

A PROCESSING METHOD FOR CALIBRATING A HYDROPHONE-GEOPHONE
SENSOR PAIR, AND A SEISMIC PROSPECTING METHOD IMPLEMENTING
THE PROCESSING ✓

5 The present invention relates to a processing method for calibrating at least one hydrophone-geophone sensor pair used in offshore seismic prospecting processing.

The invention also relates to an offshore seismic prospecting method that implements such processing.

10 For offshore seismic prospecting, use is generally made of cables carrying hydrophone sensors and towed by ships that also carry sound sources.

15 Such cables, generally referred to as "streamers" by the person skilled in the art, cannot be used in certain zones, and in particular in production zones which are cluttered with platforms.

Under such circumstances, the soundwaves emitted by the ships are received by hydrophones placed on the sea bottom.

20 In these various techniques, the recordings made by the hydrophones must be processed so as to eliminate "ghosts" from the signals obtained (where "ghosts" are primary waves carrying information about sub-surface geology and reflected at the surface of the water), and
25 also possibly to eliminate reverberations, known as "peg-legs", which correspond to multiple reflections at the surface and at the water bottom, making recordings difficult to interpret.

30 Spectrally, ghost waves are equivalent to useful data being filtered via a notch filter which removes frequencies from the signal that are multiples of $f_n = v/(2\Delta z)$, where Δz is the depth of the receivers and v is the speed of sound in water (1500 meters per second (m/s)).

35 When Δz is less than 10 m, as is the case for

conventional acquisition using hydrophones carried by a cable towed by a ship, f_n is greater than 75 Hz and said notch frequencies lie outside the usable passband. Under such circumstances, the ghost wave appears in the usable
5 passband only as attenuation, and can be eliminated by deconvolution.

However, when hydrophone sensors are placed on the water bottom, Δz is the depth of the water, which is typically 50 m, so $f_n = 15$ Hz. The passband is punctuated
10 by frequencies at which the response signal is hidden by the ghost wave. Eliminating the ghost wave by deconvolution leads to a large amount of noise being added to the results.

Recently, several techniques have been proposed in
15 which acquisition is performed by means of hydrophone and geophone sensors disposed on the sea bottom.

In particular, US 4 486 865 discloses a seismic acquisition method using hydrophones and geophones distributed in pairs at the water bottom, and in which the
20 hydrophone component and the geophone component of a given pair of sensors are deconvoluted by their previously-determined spectral functions, and the deconvoluted data is averaged to obtain an output which corresponds to the up wave immediately above the bottom of
25 the water surface, and from which the ghost waves have been eliminated.

However, the hydrophone and geophone recordings have to be calibrated before being jointly usable. A perfect hydrophone measures the pressure and a perfect
30 geophone measures the velocity. A real hydrophone measures the pressure as filtered by an instrumental response and a real geophone measures the velocity as filtered an instrumental response. By definition, a calibration operation equalizes the instrumental responses.

35 It has been proposed by US 4 979 150 a seismic

method which uses a processing which combines the hydrophone and geophone recordings and seeks to eliminate ghost waves and "peg-leg" type reverberations without requiring deconvolution to be applied to the hydrophone and geophone recordings.

With this processing, a calibration scalar is applied to the hydrophone component or to the geophone component and components calibrated in this way are summed. The calibration scalar is a function, in particular, of the reflection coefficient of the water bottom. It is implemented in a deterministic manner, on the basis of calibration shots or in a statistic manner, with the assumption that the subsoil reflectivity presents a white autocorrelation.

A similar method has also been proposed in US 5 365 492. According to this method, a calibration scalar is applied to a geophone recording in which the noise is previously cleared away. The geophone recording first cleared and calibrated is summed to that of the hydrophone, which gives the desired output without the reverberation in the water layer.

The calibration scalar is calculated by a repeated maximizing of a varimax function of the autocorrelation of the output signal.

