

PATENT SPECIFICATION

L.185.063
DRAWINGS ATTACHED
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Date of Application (No. 9710/67) and filing Complete Specification: 21 March, 1967.
Application made in United States of America (No. 535,758) on 21 March, 1966.
Complete Specification Published: 18 March, 1970.

Index at acceptance:—H4 D(G1G1, G1G2, G3B, G3P, G4A5, G7P)
International Classification:—G 01 v 1/28

COMPLETE SPECIFICATION

Seismic Exploration

We, TEXAS INSTRUMENTS INCORPORATED, a Corporation organised according to the laws of the State of Delaware, United States of America, of 13500 North Central Expressway, Dallas, Texas, United States of America, do hereby declare this invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the removal of ghosts and reverberations from seismic data, and more particularly to the utilization of two seismic sources at different elevations with two-channel filtering based on auto and cross correlation of and between the two resulting seismic records.

In seismic exploration, seismic waves are generally generated by detonating an explosive charge at a selected depth in a relatively shallow borehole on land operations or at a suitable depth below the water surface in marine operations. Other modes of generation are also employed. The resultant seismic waves travel in all directions from the source. Waves which travel downwardly through the earth are in part reflected and transmitted by the successive interfaces between subsurface earth strata.

Reflected pulses of such energy, detected at the earth's surface at a plurality of seismic detector stations spaced from the location of the shot, are separately recorded on multi-trace seismograms in variable amplitude side-by-side traces or on magnetic tape as variable amplitude analog representations of the received signals or in digital form. The coincidence in time between the similar wavelets on all or most of the traces on such a recording has long been recognized by seismic observers as indicative of reflection from the same subsurface horizon. From such time-amplitude measurements, the depths of the subsurface reflecting horizons are determined.

By moving the location of the source and the detecting spread along a given traverse, the variations of the depth of the subsurface horizons underlying the traverse can be plotted to produce subsurface contour maps.

In carrying out such operations, seismic interpreters are troubled by waves recorded on a seismogram of unwanted noise energy which obscures signal energy. It has heretofore been recognized that one source of noise which renders a seismogram difficult to interpret arises by reason of the presence of ghosts and reverberation energy. More particularly, in marine operations, the seismic energy tends to reverberate in the zone bounded by the water-air interface at the top and the water-earth interface at the bottom of the marine area. Such reverberation is also encountered in some instances in the near-surface layers in land operations. Representative of the prior art dealing with certain aspects of improving seismic data in U.S. Patent No. 3,136,974 to Sirks, which represents an attempt to eliminate reverberations and ghosts. In addition, U.S. Patent No. 2,882,988 to Dobrin represents one method of eliminating the ghost or surface multiple.

Such prior art methods for removing ghosts have been dependent upon two-channel filters based exclusively on an assumption as to the nature of the physical model in which the basic shot wavelet spectrum and the ghost complex are identical for two shots except for a difference in the primary-ghost differential arrival times. Prior deghosting techniques have consisted essentially of inverting one shot in polarity relative to the other, time shifting to align the now opposite polarity ghosts, and summing and filtering appropriately to correct the resulting distortion to primary reflections. Where the actual data fits the assumed model, the techniques may be adequate, but when primaries or ghosts have different amplitudes or frequency spectra or

incorrectly measured time shifts between the two shots, and therefore do not fit the assumed model, results frequently are unsatisfactory.

- 5 The present invention provides, in seismic exploration where first and second seismic records represent seismic waves detected at the same receiving stations in response to seismic waves generated at different elevations at the same shot location, a method of combining said records, which includes: filtering a given

trace of said first seismic record by a first time domain filter f_1 to produce a first set of output signals, filtering the corresponding trace of said second seismic record by a second time domain filter f_2 to produce a second set of output signals, and summing said first and second sets of output signals to produce a combined output trace, with said filters f_1 and f_2 bearing the relationship to said traces substantially in accordance with the matrix equation:

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$$\begin{bmatrix} \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{12}(1)\phi_{22}(1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{12}(n)\phi_{22}(n) \end{bmatrix} \\ \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{21}(1)\phi_{22}(1) \end{bmatrix} & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{21}(n)\phi_{22}(n) \end{bmatrix} & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} \end{bmatrix} \begin{bmatrix} \begin{bmatrix} -1 \\ 0 \end{bmatrix} \\ \begin{bmatrix} f_{11} \\ f_{21} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} f_{1n} \\ f_{2n} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} -P_{11} \\ -P_{12} \end{bmatrix} \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \end{bmatrix}$$

- 25 where: $\phi_{11}(n)$ is the value of the auto correlation function for said given trace of said first record taken over a period of time $n\tau$ where n is the number of noted values of said given trace from which the autocorrelation function is obtained and τ is the time interval between successive noted values.

- 30 $\phi_{22}(n)$ is a similar value for said corresponding trace of said second record;
 35 $\phi_{12}(n)$ and $\phi_{21}(n)$ are the values of the respective cross correlation functions of the given and corresponding traces of the first and second records taken over a period of time $n\tau$ where n is the number of noted values of the given and corresponding traces of the first and second records from which the cross-correlation functions are obtained and τ is the time interval between successive noted values;
 40 $-1, 0, f_{11}, f_{21}, \dots, f_{1n}, f_{2n}$ correspond respectively with the weights applied to the

successive time delay signals from said given trace and from said corresponding trace; and

P_{11} and P_{12} are uniquely identified by the solution of said matrix equation.

