

Four concerted sources 111,112,113,114 are shown grouped in the first cluster 100, but any plurality of $N \geq 2$ can be employed. Every concerted source in the first cluster is
30 induced to perform a frequency sweep that lasts for a predetermined first sweep period $SP^{(1)}$. A first actuator system 120 is arranged to actuate each of the concerted sources from the first cluster 100 according to a first slip-sweep mode, in which a first slip time $ST^{(1)}$ is imposed between starting times of successively actuated concerted sources. The first

actuator system 120 may comprise actuators 121,122,123,124 whereby each actuator is uniquely operatively coupled to uniquely one of the concerted sources in the first cluster 100. Suitably, the first actuator system 120 is operatively controlled by a first cluster controller 105.

5 Suppose n is a positive integer number, which designates the n^{th} concerted source of the N concerted sources within the first cluster ($1 \leq n-1 \leq N-1$). Any $(n-1)^{\text{th}}$ concerted source within the first cluster 100 is induced to start its frequency sweep at time $T_{(n-1)}$ and a subsequent concerted source from the same first cluster, which is the n^{th} concerted source, is induced to start its frequency sweep at time T_n whereby T_n is later by at least the first slip time $ST^{(1)}$, such that $T_n = T_{(n-1)} + ST^{(1)}$.

Likewise, four concerted sources 211,212,213,214 are shown grouped in the first cluster 200, but any plurality of $M \geq 2$ can be employed. Every concerted source in the second cluster is induced to perform a frequency sweep that lasts for a predetermined second sweep period $SP^{(2)}$, that lasts for a predetermined first sweep period $SP^{(1)}$. A second actuator system 220 is arranged to actuate each of the concerted sources from the first cluster 200 according to a second slip-sweep mode, in which a second slip time $ST^{(2)}$ is imposed between starting times of successively actuated concerted sources. The second actuator system 220 may comprise actuators 221,222,223,224 whereby each actuator is uniquely operatively coupled to uniquely one of the concerted sources in the second cluster 200. Suitably, the second actuator system 220 is operatively controlled by a second cluster controller 205.

25 Suppose m is a positive integer number, which designates the m^{th} concerted source of the M concerted sources within the second cluster ($1 \leq m-1 \leq M-1$). Any $(m-1)^{\text{th}}$ concerted source within the second cluster 200 is induced to start its frequency sweep at time $T_{(m-1)}$ and a subsequent concerted source from the same second cluster, which is the m^{th} concerted source, is induced to start its frequency sweep at time T_m whereby T_m is later by at least the second slip time $ST^{(2)}$, such that $T_m = T_{(m-1)} + ST^{(2)}$.

In the following, a cluster number i will be used instead of repeating the explanations for each cluster individually. For the first cluster 100, $i = 1$. For the second cluster 200, $i = 2$. Etc., for third and higher clusters.

In each i^{th} cluster (i.e., $ST^{(i)}$ is composed of a predetermined fixed minimum i^{th} amount of slip time $ST^{(i)}_{\min}$ that is the same for each sweep in the same i^{th} cluster, and a variable amount of slip time $\Delta ST^{(i)}$, which introduces an i^{th} slip time dither. In equation format: $ST^{(i)} = ST^{(i)}_{\min} + \Delta ST^{(i)}$ ($i = 1, 2, \dots, D$). The minimum amount of slip time is
 5 selected longer than the listening period, to allow signal processing with slip-sweep methods (for instance involving cross correlation with the pilot sweep signal). The maximum amount of slip time is selected as the sweep time plus the listening period. Longer slip times are not productive compared to standard flip-flop acquisition. In equation format: $L^{(i)} < ST^{(i)}_{\min} < L^{(i)} + SP^{(i)}$, wherein $L^{(i)}$ is the predetermined i^{th} listening
 10 period.

Suitably, the first slip time dither $\Delta ST^{(1)}$ and the second slip time dither $\Delta ST^{(2)}$ are fluctuating in an unpredictable or quasi unpredictable manner. The less predictable, the more incoherent the contribution in signals from other concerted source groups that is received in the common receiver. The actuator system for each cluster may thus comprise a
 15 random generator or quasi-random generator, configured to determine the respective slip time dithers. Such random generator or quasi-random generator may be provided in the cluster controllers.