However, the calibration scalar as proposed in US 5 365 492 supposes the assumption that the reflectivity of the geology presents a white autocorrelation.

However, this assumption, which is currently used in technic processing, is not always true.

Further, a calibration scalar is necessarily imprecise since it does not take into account the spectral variation of the coupling.

Further, the determination of the calibration scalar by an iterative processing implies that such scalar is much sensitive to noise and that therefore a step of

noise clearing is necessary.

The aims of the invention are to overcome these various drawbacks and the invention proposes a calibration processing which equalizes the instrumental responses of the hydrophone and geophone with a spectral calibration calculated with a criterium which is sturdy to noise and which is suitable for the case where both the hydrophone and geophone are noised, said criterium making no statistic assumption on the reflectivity of the sub-soil and implying no calibration shots.

More particularly, the invention provides a processing method for calibrating at least one pair of hydrophone-geophone sensors disposed on a water bottom and used in seismic prospecting processing in which a sound source emits a signal into the water and the sensors at the water bottom pick up hydrophone and geophone recordings H and G, the method being characterized in that calibration is applied to the recordings to minimize, in a time window beyond a theoretical extinction time, the energy of a signal S which is determined as a function of the hydrophone and geophone recordings and which corresponds to the source signal propagated through the layer of water to the sensor.

Thus, the processing proposed by the invention performs calibration on the assumption that the duration of emission from the seismic source is limited. This assumption is much more reliable than that of reflectivity being white as is implied in prior art statistical calibration methods.

Calibration determined using the method proposed by the invention can vary slowly with frequency in order to correct imperfections of coupling between the geophone and the water bottom.

In a preferred implementation, the hydrophone recordings H are filtered by an operator that adds a

geophone type ghost reflection thereto, and then the geophone recordings G are filtered by an operator that adds a hydrophone type reflection thereto, and a calibration is sought to provide, in a time window beyond
 5 the theoretical extinction time, best equalization of the hydrophone recordings and of the geophone recordings as filtered in this way.

Also advantageously, the geophone recordings are calibrated against the hydrophone recordings.

10 In particular:

- hydrophone data H_R and geophone data G_R is determined corresponding to the recordings H and G propagated over a go-and-return path through the layer of water;

15 • hydrophone sum data H_Σ and geophone difference data G_Δ are calculated as follows:

$$H_\Sigma = \frac{H + rH_R}{2}$$

and

20
$$G_\Delta = \frac{G - rG_R}{2}$$

where r is a transfer function modelising the surface of the water,

• calibration functions C_H and C_G are determined
 25 to minimize, beyond a theoretical extinction time, the energy of S :

$$S = C_H * H_\Sigma - C_G * G_\Delta$$

where S corresponds to the source signal propagated through the layer of water; and

30 • the hydrophone geophone data are calibrated by convolution with the calibration functions C_H and C_G .

As will be understood on reading the following description, these calibration functions C_H and C_G do not

depend on the reflectivity of the water bottom.

The invention also provides an offshore seismic prospecting method in which the above processing method is implemented and the data obtained in this way is processed
5 to deduce information therefrom about the subsoil geology.

Other characteristics and advantages of the invention appear further from the following description. The description is purely illustrative and non-limiting. It should be read with reference to the accompanying
10 drawings, in which:

- Figure 1 is a diagram showing the various quantities involved in the model used for the method of the invention;

- Figure 2 is a summary chart showing the method
15 of the invention; and

- Figures 3a to 3h show the various signals obtained in the various steps of the method of the invention in response to a synthetic source signal.

Figure 1 shows a sound source 1 emitting a signal
20 S_0 at the surface of a layer of water E, together with hydrophone sensors 2 and geophone sensors 3 disposed on the sea bottom F. The layer of water E has thickness Δz . The horizontal distance between the source 1 and the hydrophone-geophone sensor pair 2, 3 is referenced h .

