

A METHOD AND A SYSTEM FOR SIGNAL
IMPROVEMENT IN MARINE SEISMIC EXPLORATION

The invention relates to a method and a system for improving the quality of marine seismic signals. Such signals are gathered by using an array of marine seismic sources which is towed behind a vessel, said array comprising a plurality of subarrays. Each subarray carries seismic sources. The marine seismic method is a generally known geophysical exploration method to investigate the character of submarine earth formations and more particularly to survey subterranean formations.

According to said seismic method shocks at preselected submarine locations are generated periodically by marine seismic sources and various characteristics of the shock waves, causing seismic waves as they enter the earth and being reflected or refracted from submarine earth strata, are measured.

These shock waves are detected by sensitive instruments, placed at varying distances from the shock generation locations and are subsequently converted into electrical signals which may be further processed to derive data which may be plotted to obtain a picture or map of the investigated area, which may indicate the presence, if any, of structural traps capable of holding hydrocarbons like oil and/or gas.

The amplitude of the shock waves of interest is a function of the size of the shock and it will be clear that a wave having a relatively high amplitude may be studied easier than a wave having a lesser amplitude.

It has now become a usual practice in marine seismic exploration to use non-dynamite seismic sources, for example airguns. The following description will relate to airguns only, but it will be clear to those skilled in the art that

every suitable marine seismic source can be used. An example of such a suitable seismic source is a water-gun. The airguns are towed behind a marine vessel by means of a towing cable and may suddenly release confined volumes of high pressure gas, thus emitting acoustical pressure pulses having a certain acoustic energy, causing seismic waves as they enter the earth. The acoustic signal, generated by an airgun, shows a series of pressure pulses resulting in a corresponding oscillatory frequency spectrum having a fundamental frequency which is related to the depth of the airgun and the amount and pressure of released gas volume. Moreover, airguns are low intensity energy sources, so the acoustic energy waves produced by an airgun will have low amplitude and any electrical signal derived therefrom will have a relatively low signal-to-noise ratio, the signal strength produced by an airgun being several orders of magnitude less than that generated by a dynamite explosion or using other suitable explosives.

These features make a single airgun less effective as a seismic source.

Moreover, marine seismic exploration technology requires a way of detecting seismic waves, which involves added noise. For, when submerged areas are explored, the detectors cannot normally be fixedly located so as to detect a number of shocks of equal significance.

Instead it is conventional in marine seismic exploration to locate the detectors in a continuously towed streamer cable, which extends from the rear of a towing vessel, and to detect the acoustic waves, reflected from subsurface formations, while the vessel is proceeding along a prescribed course over the area of interest. However, such a procedure produces towing noise and this has a disadvantageous influence upon the quality of the signals to be obtained.

To improve both the signal strength and the signal shape it has been proposed to use a plurality of seismic sources belonging to a so-called "compact" array, in particular a "compact" array of airguns, and it has been found advantageous in marine seismic exploration to generate a plurality of acoustic waves from such an array in order to provide a composite acoustic wave of satisfactory amplitude and frequency content. Airguns having various volume capacities are generally used in such arrays in order to produce a composite acoustic wave having a broad frequency band, as airguns of various volumes generate acoustic waves with different frequency spectrum and corresponding phase spectrum, the frequency content and in particular the fundamental frequency of the generated acoustic wave being dependent upon the volume capacity of the airgun.

So, to provide a full spectrum of high energy acoustic pulses it is desirable to generate a number of acoustic waves of various fundamental frequencies.

Several arrays have been designed and implemented using an increasing number of guns and an increasing amount of compressed air power. The source strength and the signature shape of these "compact" arrays have been gradually brought at an adequate level now.

However, problems associated with noise appearance and loss of useful acoustic wave energy in water still exist and are not solved satisfactorily by the above-mentioned "compact" array prior art. For example, meaningful information contained by seismic waves directly reflected from the ocean bottom is often masked due to the reception of horizontally travelling noise caused by reflections of horizontal seismic waves from underwater obstacles and the like. So, high frequency radiation in more horizontal directions should be suppressed to avoid water trapped noise to dominate the seismic record. However, after this it might well be that still a significant

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amount of additional energy is needed to overcome the streamer noise and to compensate for non-elastic losses.

Therefore, so-called "extended" airgun arrays are designed to overcome the above-mentioned noise problems. Examples of such "extended" airgun arrays are the so-called superlong airgun array and superwide airgun array. These arrays are known to those skilled in the art and will not be described in detail.