Each cluster of concerted sources has a cluster center-of-gravity spot, which indicates the center of gravity locations of all the concerted sources within the cluster averaged over
 20 all the concerted sources within the cluster. For instance, the first and second group center-of-gravity spots of the concerted sources in the first cluster 100 are schematically represented by $\otimes$ symbol 108 and 208. The concerted sources within a single cluster are preferably relatively close to each other compared to the distance between the clusters. Preferably, all respective center-of-gravity spots of the concerted sources within a single
 25 cluster are within a cluster vicinity radius of 100 m from the cluster center-of-gravity spot to which the concerted sources belong. The first cluster center-of-gravity spot (belonging to the first cluster 100) and the second cluster center-of-gravity spot (belonging to the second cluster 200) are preferably more than 500 m removed from each other, more preferably more than 1 km removed from each other, and most preferably more than 5 km
 30 removed from each other.

Each concerted source in the i^{th} cluster is induced to perform a frequency sweep lasting for a predetermined i^{th} sweep period $SP^{(i)}$, during which time the frequency is ramped up from an i^{th} lower frequency $f^{(i)}_{\min}$ to an i^{th} upper frequency $f^{(i)}_{\max}$. Figure 2 shows a plot of frequency against time. The ramping up of frequency is illustrated linear in time, but other ramp patterns can be used if desired. Figure 2 further shows a listening time $L^{(i)}$ is maintained for each frequency in the frequency sweep.

The second frequency sweep, which is employed in the second cluster 200, may cover a frequency range that is different from the first frequency sweep which is employed in the first cluster 100. This may be done to obtain supplementary data. Some overlap may exist. For instance, the second frequency range between $f^{(2)}_{\min}$ and $f^{(2)}_{\max}$ may be selected as follows: $f^{(1)}_{\min} < f^{(2)}_{\min} < f^{(1)}_{\max}$ and $f^{(2)}_{\max} > f^{(1)}_{\max}$.

By selecting $L^{(i)} < ST^{(i)}_{\min}$ it is achieved that, disregarding harmonics, the wave fields generated in the earth by the concerted sources within one single cluster are not overlapping with each other in time-frequency domain. In the presently proposed method and system, concurrency of sources can only exist between sources that do not belong to the same cluster. None of the concerted sources within a single cluster is concurrent with any other source within the same cluster. Only sources belonging to different clusters can be concurrent.

The i^{th} slip time dither, $\Delta ST^{(i)}$, is suitably selected in a range of from 0 to $0.10 \times ST^{(i)}_{\min}$. Preferably, the i^{th} slip time dither may be selected in a smaller range, for instance in a range of from 0 to $0.020 \times ST^{(i)}_{\min}$, preferably in a range of from 0 to $0.010 \times ST^{(i)}_{\min}$. A smaller range provides higher acquisition productivity, at the cost of signal loss during post acquisition source separation. Different ranges may be used for different values of i .

The system described herein may be deployed on land or in a marine environment off-shore. Suitably, the sources are vibrators. A seismic vibrator source for use on land consists generally of a baseplate configured in contact with the ground. The baseplate is usually supported on a truck. A seismic wave is induced in the subsurface earth formation

by applying a vibratory force to the plate, and this is typically done by applying a control waveform known as a "pilot sweep" in the vibrator actuator system. The pilot sweep is generally a constant amplitude swept frequency signal, although the amplitude of the vibration may in practice be ramped up and down at the start and, respectively, finish of the sweep, for instance to manage inertia of the vibrator mass. Marine vibrators are also available, as evidenced by for instance an article from Western Geco: "Marine Vibrators and the Doppler Effect", by Dragoset, which appeared in Geophysics, Nov. 1988, pp. 1388-1398, vol. 53, No. 11. More recently, Geokinetics has introduced its AquaVib(TM) marine vibrator. Other examples exist.

Table 1 contains a legend of mathematical symbols used herein. The superscript (i) can be replaced for superscript (1) if the entity concerned relates to the entity in the first cluster (in which case $i = 1$) or for superscript (2) if the entity concerned relates to the entity in the second cluster (in which case $i = 2$).

Table 1

i	A number designating the i^{th} cluster of concerted sources of I clusters employed in the acquisition method and/or acquisition system. $I \geq 2$.
n	A number designating the n^{th} concerted source of N concerted sources within the first cluster. $N \geq 2$.
m	A number designating the m^{th} concerted source of M concerted sources within the second cluster. $M \geq 2$.
T_n	Starting time of a frequency sweep of the n^{th} concerted source within the first cluster.
T_m	Starting time of a frequency sweep of the m^{th} concerted source within the second cluster.
$SP(i)$	An i^{th} sweep period, the sweep period employed in frequency sweeps within the i^{th} cluster.
$f_{\min}^{(i)}$	An i^{th} lower frequency at which each frequency sweep for every concerted source in the i^{th} cluster starts.
$f_{\max}^{(i)}$	An i^{th} upper frequency at which each frequency sweep for every concerted source in the i^{th} cluster ends.