25 The hydrophone sensors 2 measure pressure and are isotropic. They record the sum of up soundwaves U and down soundwaves D.

The geophone sensors 3 are placed vertically on the bottom F and they measure the vertical speed of
30 soundwaves. They record the up soundwaves U, subtracting therefrom the down soundwaves D.

The signals H and G recorded by the hydrophones 2 and the geophones 3 can be written as functions of the up waves U and the down waves D, as follows:

$$35 \quad H = U + D \quad (1)$$

$$G = (U - D)/I_0 \quad (2)$$

In equation (2), I_0 is the acoustic impedance of the water ($I_0 = \rho v$, where ρ is the density of the water, and v is the speed of sound in the water).

5 To simplify the description below, it is assumed that $I_0 = 1$, since in any event the geophone is to be calibrated.

The surface of the water behaves like a reflector having a reflection coefficient of -1 and it adds a down
10 wave to the signal corresponding to the source S_0 , which down wave is equal to the up wave U , but of opposite sign.

Consequently, at the water bottom, the down wave is written as follows:

$$D = -ZU + Z^{1/2}_S S_0 \quad (3)$$

15 where Z is an operator corresponding to go-and-return propagation through the layer of water, i.e. to a time delay $\Delta t = 2\Delta z/v$ where v is the speed of sound in the layer of water, and where $Z^{1/2}_S$ is an operator corresponding to go propagation of sound between the
20 surface and the water bottom.

For a 1-D approximation, Z is merely a time delay $\Delta t = 2\Delta z/v$, and $Z^{1/2}_S$ is a time delay $\Delta z/v$.

In frequency notation, $Z = e^{-2j\pi f\Delta t}$ where f is frequency.

25 When 2-D and 3-D propagation effects are taken into account, we have the following in the (ω, k) domain, with $\omega = 2\pi f$ and k wave number:

$$-2j\Delta z \omega \sqrt{1 - v^2 k^2 / \omega^2}$$

$$Z = e^{-\frac{-2j\Delta z \omega \sqrt{1 - v^2 k^2 / \omega^2}}{v}} \quad (4)$$

30

By defining the propagated source S as follows:

$$S = Z^{1/2}_S S_0 \quad (5)$$

the expression for D becomes:

$$D = S - ZU \quad (6)$$

putting (6) into (1) and (2), gives the following modelling equations:

$$5 \quad H = S + (1 - Z)U \quad (7)$$

$$G = -S + (1 + Z)U \quad (8)$$

Consequently, S can be written:

$$10 \quad S = \frac{1 + Z}{2} H - \frac{1 - Z}{2} G \quad (9)$$

An example of calibration processing of the invention is described below with reference to Figure 2 and Figures 3a to 3h.

It will be observed that in a preferred implementation, the hydrophones and the geophones are not calibrated absolutely, but each geophone is calibrated relative to the hydrophone with which it is associated. The hydrophone is thus left unchanged and geophone calibration with spectral variation is sought so as to take into account the effects of coupling between the geophone and the water bottom. The hydrophone is left unchanged since it is a good reference: its coupling with its medium is always excellent and it is insensitive to its orientation.

Calibration is performed as follows.

Figures 3a and 3b show respectively the hydrophone recording H and the geophone recording G. To make the invention more understandable, the recording H is marked to show the primary reflection PR that contains the useful signal and also the ghost and multiple peg-leg type reflections RMF.