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The invention also provides apparatus for stacking corresponding traces on first and second seismic records representing seismic waves detected at a receiving location in response to the generation, spaced in time, of seismic waves at two different elevations at the same sending location, said apparatus comprising: a first time domain filter f_1 for filtering a given trace from said first seismic record, a second time domain filter f_2 for filtering a corresponding trace from said second seismic record, and a summation means for producing a single output trace combining the outputs of said first and second time domain filters f_1 and f_2 , with said filters f_1 and f_2 bearing the relationship to said traces substantially in accordance with the matrix equation:

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$$\begin{bmatrix}
 \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{12}(1)\phi_{22}(1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{12}(n)\phi_{22}(n) \end{bmatrix} \\
 \begin{bmatrix} \phi_{11}(1)\phi_{12}(1) \\ \phi_{21}(1)\phi_{22}(1) \end{bmatrix} & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} \\
 \vdots & \vdots & \ddots & \vdots \\
 \begin{bmatrix} \phi_{11}(n)\phi_{12}(n) \\ \phi_{21}(n)\phi_{22}(n) \end{bmatrix} & \begin{bmatrix} \phi_{11}(n-1)\phi_{12}(n-1) \\ \phi_{21}(n-1)\phi_{22}(n-1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix}
 \end{bmatrix}
 \begin{bmatrix}
 \begin{bmatrix} -1 \\ 0 \end{bmatrix} \\
 \begin{bmatrix} f_{11} \\ f_{21} \end{bmatrix} \\
 \vdots \\
 \begin{bmatrix} f_{1n} \\ f_{2n} \end{bmatrix}
 \end{bmatrix}
 =
 \begin{bmatrix}
 \begin{bmatrix} -P_{11} \\ -P_{12} \end{bmatrix} \\
 \begin{bmatrix} 0 \\ 0 \end{bmatrix} \\
 \vdots \\
 \begin{bmatrix} 0 \\ 0 \end{bmatrix}
 \end{bmatrix}$$

where

$\phi_{11}(n)$ is the value of the auto correlation function for said given trace of said first record taken over a period of time $n\tau$ where n is the number of noted values of said given trace from which the auto correlation function is obtained and τ is the time interval between successive noted values;

$\phi_{22}(n)$ is a similar value for said corresponding trace of said second record;

$\phi_{12}(n)$ and $\phi_{21}(n)$ are the values of the respective cross correlation functions of the given and corresponding traces of said first and second records taken over a period of times $n\tau$, where n is the number of noted values of the given and corresponding traces of the first and second records from which the cross correlation functions are obtained and τ is the time interval between successive noted values;

$-1, 0, f_{11}, f_{21}, \dots, f_{1n}, f_{2n}$ correspond respectively with the weights applied to the successive time delayed signals from said given trace and from said corresponding trace; and

P_{11} and P_{12} are uniquely identified by the solution of said matrix equation.

It has been found that the present invention enables (a) the removal of ghosts using a two-channel system based on the data's actual correlation statistics, which include actual re-

lative amplitude, time shift and frequency content, rather than an assumed physical model; (b) deconvolution to be effected; and (c) primary-ghost correlation to be utilized.

By way of example, an embodiment of the invention will be described with reference to the accompanying drawings in which:

FIGURE 1 illustrates a seismic exploration source and detecting system; and

FIGURE 2 illustrates an analog processing system in accordance with the present invention.

Referring now to FIGURE 1, a seismic exploring system has been shown in which seismometers 11—14 and others are included in a spread 10 located along the earth's surface. They are located along a radial line which intersects the axis of a shot hole 15. The shot hole is relatively shallow as compared with the depth of subsurface reflecting interfaces 16 and 17.

It has been found that highly improved seismograms can be produced by stacking the data present on two or more individual seismograms where such individual seismograms (each having traces corresponding to the seismometers in spread 10) are produced with a variation between them in the shot depth or in the distance from the shot hole 15 to the spread 10: such a process may be referred to as "uphole stacking". In this operation, the spread 10 is maintained at a fixed location relative to the shot hole 15 while separate shots are successively detonated at different depths in the borehole 15 to produce two

separate and distinct seismograms. The seismograms are uniquely interrelated in that the reflection energy on each of the seismograms is dependent upon the depth and attitude of the same subsurface interfaces. By combining the two records, trace by trace, or as is commonly known in the art, by stacking the two seismograms to produce a single resultant seismogram, steps are taken in accordance with this invention to assure that the reflection energy on one of the seismograms will be added to the reflection energy on the other seismogram in reinforcing relation. The unwanted noise energy can be substantially eliminated by cancellation.

In FIGURE 1, the ray paths 20 represent the direct down-going energy or the primary energy. However, since the seismic energy travels in all directions from the shot, at least one important ray path is the path 21 and the surface reflection path 22. Energy traveling this path is generally known as the surface multiple. When the energy traveling past paths 21 and 22 is ultimately received in the detecting spread 10, the primary reflection is combined with the ghost of surface multiple to obscure and render difficult the interpretation of the seismogram. It is such unwanted noise that is to be eliminated by the use of an uphole stack. The present invention is directed to carrying out the uphole stacking process in such a manner as to optimize the signal enhancement and noise elimination.

In accordance with the present invention, two shots 31 and 32 are produced in shot point 15 from two different depths, shot 31 being deeper than the shallow shot 32. Two separate seismograms are produced, each having a plurality of traces corresponding in number with the geophones in the spread 10.