$L^{(i)}$	Predetermined i^{th} listening period determining the record length of seismic responses selected for frequency sweeps within the i^{th} cluster.
$ST^{(i)}$	An i^{th} slip time, which dictates the regulated starting time of a subsequent concerted source within the i^{th} cluster compared to the starting time of a preceding concerted source within the i^{th} cluster.
$ST^{(i)}_{\min}$	Predetermined fixed minimum i^{th} amount of slip time used within the i^{th} cluster.
$\Delta ST^{(i)}$	An i^{th} slip time dither time used within the i^{th} cluster, which together with the predetermined fixed minimum first amount of slip time determines the i^{th} slip time.

If for example n is a subsequent concerted source within the first cluster, then $n-1$ is the preceding concerted source within the same cluster.

The person skilled in the art will understand that the present invention can be carried out in many various ways without departing from the scope of the appended claims.

What is claimed is:

1. A system for acquisition of seismic data by recording seismic signals induced by a plurality of sources with a common seismic receiver, comprising:
 - a first plurality of concerted sources that are time regulated with respect to each other to operate in a first slip-sweep mode, whereby all concerted sources that are time regulated with respect to each other are grouped in a first cluster;
 - a first actuator system arranged to actuate each of the concerted sources from the first cluster according to said first slip-sweep mode, whereby each concerted source within the first plurality is induced to perform a frequency sweep lasting for the predetermined first sweep period $SP^{(1)}$ and wherein a regulated first slip time $ST^{(1)}$ is imposed between starting times of successively actuated concerted sources of the first plurality, wherein $ST^{(1)} = ST^{(1)}_{\min} + \Delta ST^{(1)}$, wherein $ST^{(1)}_{\min}$ is a predetermined fixed minimum first amount of slip time which is the same for each sweep in the first cluster whereby $L^{(1)} < ST^{(1)}_{\min} < L^{(1)} + SP^{(1)}$, wherein $L^{(1)}$ is a predetermined first listening period and wherein $\Delta ST^{(1)}$ represents a first slip time dither;
 - a second plurality of concerted sources that are time regulated with respect to each other to operate in a second slip-sweep mode, whereby all concerted sources that are time regulated with respect to each other are grouped in a second cluster;
 - a second actuator system arranged to actuate each of the concerted sources from the second cluster according to said second slip-sweep mode, whereby each concerted source within the second plurality is induced to perform a frequency sweep lasting for the predetermined second sweep period $SP^{(2)}$ and wherein a regulated second slip time $ST^{(2)}$ is imposed between starting times of successively actuated concerted sources of the second plurality wherein $ST^{(2)} = ST^{(2)}_{\min} + \Delta ST^{(2)}$, wherein $ST^{(2)}_{\min}$ is a predetermined fixed minimum second amount of slip time which is the same for each sweep in the second cluster whereby $L^{(2)} < ST^{(2)}_{\min} < L^{(2)} + SP^{(2)}$, wherein $L^{(2)}$ is a predetermined second listening period and wherein $\Delta ST^{(2)}$ represents a second slip time dither; and
 - a common seismic receiver configured to measure seismic signals induced by said first plurality of concerted sources of the first cluster and seismic signals induced by said second plurality of concerted sources of the second cluster;

wherein the second cluster is independent from the first cluster whereby no time regulation is imposed between sources that do not belong to the same cluster.

2. The system of claim 1, wherein the first slip-sweep mode comprises an $(n-1)^{\text{th}}$ concerted source from the first plurality is induced to start its frequency sweep at time $T_{(n-1)}$ and an n^{th} concerted source from the first plurality is induced to start its frequency sweep at time T_n whereby T_n is later than the starting times of the $(n-1)^{\text{th}}$ concerted source by at least the first slip time $ST^{(1)}$, such that $T_n = T_{(n-1)} + ST^{(1)}$; and

wherein the second slip-sweep mode comprises an $(m-1)^{\text{th}}$ concerted source from the second plurality is induced to start its frequency sweep at time $T_{(m-1)}$ and an m^{th} concerted source from the second plurality is induced to start its frequency sweep at time T_m whereby T_m is later than the starting times of the $(m-1)^{\text{th}}$ concerted source by at least the second slip time $ST^{(2)}$, such that $T_m = T_{(m-1)} + ST^{(2)}$.