The hydrophone and geophone data H_R and G_R (Figures 3c, 3d) propagated over a go-and-return path in

the layer of water are calculated as follows:

$$H_R = ZH \quad (10)$$

$$G_R = ZG \quad (11)$$

When using a one-dimensional approximation,
5 equations (10) and (11) are written as follows:

$$H_R(t) = H(t - \frac{2\Delta z}{v}) \quad (12)$$

v

$$G_R(t) = G(t - \frac{2\Delta z}{v}) \quad (13)$$

v

10

Thereafter, the following magnitudes are calculated: hydrophone sum H_Σ (Figure 3e) and geophone difference G_Δ (Figure 3f):

$$H_\Sigma = \frac{H + H_R}{2} \quad (14)$$

15

2

$$G_\Delta = \frac{G - G_R}{2} \quad (15)$$

2

which makes it possible to write equation (9) giving the
20 propagated source S , in the following form:

$$S = H_\Sigma - G_\Delta \quad (16)$$

The true propagated seismic source S_{true} is zero
after a certain amount of time. For each source position
and receiver position, it is possible to calculate the
25 start time T_s of the seismic source:

$$T_s = (\Delta z^2 + h^2)^{1/2}/v,$$

and its extinction time $T_E = T_s + \Delta T_s$, where ΔT_s is the
duration of the source. S_{true} must be zero beyond the
extinction time T_E .

30

Also, the propagation operator Z which corresponds
to go-and-return propagation through the layer of water
is merely an approximate operator. In the equation

$Z = e^{-2j\pi f 2\Delta z/v}$, a 1-D approximation is being made which consists in assuming that waves propagate in a direction that is close to the vertical.

This approximation is valid only in a certain zone of data. This valid zone can be defined for each trace by a validity time T_{1D} beyond which the 1-D approximation is acceptable. The validity time T_{1D} needs to be greater with increasing horizontal distance h of the trace.

Thus, beyond the extinction time T_E and in the zone where the source operator Z is valid, the source S as calculated by (9) must be zero. Naturally, this is true only if the data from the hydrophone and the geophone is well calibrated.

This assumption is used for calibrating the geophone against the hydrophone.

More particularly, the geophone is calibrated against the hydrophone by calculating a transfer function which, when applied to the geophone, minimizes the estimated source energy in a time window situated simultaneously beyond the source extinction time and the validity time of the propagation operator.

This function $C(t)$ is such that:

$$S(t) = H_{\Sigma}(t) - C(t) * G_{\Delta}(t) \quad (17)$$

has a minimum normalized value in the time window

$t \in [T, T_{\max}]$, where T is a time greater than or equal to T_E and to T_{1D} , and where $T_{\max}$ is a time shorter than the recording time for one shot.

For example, with the normalized value $L2$, this gives the least squares system $GC = H$:

5

$[p_1, p_2]$ being indices corresponding to the interval

10

The minimized energy is $E = H^T (H - GC)$.

15

20

25

$$S = C_H * H_{\Sigma} - C_G * G_{\Delta},$$

30

The calibration of the geophone recordings on the

hydrophone recordings is however preferred ($C_H = 1$).

Once $C(t)$ has been calculated, calibrated geophone data is calculated by convolution between the geophone data and $C(t)$.

5 It is also possible to calculate a transfer function for the water surface that has been assumed above to be a perfect mirror having a reflection coefficient of -1 . To do this, it is assumed that the water surface acts as though it had a transfer function
10 $-r(t)$, where $r(t)$ is a given time medium. For this purpose, equation (6) is replaced by:

$$D = S - rZU \quad (6')$$

By writing the calibrated geophone data $G'(t) = C(t)*G(t)$, new expressions can be deduced for H ,
15 G , and S , by replacing equations (7) to (9), as follows:

$$H = S + (1 - rZ)U \quad (7')$$

$$G = -S + (1 + rZ)U \quad (8')$$

$$S = \frac{1 + rZ}{2} H - \frac{1 - rZ}{2} G \quad (9')$$

20 Using the notation $G'R = ZG'$, S is put into the following form:

$$S = \frac{H - G'}{2} + r \frac{H_R + G'_R}{2} \quad (20)$$

25 $(H - G')$ and $(H_R + G'_R)$ are thus calculated after which $r(t)$ is calculated so as to minimize equation (20) for S in a given time window.