Consider two such seismic traces $x_1(t)$ and $x_2(t)$ produced from two shots 31 and 32 at different (deeper and shallower, respectively) depths in a shot hole. A subsurface impulse response will be referred to as $s(t)$, shot wavelets or filtering functions due to shot coupling and near-surface geological conditions for initially down-going primary energy will be referred to as $h_1(\tau)$ and $h_2(\tau)$ for shots 31 and 32, respectively, and ghost wavelets or filtering functions, including reflection coefficients for ghosts, the energy going initially up from the shot, then reflected down from interfaces above the shot will be noted as $g_1(\tau)$ and $g_2(\tau)$. (τ is to be taken in the usual sense as a variable time interval).

In the absence of filtering effects h and g , the primary energy from the deeper and shallower shots 31 and 32 would be $s(t)$ and $s(t - \Delta\tau_{12})$, respectively, and the ghost energy reflected from a surface above would be $s(t - \tau_1)$ and $s(t - \Delta\tau_{12} - \tau_2)$ where τ_1 and $2\tau_2$ are respectively the times for the upgoing impulses from the deeper and shallower shots to leave the respective shot locations, reflect from the surface, and return to the respective shot locations as down-going energy.

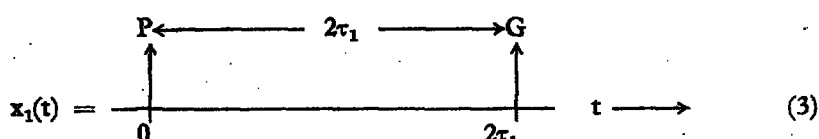
Then without filtering effects h and g ,

$$x_1(t) = s(t) + s(t - 2\tau_1) \quad (1)$$

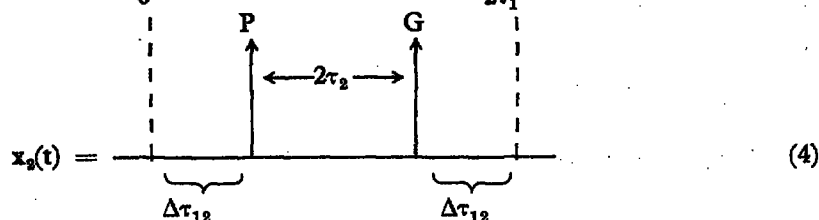
$$x_2(t) = s(t - \Delta\tau_{12}) + s(t - \Delta\tau_{12} - 2\tau_2) \quad (2)$$

where: $\Delta\tau_{12} = \tau_1 - \tau_2$.

This may be expressed in the form:



$$x_1(t) = \quad (3)$$



$$x_2(t) = \quad (4)$$

If the filtering effects h and g are included, Equations (1) and (2) become:

$$x_1(t) = s(t) * h_1(\tau) + s(t - 2\tau_1) * g_1(\tau) \quad (5)$$

$$x_2(t) = s(t - \Delta\tau_{12}) * h_2(\tau) + s(t - \Delta\tau_{12} - 2\tau_2) * g_2(\tau) \quad (6)$$

This may be represented as:

$$x_1(t) = s(t) * y_1(\tau) \quad (7)$$

$$x_2(t) = s(t - \Delta\tau_{12}) * y_2(\tau) \quad (8)$$

where: $y_1(\tau) = h_1(\tau) + \delta(\tau - 2\tau_1) * g_1(\tau)$;

$$y_2(\tau) = h_2(\tau) + \delta(\tau - 2\tau_2) * g_2(\tau)$$

and $y_1(\tau) = 0$ when $\tau < 0$,

$$y_2(\tau) = 0 \text{ when } \tau < 0.$$

and where the symbol $*$ denotes convolution.

Hence the recorded trace at any time t consists of initial energy representing $s(t)$ plus some combination of $s(t - \tau)$ for previous times (τ) earlier.

5 Seismic interpreters are interested almost exclusively only in that part of a trace that is not dependent on previous time, or in other words, is not predictable on the basis 10 of previous events. By this invention, there

is removed from the trace in (as will be seen later) at least mean square error sense, any dependence on the past of $x_1(t)$ or $x_2(t)$ by using the correlation of and between $x_1(t)$ and $x_2(t)$ to predict $x_1(t)$ from the past (relative to time t) of both $x_1(t)$ and $x_2(t)$ and subtracting that prediction from the trace to give a function which at any time t could be expressed as:

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$$e_1(t) = x_1(t) * [\delta(\tau) - f_1(\tau)] - x_2(t) * f_2(\tau) \quad (9)$$

where: $f_1(\tau) = 0$ when $\tau \leq 0$;

and $f_2(\tau) = 0$ when $\tau \leq 0$.

Here $e(t)$ represents that part of $x_1(t)$ that is not predictable on the basis of the past of x_1 or x_2 , hence could be called a "two channel prediction error". Minimizing the prediction error corresponds to removing from $x_1(t)$ as much of it as is a function of (correlation with) the past.