3. The system of claim 1 or 2, wherein the i^{th} slip time dither $\Delta ST^{(i)}$ is in a range of from 0 to $0.10 \times ST^{(i)}_{\text{min}}$, preferably in a range of from 0 to $0.020 \times ST^{(i)}_{\text{min}}$, more preferably in a range of from a range of from 0 to $0.010 \times ST^{(i)}_{\text{min}}$, whereby $i = 1$ or 2 .

4. The system of any one of claims 1 to 3, wherein the first slip time dither and/or the second slip time dither is unpredictable or quasi unpredictable.

5. The system of any one of claims 1 to 4, wherein the first actuator system is operatively controlled by a first cluster controller and the second actuator system is operatively controlled by a second cluster controller.

6. The system of claim 5, wherein the first cluster controller and the second cluster controller both comprise a random generator or quasi-random generator, configured to determine $\Delta ST^{(1)}$ respectively $\Delta ST^{(2)}$ for each sweep.

7. The system of any one of claims 1 to 6, wherein each concerted source in first plurality is laterally separated from each other concerted source in the first plurality, and wherein each concerted source in the second plurality is laterally separated from each other concerted source in the second plurality.

8. The system of any one of claims 1 to 7, wherein the frequency sweep for every concerted source in the i^{th} cluster starts at an i^{th} lower frequency $f^{(i)}_{\min}$ and ends at an i^{th} upper frequency $f^{(i)}_{\max}$, wherein $f^{(i)}_{\min} < f^{(i)}_{\max}$, whereby $i = 1$ or 2 .

9. The system of any one of claims 1 to 8, wherein the first cluster comprises no other source than said concerted sources that are time regulated with respect to each other and wherein said second cluster comprises no other source than said concerted sources that are time regulated with respect to each other.

10. The system of any one of claims 1 to 9, wherein all respective center-of-gravity spots of the concerted sources within the first plurality are within a first cluster vicinity radius of 100 m from a first cluster center-of-gravity spot for the first cluster, and wherein all respective group center-of-gravity spots of the concerted sources within the second plurality are within a second cluster vicinity radius of 100 m from a second cluster center-of-gravity spot for the second cluster.

11. The system of claim 10, wherein the first cluster center-of-gravity spot and the second cluster center-of-gravity spot are more than 500 m removed from each other.

12. A method for acquisition of seismic data by recording seismic signals induced by a plurality of sources with a common seismic receiver, comprising:

- operating a first plurality of concerted sources in a first slip-sweep mode, comprising inducing each concerted source within the first plurality to perform a frequency sweep lasting for the predetermined first sweep period $SP^{(1)}$ and imposing a regulated first slip time $ST^{(1)}$ between starting times of successively actuated concerted sources of the first plurality, wherein all concerted sources that are time regulated with respect to each other are grouped in a first cluster, and wherein $ST^{(1)} = ST^{(1)}_{\min} + \Delta ST^{(1)}$, wherein $ST^{(1)}_{\min}$ is a predetermined fixed minimum first amount of slip time which is the same for each sweep in the first cluster whereby $L^{(1)} < ST^{(1)}_{\min} < L^{(1)} + SP^{(1)}$, wherein $L^{(1)}$ is a predetermined first listening period and wherein $\Delta ST^{(1)}$ represents a first slip time dither;
- operating a second plurality of concerted sources in a second slip-sweep mode, comprising inducing each concerted source within the second plurality to perform a frequency sweep lasting for the predetermined second sweep period $SP^{(2)}$ and imposing a regulated second slip time $ST^{(2)}$ between starting times of successively actuated concerted sources of the second plurality, wherein all concerted sources that are time regulated with

respect to each other are grouped in a second cluster, and wherein $ST^{(2)} = ST^{(2)}_{\min} + \Delta ST^{(2)}$, wherein $ST^{(2)}_{\min}$ is a predetermined fixed minimum second amount of slip time which is the same for each sweep in the second cluster whereby $L^{(2)} < ST^{(2)}_{\min} < L^{(2)} + SP^{(2)}$, wherein $L^{(2)}$ is a predetermined second listening period and wherein $\Delta ST^{(2)}$ represents a second slip time dither

- recording seismic signals induced by said first plurality of concerted sources of the first cluster and seismic signals induced by said second plurality of concerted sources of the second cluster as measured in a common receiver;

wherein the second cluster is operated independently from the first cluster whereby no time regulation is imposed between sources that do not belong to the same cluster.