The calibration $C(t)$ can be recalculated with the water surface modelled by a transfer function $-r(t)$. From
30 (9'), equations (14) and (15) need to be replaced as follows:

$$H_\Sigma = \frac{H}{2} + r \frac{H_R}{2} \quad (14')$$

$$G_A = \frac{G - rG_R}{2} \quad (15')$$

When $C(t)$ is calculated, it is also possible to calculate the propagated source $S(t)$ from equation (17).

5 The source S obtained in this way is shown in Figure 3g. As can be seen from the figure, this signal is of minimal energy, with the primary reflections and the ghost and peg-leg reflections being eliminated therefrom after reception of the source signal.

10 It is also possible to truncate the source $S(t)$ for values $t \in [T, T_{\max}]$. This truncated portion is used for quality control purposes, in which it is checked that it presents the least possible energy, and above all the least possible coherent energy.

15 Naturally, it is desirable for the calibration transfer function to be unique and to depend only on the characteristics of the hydrophone and of the geophone. To this end, use is made of collections of data from a common receiver, i.e. the seismic traces corresponding to
20 different positions of the seismic source for each pair of sensors 2 and 3 are combined, and a single calibration function is calculated for the entire collection.

To this end, for each seismic trace of index i , where i is the position index of the seismic source, the
25 horizontal distance of the trace $h(i)$ and the depth of the water at the position of receiver Δz are used to calculate the extinction time of the source $T_E(i)$ and the validity time $T_{1D}(i)$ of the 1-D approximation which consists in replacing the propagation operator Z by a time delay $\Delta t =$
30 $2\Delta z/v$.

Thereafter, the estimated source energy is minimized for all indices i and for times greater than $T_E(i)$ and $T_{1D}(i)$. This amounts to calculating the various matrices G_i and the various second members H_i of equation

(18) for times $T_i \geq \text{MAX} [T_E(i), T_{1D}(i)]$ and in inverting the system:

$$(\sum_i G_i)C = \sum_i H_i \quad (21)$$

5 obtained by summing the matrices and by summing the second members to have a single calibration function C for each receiver collection.

Once the calibration function $C(t)$ has been calculated, calibrated geophone data is calculated by
10 convoluting all of the geophone traces of the common receiver collection with $C(t)$.

In the seismic prospecting method proposed by the invention, this data is then processed to deduce therefrom information about the geology of the subsoil.

15 One example of such processing is given below.

Naturally, other kinds of processing could also be envisaged.

After calculating the calibrated geophone data

$G' = C * G$ (shown in Figure 3h);

20 $G'R = C * G_R$; and

$G'_\Delta = C * G_\Delta$;

the hydrophone difference and geophone sum channels are calculated as follows:

$$H_\Delta = \frac{H - H_R}{2} \quad (22)$$

25

$$G'_\Sigma = \frac{G' + G'_R}{2} \quad (23)$$

Thereafter, the source and the truncated source
30 are calculated by:

$$S = H'_\Sigma - G'_\Delta \quad (24)$$

The propagated source S is then truncated into a source S_T where:

$$S_T = \text{truncated } S \quad (25)$$

Thereafter the matched filtering is calculated:

$$M = H_{\Delta} - G' \Sigma \quad (26)$$

and the delayed up wave:

$$U_R = \frac{S_T - M}{2} \quad (27)$$

Finally, the output is calculated:

$$U = Z^{-1} U_R \quad (28)$$

In the one-dimensional approximation, Z^{-1} is an operator corresponding to a time advance of $2\Delta z/v$, i.e. (28) can be written as follows:

$$U(t) = U_R(t + 2\Delta z/v) \quad (29)$$

The output U no longer has the receiver ghost and it presents attenuated noise because it is calculated from S_T which has low noise since it is truncated, and from M which also has low noise since it corresponds to a matched filter.

D can also be deduced by replacing U in equation (5) by the expression therefor (28):

$$D = \frac{S_T + M}{2} \quad (30)$$

In conventional manner for the person skilled in the art, the peg-leg type secondary oscillations that appear in the same manner in the hydrophone and geophone data can be eliminated by subsequent processing.