In particular, these "extended" arrays provide seismic signals, which have an unsatisfactory signature shape. The signature shape can for example be characterized by the primary-to-bubble ratio. The term "primary-to-bubble" ratio (P/B ratio) is known to those skilled in the art and can be defined as the ratio between the amplitudes of the first two significant signal-peaks of the received signal. Conventional extended arrays such as superlong airgun arrays and superwide airgun arrays provide P/B ratios of less than 6. However, presently a P/B ratio of more than 8 is required.

Accordingly, it is an object of the present invention to provide a method for marine seismic exploration to be used with extended marine seismic arrays, which provides seismic signals of high quality. More particularly, it is an object of the method according to the present invention to provide an improved primary-to-bubble ratio and signature shape of the seismic signals.

The invention therefore provides a method for improving the signature shape of marine seismic signals, said signals being gathered by towing an extended marine seismic array and a receiver cable behind a vessel, wherein the said marine seismic array consists of at least two seismic subarrays, each subarray comprising a number of seismic sources, the sources of the said marine seismic array being characterized by parameters $T_{A,i}^*$ respectively, in which $i = 1 \dots n$ and $A = 1 \dots N$, n being the maximum number of seismic sources in a subarray and N being the total number of subarrays; and wherein each parameter $T_{A,i}^*$ is a function of individual parameters $T_{A,i}$ wherein $T_{A,i}$ stands for $P_{A,i}$ and/or $V_{A,i}$ and/or $d_{A,i}$, in which $P_{A,i}$, $V_{A,i}$, $d_{A,i}$, respectively, represent the operating pressure,

gun volume and towing depth of the respective seismic sources in the respective subarrays, and wherein the said individual parameters $T_{A,i}$ of the seismic array satisfy the following predetermined mutual relation:

$$\frac{T_{A,i}}{T_{A,i-1}} = \frac{T_{B,i}}{T_{B,i-1}} = c_i,$$

c_i representing a constant; and wherein further the following relation exists between the parameters: $T_{A,i} \neq T_{B,i}$ for at least one of these parameters, wherein $A \neq B$ and $A = 1 \dots N$, $B = 1 \dots N$, and $T_{B,i}$ representing similar to $T_{A,i}$ individual parameters of one of the sources in one of the subarrays.

The invention also provides a system for carrying out the method, comprising an extended marine seismic array and a receiver cable behind a vessel, wherein the said marine seismic array consists of at least two seismic subarrays, each subarray comprising a number of seismic sources, the sources of the said marine seismic array being characterized by parameters $T_{A,i}^*$ respectively, in which $i = 1 \dots n$ and $A = 1 \dots N$, n being the maximum number of seismic sources in a subarray and N being the total number of subarrays; and wherein each parameter $T_{A,i}^*$ is a function of individual parameters $T_{A,i}$ wherein $T_{A,i}$ stands for $P_{A,i}$ and/or $V_{A,i}$ and/or $d_{A,i}$, in which $P_{A,i}$, $V_{A,i}$, $d_{A,i}$, respectively, represent the operating pressure, gun volume and towing depth of the respective seismic sources in the respective subarrays, and wherein the said individual parameters $T_{A,i}$ of the seismic array satisfy the following predetermined mutual relation:

$$\frac{T_{A,i}}{T_{A,i-1}} = \frac{T_{B,i}}{T_{B,i-1}} = c_i,$$

c_i representing a constant; and wherein further the following relation exists between the parameters: $T_{A,i} \neq T_{B,i}$ for at least one of these parameters, wherein $A \neq B$ and $A = 1 \dots N$, $B = 1 \dots N$, and $T_{B,i}$ representing similar to $T_{A,i}$ individual parameters of one of the sources in one of the subarrays.

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In an advantageous embodiment of the invention the parameters $\frac{T_{1,i}}{T_{1,i-1}} = \frac{T_{2,i}}{T_{2,i-1}} = c_i$ and $T_{1,i} \neq T_{2,i}$.

In another advantageous embodiment of the invention $\frac{T_{2,i}}{T_{2,i-1}} = \frac{T_{3,i}}{T_{3,i-1}} = \frac{T_{4,i}}{T_{4,i-1}} = \dots = \frac{T_{N,i}}{T_{N,i-1}} = c_i$ and $T_{2,i} \neq T_{3,i} \neq \dots \neq T_{N,i}$.

In another advantageous embodiment of the invention $\frac{T_{1,i}}{T_{1,i-1}} = \frac{T_{2,i}}{T_{2,i-1}} = \frac{T_{3,i}}{T_{3,i-1}} = \dots = \frac{T_{6,i}}{T_{6,i-1}} = c_i$, and $(T_{1,i} = T_{4,i}) \neq (T_{2,i} = T_{5,i}) \neq (T_{3,i} = T_{6,i})$.