The filters $f_1(t)$ and $f_2(t)$ are found as follows. The two channels $x_1(t)$ and $x_2(t)$ are first employed based on the assumption that the desired output $e(t)$ is that part of $x_1(t)$

that is not predictable (the prediction error) on the basis of the past of either $x_1(t)$ or

$x_2(t)$. Then, if the function $x_1(t)$ is an estimate or prediction of $x_1(t)$ based on the past of $x_1(t)$ and $x_2(t)$, and $x_1(t)$ and $x_2(t)$ are sampled at discrete equally spaced time points represented as x_{1t} and x_{2t} where t is a time index and using N points in the past of x_{1t} and x_{2t} as the prediction basis,

$$x_{1t} = x_{1(t-1)}f_{11} + x_{2(t-1)}f_{21} + x_{1(t-2)}f_{12} + x_{2(t-2)}f_{22} + \dots + x_{1(t-n)}f_{1n} + x_{2(t-n)}f_{2n} \quad (10)$$

or stated otherwise,

$$x_{1t} = \sum_{n=1}^N x_{1,t-n}f_{1,n} + x_{2,t-n}f_{2,n} \quad (11)$$

In this case, the prediction error trace is:

$$e_t = x_{1t} - \hat{x}_{1t} = x_{1t} - \sum_{n=1}^N x_{1,t-n}f_{1,n} - x_{2,t-n}f_{2,n} \quad (12)$$

If $e(t)$ is minimized on a mean square basis,

$$\text{then } e_t x_{1,t-n} = 0 \text{ for } n > 0, \quad (13)$$

$$\text{and } e_t x_{2,t-n} = 0 \text{ for } n > 0; \quad (14)$$

where: $(\quad)$ indicates a time average.

This will be true since any non-zero time averaged product between the output and either of the input's past values would indicate that there remained some predictability between e_t and either x_{1t} or x_{2t} .

If the quantities,

$$x_{1,t} x_{1,t-m} = \phi_{11}(m) \quad (15)$$

$$x_{1,t} x_{2,t-m} = \phi_{12}(m) \quad (16)$$

$$x_{2,t} x_{2,t-m} = \phi_{22}(m) \quad (17)$$

$$x_{2,t} x_{1,t-m} = \phi_{21}(m) \quad (18)$$

the following relationships are true:

$$e_t x_{1,t-m} = \sum_{n=1}^N x_{1,t} x_{1,t-m} - x_{1,t-n} x_{1,t-m} f_{1,n} - x_{2,t-n} x_{1,t-m} f_{2,n} = 0 \quad (19)$$

$$\overline{e_t x_{1,t-m}} = \sum_1^N \phi_{11}(m) - \phi_{11}(n-m) f_{1,n} - \phi_{21}(n-m) f_{2,n} = 0 \quad (20)$$

$$\overline{e_t x_{2,t-m}} = \sum_1^N \phi_{12}(m) - \phi_{12}(n-m) f_{1,n} - \phi_{22}(n-m) f_{2,n} = 0 \quad (21)$$

It will be seen that since there should be no correlation between the error trace e_t and the prediction $\hat{x}_1(t)$, i.e., $\overline{e_t \hat{x}_{1,t}} = 0$, the following relationship will be true:

$$P_{11} = \overline{e_t^2} = \overline{e_t (\hat{x}_{1,t} - x_{1,t})} = \overline{e_t x_{1,t}} = \sum_1^N \phi_{11}(0) - \phi_{11}(n) f_{1,n} - \phi_{21}(n) f_{2,n} = \overline{e_t^2} \quad (22)$$

and

$$P_{12} = \overline{e_t x_{2,t}} = \sum_1^N \phi_{12}(0) - \phi_{12}(n) f_{1,n} - \phi_{22}(n) f_{2,n} = P_{12} \quad (23)$$

From Equation (22) it will be understood that P_{11} is an auto correlation coefficient in terms of the power in the output or error trace e_t (after filtration and summation). More particularly, it is the cross correlation between the error signal e_t and $\hat{x}_{1,t}$. The quantity P_{11} is a scalar quantity produced in accordance with the relations set out in Equation (22). P_{12} is a cross correlation factor, i.e., the cross power between the error signal e_t and the second trace $x_{2,t}$ and is likewise a scalar quantity. Equations (22) and (23) can then be expressed in matrix form:

$$\begin{bmatrix} \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{12}(1)\phi_{22}(1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{12}(n)\phi_{22}(n) \end{bmatrix} \\ \begin{bmatrix} \phi_{11}(1)\phi_{12}(1) \\ \phi_{21}(1)\phi_{22}(1) \end{bmatrix} & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{bmatrix} \phi_{11}(n)\phi_{12}(n) \\ \phi_{21}(n)\phi_{22}(n) \end{bmatrix} & \begin{bmatrix} \phi_{11}(n-1)\phi_{12}(n-1) \\ \phi_{21}(n-1)\phi_{22}(n-1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} \end{bmatrix} \begin{bmatrix} -1 \\ 0 \\ f_{11} \\ f_{21} \\ \vdots \\ f_{1n} \\ f_{2n} \end{bmatrix} = \begin{bmatrix} -P_{11} \\ -P_{12} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad (24)$$

where: $\phi_{11}(n)$ is the value of the auto correlation function of trace x_1 for $\tau = n$;
 $\phi_{22}(n)$ is a similar value based on trace x_2 ;
 $\phi_{12}(n)$ and $\phi_{21}(n)$ are the values of the respective cross correlation functions of traces x_1 and x_2 for $\tau = n$;
 $-1, 0, f_{11}, f_{21}, \dots, f_{1n}, f_{2n}$ correspond respectively to the weights applied to the successive members of the two sets of seismic traces; and
 P_{11} and P_{12} are uniquely identified by the solution of the equation.

Since the number of unknowns in Equation (24) does not exceed the number of equations, a solution is possible. The solution may be determined for the unknowns by a brute force method. Preferably, however, the equations can be evaluated to produce physical representations of the unknowns. More simply, evaluation can be effected by a known procedure, such as that outlined by Ralph Wiggins in an article entitled "Recursive Solution to the Multi-Channel Filtering Problem", in *Journal of Geophysical Research*, Vol. 70, No. 8, to yield the multi-channel prediction error filters f_{1n} and f_{2n} , plus the output power e_{1t}^2 and the correlation coefficient P_{12} between $e_1(t)$ and $x_2(t)$.