CLAIMS

- 1/ A processing method for calibrating at least one pair of hydrophone-geophone sensors disposed on a water bottom and used in seismic prospecting processing in which a sound source emits a signal into the water and the sensors at the water bottom pick up hydrophone and geophone recordings H and G, the method being characterized in that calibration is applied to the recordings to minimize, in a time window beyond a theoretical extinction time, the energy of a signal S which is determined as a function of the hydrophone and geophone recordings and which corresponds to the source signal propagated through the layer of water to the sensor.
- 2/ A method according to claim 1, characterized in that the hydrophone recordings H are filtered by an operator that adds a geophone type ghost reflection thereto, and then the geophone recordings G are filtered by an operator that adds a hydrophone type reflection thereto, and in that a calibration is sought to provide, in a time window beyond the theoretical extinction time, best equalization of the hydrophone recordings and of the geophone recordings as filtered in this way.
- 3/ A method according to claim 1 or 2, characterized in that the geophone recordings are calibrated against the hydrophone recordings.
- 4/ A method according to claim 1, characterized by the following steps:
- hydrophone data H_R and geophone data G_R is determined corresponding to the recordings H and G propagated over a go-and-return path through the layer of water;
 - hydrophone sum data H_Σ and geophone difference



data G_A are calculated as follows:

$$H_Z = \frac{H + rH_R}{2}$$

and

5
$$G_A = \frac{G - rG_R}{2}$$

where r is a transfer function modelising the surface of the water,

• calibration functions C_H and C_G are determined to
10 minimize, beyond a theoretical extinction time, the energy of S :

$$S = C_H * H_Z - C_G * G_A$$

where S corresponds to the source signal propagated through the layer of water; and

15 • the hydrophone geophone data are calibrated by convolution with the calibration functions C_H and C_G .

5/ A method according to claims 3 and 4, characterized in that C_H is chosen equal to 1.

20

6/ A method according to claim 4, characterized in that r is chosen equal to 1.

25 7/ A method according to any preceding claim, characterized in that physical parameters are determined by minimizing the energy of the signal S in a time window beyond the theoretical extinction time.

30 8/ A method according to claim 6, characterized in that the depth Δz of the layer of water is determined by calculating, for a plurality of values Δz , the energy of the signal S in a time window beyond its theoretical extinction time, and by selecting the value of Dz that minimizes said energy.



9/ A method according to claims 4 and 7, characterized in that the transfer function $\underline{r}$ of the water surface is determined in minimizing the energy of the signal S in a time window beyond its theoretical extinction time.

10/ A method according to any preceding claim, characterized in that it includes quality control in which it is verified that the propagated source signal S determined as a function of the calibrated hydrophone and geophone recordings contains minimal energy in a time window beyond its theoretical extinction time.

11/ A method according to claim 4, characterized in that in order to determine the hydrophone data H_R and the geophone data G_R , an operator Z is applied to the hydrophone recordings H and to the geophone recordings G, where the operator Z corresponds to propagation along a go-and-return path in the layer of water, and in that, in order to determine the calibration function C, energy S is minimized both beyond its theoretical extinction time and in the domain in which the approximation to which the operator Z corresponds is valid.

12/ A method according to any preceding claim, characterized in that for a collection of seismic traces sharing a common receiver, a calibration function is determined for the hydrophone-geophone pair of sensors that minimizes the energy of the signal S over all of the seismic traces.

13/ A method of offshore seismic prospecting by means of at least one pair of hydrophone-geophone sensors disposed on a water bottom, in which a sound source emits a signal into the water and the sensors at the water bottom pick up



hydrophone recordings H and geophone recordings G, the method being characterized in that the processing method for calibration according to any preceding claim is implemented and the data obtained thereby is processed to

5 deduce information about the geology of the subsoil.