The relation $\frac{T_{A,i}}{T_{B,i}}$ can be varied by varying the relations $\frac{P_{A,i}}{P_{B,i}}$ and/or $\frac{V_{A,i}}{V_{B,i}}$ and/or $\frac{d_{A,i}}{d_{B,i}}$ wherein

$B = 1 \dots N$ and $A = 1 \dots N$, and $A \neq B$.

These different values may be chosen from a determined range, for example 2-15 meter for d and 20-2000 cu.inch for V . It will be appreciated that any suitable technical manner of changing the said parameters can be used. Such technical manners are known to those skilled in the art and will not be described in detail.

The invention will now be described by way of example in more detail with reference to the accompanying drawings, in which:

fig. 1 shows an example of a seismic source array, in which $N = 6$ and $n = 6$ which can be used for carrying out the method of the invention;

fig. 2 shows an example of an improved seismic source signal obtained according to the method and apparatus of the invention;

figs. 3a, b show graphs representing the influence of a change of a so-called "scale factor"

$$\frac{P_{A,i}}{P_{B,i}} \text{ or } \frac{V_{A,i}}{V_{B,i}}$$

on the P/B ratio;

figs. 4a, b show graphs representing the influence of a change of depth of a subarray on the P/B ratio.

With reference now to fig. 1 of the drawings an example of a so-called "superwide" seismic source array, which can be used for carrying out the method of the invention, has been represented schematically. A vessel 1 tows a seismic source array consisting of six subarrays 3, 4, 5, 6, 7, 8 (thus, $N = 6$). Each subarray is connected by means of any suitable connecting means 2 such as a cable to the vessel 1. Each subarray carries a number of six seismic sources such as airguns (schematically shown) (thus, $n = 6$).

Technical details of a seismic source array as such are known to those skilled in the art and will not be described.

However, it will be appreciated that the method of the invention can be carried out with any seismic source array suitable for the purpose, for example a so-called "superlong" seismic source array (not shown).

The parameters $T_{A,i}^*$ can be represented for the first subarray as follows:

$T_{1,1}^*, T_{1,2}^*, T_{1,3}^*, T_{1,4}^*, T_{1,5}^*$ and $T_{1,6}^*$, each $T_{1,i}^*$ ($i = 1 \dots 6$) being a function of individual parameters $T_{1,i}$ (operating pressure, gun volume and towing depth) of each seismic source in the first subarray. The parameter $T_{A,i}^*$ can be determined as the dominant time period of the signal received.

The parameters $T_{A,i}^*$ can be represented for the sixth subarray as follows:

$T_{6,1}^*, T_{6,2}^*, T_{6,3}^*, T_{6,4}^*, T_{6,5}^*$ and $T_{6,6}^*$, each $T_{6,i}^*$ ($i = 1 \dots 6$) being a function of individual parameters $T_{6,i}$ (operating pressure, gun volume and towing depth) of each seismic source in the sixth

subarray.

The parameters of the remaining subarrays can be represented in a similar way (not shown for reasons of clarity).

5 The parameters $T_{1,i}$ and $T_{2,i}$ have a mutual predetermined relationship:

$$\frac{T_{1,i}}{T_{1,i-1}} = \frac{T_{2,i}}{T_{2,i-1}} = c_i \text{ and } T_{1,i} \neq T_{2,i}.$$

Thus: $T_{1,2} = c_2 T_{1,1}$, $T_{1,3} = c_3 T_{1,2} \dots$
 $\dots T_{1,6} = c_6 T_{1,5}$ and $T_{2,i} = \delta T_{1,i}$,

10 wherein $\delta \neq 1$. In this way a so-called "scaled" array is obtained.

With reference now to fig. 2 of the drawings the horizontal axis represents the time t , whereas the vertical axis represents the signal amplitude. The signal has been
 15 obtained as follows: an extended seismic array such as a "superwide" array consisting of two subarrays was towed behind a vessel, each subarray comprising 7 airguns. One subarray was towed at the conventional depth of about 6-8 meter in particular 7.5 meter, the total seismic source volume of this
 20 subarray being 910 cu.in. The other subarray was towed at a depth of 5 meter, the total seismic source volume of this subarray being 1390 cu.in.