Based on the foregoing, a method of generating the prediction error function involves:

A. Using sampled data and digital computer:

1. Sample $x_1(t)$ and $x_2(t)$ obtaining x_{1t} and x_{2t} , respectively.
2. Generate physical functions representative of the correlation coefficients $\phi_{11}(n)$, $\phi_{22}(n)$, $\phi_{12}(n)$, and $\phi_{21}(n)$.
3. Generate physical functions representative of the matrix equations above to obtain the f_{1n} and f_{2n} values.
4. Generate a function representative of

$$e_{1t} = x_{1t} - [\Sigma(x_{1,t-n} * f_{1n} + x_{2,t-n} * f_{2n})]; \text{ or} \quad (25)$$

B. Using analog techniques:

1. Use multipliers, delay lines, and integrators to measure estimates of $\phi_{11}(n)$, $\phi_{22}(n)$, $\phi_{12}(n)$, and $\phi_{21}(n)$.
2. Generate functions representative of the solution to the matrix equations for delay line filters $f_1(\tau)$ and $f_2(\tau)$.
3. Apply the delay line filters $f_1(\tau)$ and $f_2(\tau)$ as shown in FIGURE 2.

Inasmuch as any ghosts, reverberation or shot wavelets remaining in the data would constitute a dependence on past events in x_1 or x_2 , and this dependence is removed on a least mean square error basis by the process described, and inasmuch as any relative scaling of ghosts and/or primaries between the two shots $x_1(t)$ and $x_2(t)$ is implicit in the correlation functions hence reflected in the matrix equations for f_{1t} and f_{2t} , then it is clear that any such ghost reverberations and shot wavelets are effectively removed by the present invention without requiring a priori

knowledge or assumption about their existence or relative scaling between shots.

In the analog system shown in FIGURE 2, a drum 40 is driven by a motor 41 at a uniform speed so that trace $x_1(t)$ cyclically will be produced. By way of example, the resultant signal on output channel 42 may be representative of the seismic waves detected by seismometer 11, FIGURE 1, and recorded on trace 43 of the upper record 44 dependent upon waves produced by detonation of an explosive charge 31. Simultaneously, a signal $x_2(t)$ appears on channel 45. This signal is

representative of the waveforms similarly detected by seismometer 11 and recorded on channel 46 of the record 47 in response to waves produced by detonation of an explosive charge 32.

The channel 42 is connected to a multiplier 50 and to an adjustable delay unit 51 whose output also is connected to multiplier 50. The output of multiplier 50 is connected by way of a switch 52 to an integrator 53. Switch 52 is coupled by way of a linkage 54 to the drive on drum 40 to close the switch 52 for a time gate t_1 to t_2 as may be selected for producing the auto correlation function of the signal $x_1(t)$. The output of the integrator 53 is connected to a suitable registering unit 55. By adjusting the delay line 51 between successive cycles of the drum 40, the complete auto correlation function ϕ_{11} may be produced and made available at the output of the registering unit 55.

Similarly, the output channel 45 is connected to a multiplier 60 and to a delay unit 61. The output of multiplier 60 is connected by way of a switch 62 to an integrator 63, whose output is connected to a registering device 65. The switch 62 is coupled by way of linkage 64 to the drive for the drum 40. Thus, in the register 65, the auto correlation function ϕ_{22} for the signal $x_2(t)$ is available with limits as set by timer 69.

Channel 42 is also coupled to a third multiplier 70. The channel 45 is connected to the input of a third delay unit 71. The multiplier 70 is coupled by way of switch 72 to an integrator 73. The output of the integrator is connected to a register or storage element 75. Switch 72 is coupled by way of linkage 74 to the drive for the drum 40. Thus, the cross correlation function ϕ_{12} between the two traces $x_1(t)$ and $x_2(t)$ is available at the unit 75. It should be understood that the cross correlation function ϕ_{21} is the time reverse of the cross correlation function ϕ_{12} and would be derived by a reversal of the time coefficients for ϕ_{12} in a suitable control structure, such as a computer controller. Alternatively, the cross correlation function ϕ_{21} could be developed in a manner analogous to the development of the auto correlation functions ϕ_{11} and ϕ_{22} and the cross correlation function ϕ_{12} by coupling channel 42 to a fourth multiplier (not shown) through a fourth delay unit (not shown) and coupling the chan-

nel 45 directly to the fourth multiplier. It will be understood that the functions $K\phi_{11}(\tau)$, $K\phi_{22}(\tau)$, and $K\phi_{12}(\tau)$ shown in Figure 2 respectively represent the outputs of units 55, 65 and 75 for a particular delay (τ) in the delay unit 51, 61, or 71 corresponding thereto. In this respect, the auto correlation function of $\phi_{11}(n)$ for trace $x_1(t)$, for example, is the value of the auto correlation function obtained for a particular delay $n(\tau)$ in the delay unit 51. The cross correlation functions and the auto correlation functions thus produced are available for determination of the weights to be given to the filter elements.