13. The method of claim 12, wherein the first slip-sweep mode comprises inducing an $(n-1)^{th}$ concerted source from the first plurality to start its frequency sweep at time $T_{(n-1)}$ and inducing an n^{th} concerted source from the first plurality to start its frequency sweep at time T_n whereby T_n is later than the starting times of the $(n-1)^{th}$ concerted source by at least the first slip time $ST^{(1)}$, such that $T_n = T_{(n-1)} + ST^{(1)}$; and

wherein the second slip-sweep mode comprises inducing an $(m-1)^{th}$ concerted source from the second plurality to start its frequency sweep at time $T_{(m-1)}$ and inducing an m^{th} concerted source from the second plurality to start its frequency sweep at time T_m whereby T_m is later than the starting times of the $(m-1)^{th}$ concerted source by at least the second slip time $ST^{(2)}$, such that $T_m = T_{(m-1)} + ST^{(2)}$.

14. The method of claim 12 or 13, wherein the first cluster comprises no other source than said concerted sources that are time regulated with respect to each other and wherein said second cluster comprises no other source than said concerted sources that are time regulated with respect to each other.

15. The method of any one of claims 12 to 14, wherein all respective center-of-gravity spots of the concerted sources within the first plurality are within a first cluster vicinity radius of 100 m from a first cluster center-of-gravity spot for the first cluster, and wherein all respective group center-of-gravity spots of the concerted sources within the second plurality are within a second cluster vicinity radius of 100 m from a second cluster center-of-gravity spot for the second cluster.

16. The system of claim 15, wherein the first cluster center-of-gravity spot and the second cluster center-of-gravity spot are more than 500 m removed from each other.