The seismic sources of the array were fired and a resulting signal as shown in fig. 2 was obtained. From fig. 2
 25 it will be clear that the resulting signal is improved significantly, since a P/B ratio (ratio between the amplitudes of peaks A and B) of 9.5 was obtained. This is much better than the conventional P/B ratio of 5.6. It will be appreciated that provisions are to be made to compensate for asynchronous
 30 emitted shock waves as produced for shock waves at different depths.

In figs. 3a and 3b the horizontal axes represent the variation in "scale factor"

$$\left(\frac{P_{1,1}}{P_{2,1}} \text{ or } \frac{V_{1,1}}{V_{2,1}} \right)$$

whereas the vertical axes represent the obtained primary/
Bubble ratio of the seismic signals. The parameters P and V
have already been defined earlier. In this figure the scale is
a logarithmic scale, but it will be clear that any scale
suitable for the purpose can be applied.

Fig. 3a represents the results of experiments obtained
with a seismic array comprising two 7-gun subarrays which were
towed behind a vessel at a depth of 8 meter. The gun volume of
one subarray has remained the same, whereas the gun volumes of
the second subarray were varied, such that

$$V_{2,1} = \gamma V_{1,1}; V_{2,2} = \gamma V_{1,2} \dots\dots\dots$$

$$\dots\dots\dots V_{2,7} = \gamma V_{1,7}$$

wherein γ represents a "scale factor".

Experiments were also carried out with a seismic array
comprising two 5-gun subarrays, towed at a depth of 8 meter.
The results are represented in fig. 3b.

It appears from figs. 3a, b that increasing gun volumes
in the second array are attractive.

Figs. 4a, b show the results of a very attractive method,
viz. depth variation of the second subarray. In these experi-
ments again seismic arrays comprising two 7-gun subarrays and
two 5-gun subarrays, respectively, have been used. One 5-gun
subarray or one 7-gun subarray respectively were kept at a
constant conventional depth of about 8 meter, whereas the
second subarray depth has been varied.

The second subarray depth is represented along the
horizontal axes in figs. 4a, b whereas the vertical axes
represent the P/B ratios of the obtained signals.

Fig. 4a represents the results of one 7-gun subarray at a
depth of about 8 meter and one 7-gun subarray at varying
depth, whereas fig. 4b represents the results of one 5-gun
subarray at a depth of about 8 meter and one 5-gun subarray at

varying depth.

It appears from figs. 4a, b that advantageous P/B ratios can be obtained at shallow depths.

5 For optimum P/B ratio improvement both P or V variation and depth variation could be applied in a limited range.

It will be appreciated that the method of the invention is not restricted to the towing of an array comprising only two subarrays or the use of 5- or 7-guns in each subarray.

10 Any number of subarrays, number of guns and kind of guns in a subarray suitable for the purpose can be applied.

Various modifications of the invention will become apparent to those skilled in the art from the foregoing description and accompanying drawings. Such modifications are intended to fall within the scope of the appended claims.



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C L A I M S

1. A method for improving the signature shape of marine seismic signals, said signals being gathered by towing an extended marine seismic array and a receiver cable behind a vessel, wherein the said marine seismic array consists of at least two seismic subarrays, each subarray comprising a number of seismic sources, the sources of the said marine seismic array being characterized by parameters $T_{A,i}^*$ respectively, in which $i = 1 \dots n$ and $A = 1 \dots N$, n being the maximum number of seismic sources in a subarray and N being the total number of subarrays; and wherein each parameter $T_{A,i}^*$ is a function of individual parameters $T_{A,i}$ wherein $T_{A,i}$ stands for $P_{A,i}$ and/or $V_{A,i}$ and/or $d_{A,i}$, in which $P_{A,i}$, $V_{A,i}$, $d_{A,i}$, respectively, represent the operating pressure, gun volume and towing depth of the respective seismic sources in the respective subarrays, and wherein the said individual parameters $T_{A,i}$ of the seismic array satisfy the following predetermined mutual relation:

$$\frac{T_{A,i}}{T_{A,i-1}} = \frac{T_{B,i}}{T_{B,i-1}} = c_1,$$

c_1 representing a constant; and wherein further the following relation exists between the parameters: $T_{A,i} \neq T_{B,i}$ for at least one of these parameters, wherein $A \neq B$ and $A = 1 \dots N$, $B = 1 \dots N$, and $T_{B,i}$ representing similar to $T_{A,i}$ individual parameters of one of the sources in one of the subarrays.