Further to illustrate the use of the cross correlation and auto correlation functions, it will be assumed that the signal $x_1(t)$ is stored on drum 80 and signal $x_2(t)$ is stored on magnetic drum 81. A first pick-up head 83 senses the signal $x_1(t)$ and applies the latter signal by way of channel 84 to a summation unit 85. Similarly, heads 86, 87, 88, ... pick up representations of the signal $x_1(t)$ delayed by successive time intervals τ , each of these time intervals being adjusted to be equal (for any given set of seismic data) to the delay τ in delay units 51, 61, 71 for that set of data. The time-delayed representations of the signal $x_1(t)$ are then applied to a summation unit 90 by way of attenuators 91-94, respectively. The output of the summation unit 90 is applied by way of channel 95 to the summation unit 85.

Similarly, the signal $x_2(t)$ is recorded on drum 81 and is sensed by detecting heads 96, 97, ... 99. The latter signals are then applied by way of attenuators 101, 102, and 103 to a summation unit 104. The output of summation unit 104 is applied by way of channel 105 to the summation unit 85. A computer-controller 110, coupled at its input to units 55, 65, and 75, is operatively connected by linkages 111, 112, 113, ... 114 to the attenuators 91-94, which operate on the trace $x_1(t)$. The computer also is operatively connected by linkages 115-117 to attenuators 101-103 which operate on trace $x_2(t)$. The output from summation unit 85 is then stored on drum 40 by way of channel 106. Thus, there is produced on the output channel 106 leading from the summation unit, the signal

$$e_{1t} = x_{1t} - [\Sigma(x_{1,t-n} * f_{1n} + x_{2,t-n} * f_{2n})].$$

The computer-controller 110, (which in the system shown in Fig. 2 is of analog form but which, in other systems, may be of digital form) is described in its essential character by Equation (24). The computer-controller is of the type generally well known in the art

as a sampled data system and periodic controller. More particularly, it may be of the type shown in *Handbook of Automation, Computation, and Control*, Volume 1, by Grabbe et al., John Wiley & Sons, 1958, at Chapter 26, wherein analog, digital and combined

systems are described. The process controller, in terms of the systems illustrated on page 26—05 may control the filtering where the "process" of such system is involved in the operation of the drums 80 and 81 with one control actuator for each of the channels involved in the present filtering process. The "periodic switch" will be actuated by the linkage 119 of FIGURE 2 thereby to adjust the attenuators at the end of each cycle of evaluation of the auto and cross correlation functions. The attenuators will be adjusted, for example, as generally indicated at page 26—05 of the above *Handbook*, wherein a motor is driven in a balanceable circuit for each attenuator in FIGURE 2 in dependence upon an error signal representing one element f in the solution of Equation (24) for adjustment of a given attenuator.

It will be recognized, however, that the analog elements of FIGURE 2 may be entirely eliminated except as is necessary to provide input traces to a computer. The computer itself may be programmed successively to produce and store physical representations of the necessary cross and auto correlation functions, physical representations of the solution to Equation (24), and physical representations of the stacked trace resulting from filtering and summing in accordance with Equation (25).

In FIGURE 2, the dotted intervals between playback heads 88 and 89 and between heads 97 and 99 indicate that ordinarily many more elements will be employed in the time domain filter than are represented by the five channels on drum 80 and the three channels on drum 81. In practice, the number of elements employed for each trace, i.e., the number represented by the pick-up heads 86—89, has been in the range of 18 to 24. The number that will be employed is necessarily related to the capacity of the processing equipment available and must be balanced against the economics involved. The tape transports shown in FIGURE 2 may be of a suitable type equipped to provide a plurality of time delayed representations of each of the traces $x_1(t)$ and $x_2(t)$.

Auto and cross correlation function generator systems have been shown only schematically in FIGURE 2. Such generators are in general well known. One unit suitable for use in connection with the present invention is described in U.S. Patent No. 2,794,965, issued June 4, 1957, to W. J. Yost. Referring now to said patent, there is disclosed, in Figure 4, an apparatus for obtaining the auto correlation function and a description thereof in column 6, lines 15—66. The seismic trace is recorded on the reproducible record 100 and the auto correlation function coefficients are produced on the chart 113. The spacing between the detectors 102, 103, etc. defines the sampling interval τ , as disclosed by Yost.

It is to be understood that each record to be stacked may be in the form of a magnetic tape on which are stored 24 or more traces of raw seismic data obtained from a linear equi-spaced seismometer array of the type shown in FIGURE 1. It may be a variable area photographic recording or other recording of phonographically reproducible form as well known in the seismic art. The traces may be processed as electrical signals obtained directly from data stored on magnetic tape in analog form or obtained from a suitable storage device in digital form. Two multi-trace records related by reason of detection in a common spread of seismic waves successively produced at different depths at the same shot location may thus be stacked on a trace-by-trace basis.

The invention has been described primarily as applied to processing data obtained from land seismic exploration. However, the invention may also be applied to data obtained from sampling acoustic waves detected in marine seismic exploration wherein underwater acoustic energy from submerged shots is successively received by a hydrophone array. It will be apparent that the data stacked in accordance with the invention may be derived from a two-dimensional seismic array. It will further be apparent that while the description has been directed primarily to stacking two seismic traces, more than two seismic traces obtained for the same array and shot location may be stacked by sequentially processing successive pairs of records.

It is to be understood that the method and apparatus above described for carrying out the invention are to be taken as illustrative only. Numerous other arrangements may be employed by those skilled in the art in order to achieve the beneficial results of the present invention. While the operation is most expeditiously accommodated through the instrumentality of a digital computer, it will be recognized that it may be accommodated in analog form, as above described and illustrated.