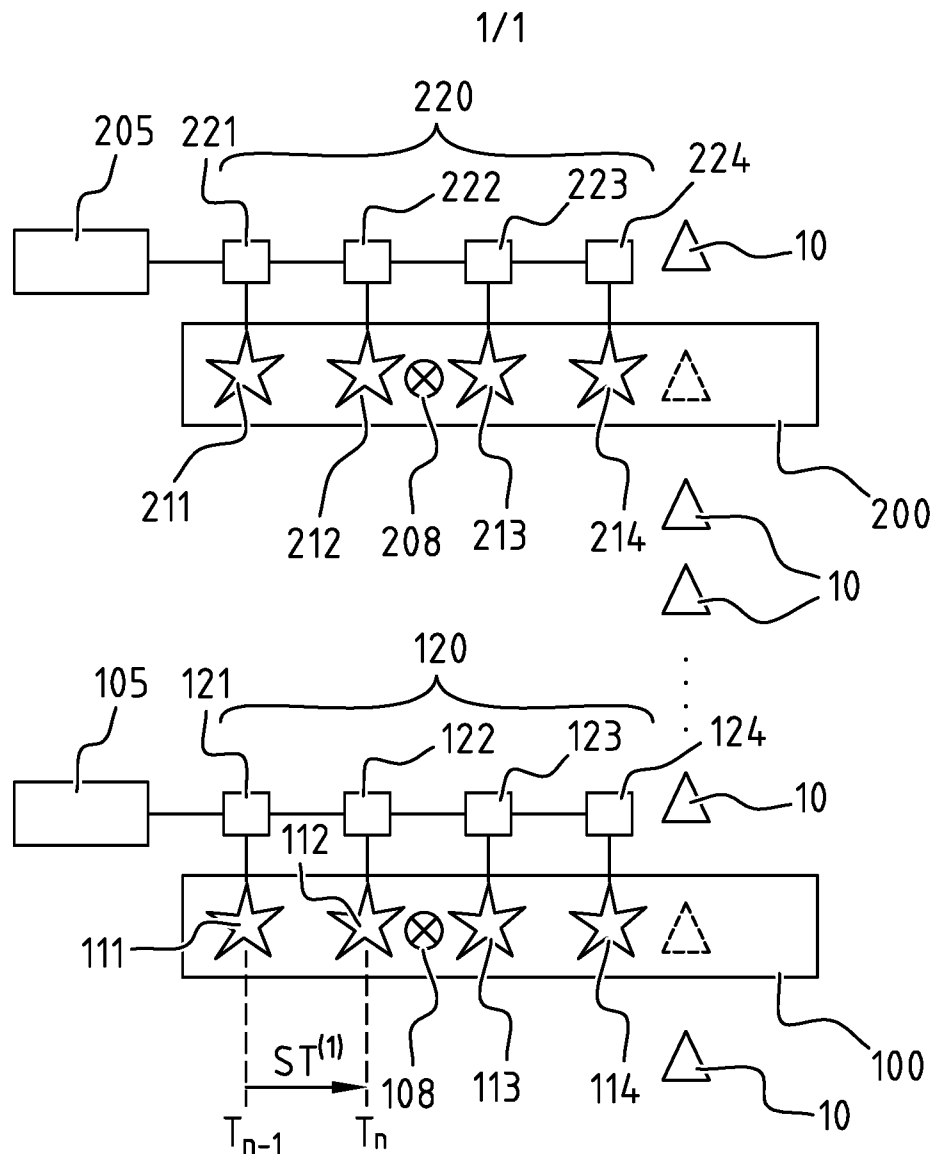


FIG. 1

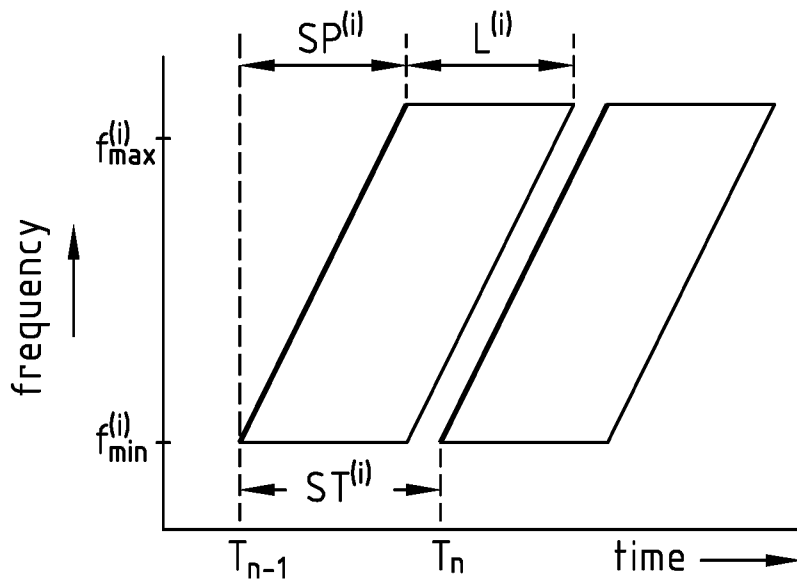


FIG. 2

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/061860

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V1/00
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 2015/177397 A1 (BAGAINI CLAUDIO [GB] ET AL) 25 June 2015 (2015-06-25)	1,2,4-7, 9-16
Y	paragraphs [0006], [0022] - paragraph [0028] paragraph [0033] - paragraph [0035]; figure 2	3,8
Y	----- CLAUDIO BAGAINI ET AL: "Dithered slip-sweep acquisition", SEG TECHNICAL PROGRAM EXPANDED ABSTRACTS 2010, 1 January 2010 (2010-01-01), pages 91-95, XP055203933, DOI: 10.1190/1.3513927 abstract page 93, column 1 ----- -/--	3



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

2 August 2017

Date of mailing of the international search report

10/08/2017

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/061860

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WAMS J ET AL: "Recent developments in 3-D acquisition techniques using vibroseis in Oman", THE LEADING EDGE, SOCIETY OF EXPLORATION GEOPHYSICISTS, US, vol. 17, no. 8, 1 August 1998 (1998-08-01) , pages 1053-1059, XP002385367, ISSN: 1070-485X, DOI: 10.1190/1.1438089 abstract; figure 5 -----	8
A	WO 2013/105075 A1 (GECO TECHNOLOGY BV [NL]; WESTERNGECO LLC [US]; SCHLUMBERGER CA LTD [CA] 18 July 2013 (2013-07-18) paragraphs [0011], [0045] paragraph [0051] - paragraph [0054] -----	1,12

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/061860

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2015177397 A1	25-06-2015	EG 26981 A	01-03-2015
		US 2010085836 A1	08-04-2010
		US 2015177397 A1	25-06-2015

WO 2013105075 A1	18-07-2013	AU 2013208642 A1	28-08-2014
		AU 2016203055 A1	26-05-2016
		CA 2860927 A1	18-07-2013
		EP 2802904 A1	19-11-2014
		MX 338314 B	12-04-2016
		RU 2014133166 A	10-03-2016
		US 2014362663 A1	11-12-2014
		WO 2013105075 A1	18-07-2013