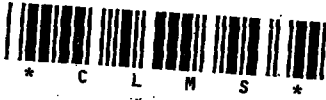
2. The method as claimed in claim 1, wherein

$$\frac{T_{1,i}}{T_{1,i-1}} = \frac{T_{2,i}}{T_{2,i-1}} = c_1 \text{ and } T_{1,i} \neq T_{2,i}.$$

3. The method as claimed in claims 1 or 2, wherein

$$\frac{T_{2,i}}{T_{2,i-1}} = \frac{T_{3,i}}{T_{3,i-1}} = \frac{T_{4,i}}{T_{4,i-1}} = \dots = \frac{T_{N,i}}{T_{N,i-1}} = c_1$$

and $T_{2,i} \neq T_{3,i} \neq T_{4,i} \neq \dots \neq T_{N,i}$.



4. The method as claimed in claims 1 or 2, wherein

$$\frac{T_{1,i}}{T_{1,i-1}} = \frac{T_{2,i}}{T_{2,i-1}} = \frac{T_{3,i}}{T_{3,i-1}} = \frac{T_{4,i}}{T_{4,i-1}} = \frac{T_{5,i}}{T_{5,i-1}} = \frac{T_{6,i}}{T_{6,i-1}} = c_i$$

and $(T_{1,i} = T_{4,i}) \neq (T_{2,i} = T_{5,i}) \neq (T_{3,i} = T_{6,i})$.

5. The method as claimed in any one of claims 1-4, comprising the step of varying the relation $\frac{P_{A,i}}{P_{B,i}}$ and thus

$\frac{T_{A,i}}{T_{B,i}}$, wherein $B = 1 \dots N$ and $A = 1 \dots N$ and $A \neq B$.

6. The method as claimed in any one of claims 1-5, comprising the step of varying the relation $\frac{V_{A,i}}{V_{B,i}}$ and thus

$\frac{T_{A,i}}{T_{B,i}}$, wherein $B = 1 \dots N$ and $A = 1 \dots N$, and $A \neq B$.

10 7. The method as claimed in any one of claims 1-6, comprising the step of varying the relation $\frac{d_{A,i}}{d_{B,i}}$ and thus

$\frac{T_{A,i}}{T_{B,i}}$, wherein $B = 1 \dots N$ and $A = 1 \dots N$, and $A \neq B$.

15 8. The method as claimed in claim 7, comprising the step of varying the depth, on which at least one subarray is towed, between 2-15 meter.

9. The method as claimed in claim 8, wherein the other subarray or subarrays are towed at the depth of about 6-8 meter.

20 10. The method as claimed in claim 8 or 9, wherein the depth of at least one subarray is about 5 meter and the depth of the other subarray or subarrays is about 7.5 meter.

11. The method as claimed in claim 6, comprising the step of varying the seismic source volume of a subarray between 20-2000 cu.in.

25 12. The method as claimed in claim 11, wherein the seismic source volume of at least one subarray is about 910 cu.in., and of the other subarray or subarrays is about 1390 cu.in.



13. A system for carrying out the method as claimed in claims 1-12, comprising an extended marine seismic array and a receiver cable behind a vessel, wherein the said marine seismic array consists of at least two seismic subarrays, each subarray comprising a number of seismic sources, the sources of the said marine seismic array being characterized by parameters $T_{A,i}^*$ respectively, in which $i = 1 \dots n$ and $A = 1 \dots N$, n being the maximum number of seismic sources in a subarray and N being the total number of subarrays; and wherein each parameter $T_{A,i}^*$ is a function of individual parameters $T_{A,i}$ wherein $T_{A,i}$ stands for $P_{A,i}$ and/or $V_{A,i}$ and/or $d_{A,i}$, in which $P_{A,i}$, $V_{A,i}$, $d_{A,i}$, respectively, represent the operating pressure, gun volume and towing depth of the respective seismic sources in the respective subarrays, and wherein the said individual parameters $T_{A,i}$ of the seismic array satisfy the following predetermined mutual relation:

$$\frac{T_{A,i}}{T_{A,i-1}} = \frac{T_{B,i}}{T_{B,i-1}} = c_i,$$

c_i representing a constant; and wherein further the following relation exists between the parameters: $T_{A,i} \neq T_{B,i}$ for at least one of these parameters, wherein $A \neq B$ and $A = 1 \dots N$, $B = 1 \dots N$, and $T_{B,i}$ representing similar to $T_{A,i}$ individual parameters of one of the sources in one of the subarrays.

14. Method for improving the signature shape of marine seismic signals, substantially as described in the specification with reference to figs. 1-4 of the drawings.

15. System for carrying out the method substantially as described in the specification with reference to the drawings.