A suitable digital computer for generating the filter weights may be the IBM 7074 Digital Computer which includes a peripheral computer, the IBM 1401, for generating the program for the IBM 7074 to satisfy Equation (24).

The input data applied to said IBM computer is digitally coded auto and cross correlation function coefficients such as may be stored by units 55, 65, and 75. The program for said IBM computer is obtained by writing the Equation (24) in Fortran language and arranging the results on IBM 866424 cards which are then fed into the IBM 1401 peripheral computer for generating the program. The digitally coded values of the top elements of the two column matrices of Equation (24) are also included in the program. In this

manner, the IBM 7074 computer is used to generate the filter weights defined by Equation (24).

However, it is pointed out that other digital computers may be used to generate the filter weights, for example, the IBM 704, the IBM 1620, the General Electric 225, or the Control Data 1604 Digital Computer. The procedures for programming these computers to perform the arithmetic operations designated by Equation (24) are conventional to those skilled in the art.

The invention has heretofore been described in conjunction with analog seismic traces $x(t)$ obtained from a seismometer output or from a magnetic tape recording and deriving therefrom its auto and cross correlation functions by the modified apparatus disclosed in the Yost patent. However, this should not be construed in a limiting sense, since the analog seismic trace may be converted into digital form by an analog-to-digital converter, recorded on a magnetic tape and thereafter applied as the input to a digital computer such as the IBM 7074 for generating the autocorrelation function coefficients ϕ . In this regard, the input seismic trace is a digital signal or signals representative of seismic waves as detected or effectively detected at a seismometer location.

When the seismic traces $x_1(t)$ and $x_2(t)$ are represented digitally, the sampling interval used in the analog-to-digital converter is commonly referred to as Δt and the number of sample points along the trace is n , thereby defining the time interval of the seismic trace (t_1 to t_2) of FIGURE 2 as $n\Delta t$. At (which

is conventionally used to designate the sampling interval in the analog-to-digital converter) has no relation to the expression Δt_{12} appearing earlier in this Specification. The sampling interval τ of the auto correlation function is usually an integral multiple of Δt .

The digitally coded auto correlation function coefficients ϕ at the output of the IBM 7074 computer may then be applied to the input of the computer with the appropriate program as previously described in order to generate the filter weights f . Additionally, after the weights f have been generated, they may be incorporated into the program of the computer in order to process the input digitally coded traces $x_1(t)$ and $x_2(t)$ as functionally illustrated by the analog operation in FIGURE 2.

WHAT WE CLAIM IS:—

1. In seismic exploration where first and second seismic records represent seismic waves detected at the same receiving stations in response to seismic waves generated at different elevations at the same shot location, a method of combining said records, which includes: filtering a given trace of said first seismic record by a first time domain filter f_1 to produce a first set of output signals, filtering the corresponding trace of said second seismic record by a second time domain filter f_2 to produce a second set of output signals, and summing said first and second sets of output signals to produce a combined output trace, with said filters f_1 and f_2 bearing the relationship to said traces substantially in accordance with the matrix equation:

$$\begin{bmatrix} \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{12}(1)\phi_{22}(1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{12}(n)\phi_{22}(n) \end{bmatrix} \\ \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{21}(1)\phi_{22}(1) \end{bmatrix} & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{21}(n)\phi_{22}(n) \end{bmatrix} & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{21}(n-1)\phi_{22}(n-1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} \end{bmatrix} \begin{bmatrix} \begin{bmatrix} -1 \\ 0 \end{bmatrix} \\ \begin{bmatrix} f_{11} \\ f_{21} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} f_{1n} \\ f_{2n} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} -P_{11} \\ -P_{12} \end{bmatrix} \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \end{bmatrix}$$



manner, the IBM 7074 computer is used to generate the filter weights defined by Equation (24).

However, it is pointed out that other digital computers may be used to generate the filter weights, for example, the IBM 704, the IBM 1620, the General Electric 225, or the Control Data 1604 Digital Computer. The procedures for programming these computers to perform the arithmetic operations designated by Equation (24) are conventional to those skilled in the art.

The invention has heretofore been described in conjunction with analog seismic traces $x(t)$ obtained from a seismometer output or from a magnetic tape recording and deriving therefrom its auto and cross correlation functions by the modified apparatus disclosed in the Yost patent. However, this should not be construed in a limiting sense, since the analog seismic trace may be converted into digital form by an analog-to-digital converter, recorded on a magnetic tape and thereafter applied as the input to a digital computer such as the IBM 7074 for generating the autocorrelation function coefficients ϕ . In this regard, the input seismic trace is a digital signal or signals representative of seismic waves as detected or effectively detected at a seismometer location.

When the seismic traces $x_1(t)$ and $x_2(t)$ are represented digitally, the sampling interval used in the analog-to-digital converter is commonly referred to as Δt and the number of sample points along the trace is n , thereby defining the time interval of the seismic trace (t_1 to t_2) of FIGURE 2 as $n\Delta t$. Δt (which

is conventionally used to designate the sampling interval in the analog-to-digital converter) has no relation to the expression $\Delta\tau_{12}$ appearing earlier in this Specification. The sampling interval τ of the auto correlation function is usually an integral multiple of Δt .

The digitally coded auto correlation function coefficients ϕ at the output of the IBM 7074 computer may then be applied to the input of the computer with the appropriate program as previously described in order to generate the filter weights f . Additionally, after the weights f have been generated, they may be incorporated into the program of the computer in order to process the input digitally coded traces $x_1(t)$ and $x_2(t)$ as functionally illustrated by the analog operation in FIGURE 2.

WHAT WE CLAIM IS:—

1. In seismic exploration where first and second seismic records represent seismic waves detected at the same receiving stations in response to seismic waves generated at different elevations at the same shot location, a method of combining said records, which includes: filtering a given trace of said first seismic record by a first time domain filter f_1 to produce a first set of output signals, filtering the corresponding trace of said second seismic record by a second time domain filter f_2 to produce a second set of output signals, and summing said first and second sets of output signals to produce a combined output trace, with said filters f_1 and f_2 bearing the relationship to said traces substantially in accordance with the matrix equation:

$$\begin{bmatrix} \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{12}(1)\phi_{22}(1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{12}(n)\phi_{22}(n) \end{bmatrix} \\ \begin{bmatrix} \phi_{11}(1)\phi_{12}(1) \\ \phi_{21}(1)\phi_{22}(1) \end{bmatrix} & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{bmatrix} \phi_{11}(n)\phi_{12}(n) \\ \phi_{21}(n)\phi_{22}(n) \end{bmatrix} & \begin{bmatrix} \phi_{11}(n-1)\phi_{12}(n-1) \\ \phi_{21}(n-1)\phi_{22}(n-1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} \end{bmatrix} \begin{bmatrix} \begin{bmatrix} -1 \\ 0 \end{bmatrix} \\ f_{11} \\ f_{21} \\ \vdots \\ f_{1n} \\ f_{2n} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} -P_{11} \\ -P_{12} \end{bmatrix} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

where:

- 5 $\phi_{11}(n)$ is the value of the auto correlation function for said given trace of said first record taken over a period of time $n\tau$ where n is the number of noted values of said given trace from which the auto correlation function is obtained and τ is the time interval between successive noted values;
- 10 $\phi_{22}(n)$ is a similar value for said corresponding trace of said second records;
- 15 $\phi_{12}(n)$ and $\phi_{21}(n)$ are the values of the respective cross correlation functions of the given and corresponding traces of the first and second records taken over a period of time $n\tau$ where n is the number of noted values of the given and corresponding traces of the first and second records from which the cross-correlation functions are obtained and τ is the time interval between successive noted values;
- 20 $-1, 0, f_{11}, f_{21}, \dots, f_{1n}, f_{2n}$ correspond respectively with the weights applied to the successive time delayed signals from said given trace and from said corresponding trace; and
- 25 P_{11} and P_{12} are uniquely identified by the solution of said matrix equation.

- 30 2. A method as set forth in Claim 1, in which the seismic waves are generated at

spaced time intervals and at two different elevations in the same shot hole.

3. A method as set forth in Claim 1 or Claim 2, further including producing a first record of seismic waves generated at a first elevation at a source location and detected at a receiving station spaced from said source location, and generating a second record of seismic waves generated at a second elevation at said source location and detected at said receiving station prior to the filtering of a given trace of the first seismic record and the corresponding trace of the second seismic record by said first and second time domain filters f_1 and f_2 , respectively.

4. Apparatus for stacking corresponding traces on first and second seismic records representing seismic waves detected at a receiving location in response to the generation, spaced in time, of seismic waves at two different elevations at the same sending location, said apparatus comprising: a first time domain filter f_1 for filtering a given trace from said first seismic record, a second time domain filter f_2 for filtering a corresponding trace from said second seismic record, and a summation means for producing a single output trace combining the outputs of said first and second time domain filters f_1 and f_2 , with said filters f_1 and f_2 bearing the relationship to said traces substantially in accordance with the matrix equation:

$$\begin{bmatrix} \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \begin{bmatrix} \phi_{11}(1)\phi_{21}(1) \\ \phi_{12}(1)\phi_{22}(1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n)\phi_{21}(n) \\ \phi_{12}(n)\phi_{22}(n) \end{bmatrix} \\ \begin{bmatrix} \phi_{11}(1)\phi_{12}(1) \\ \phi_{21}(1)\phi_{22}(1) \end{bmatrix} & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(n-1)\phi_{21}(n-1) \\ \phi_{12}(n-1)\phi_{22}(n-1) \end{bmatrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{bmatrix} \phi_{11}(n)\phi_{12}(n) \\ \phi_{21}(n)\phi_{22}(n) \end{bmatrix} & \begin{bmatrix} \phi_{11}(n-1)\phi_{12}(n-1) \\ \phi_{21}(n-1)\phi_{22}(n-1) \end{bmatrix} & \dots & \begin{bmatrix} \phi_{11}(0)\phi_{21}(0) \\ \phi_{12}(0)\phi_{22}(0) \end{bmatrix} \end{bmatrix} \begin{bmatrix} \begin{bmatrix} -1 \\ 0 \end{bmatrix} \\ \begin{bmatrix} f_{11} \\ f_{21} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} f_{1n} \\ f_{2n} \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} -P_{11} \\ -P_{12} \end{bmatrix} \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \end{bmatrix}$$

where:

- 65 $\phi_{11}(n)$ is the value of the auto correlation function for said given trace of said first record taken over a period of

time $n\tau$ where n is the number of noted values of said given trace from which the auto correlation function is obtained and τ is the time interval between successive noted values;



$\phi_{22}(n)$ is a similar value for said corresponding trace of said second record;

$\phi_{12}(n)$ and $\phi_{21}(n)$ are the values of the respective cross correlation functions of the given and corresponding traces of said first and second records taken over a period of time $n\tau$ where n is the number of noted values of the given and corresponding traces of the first and second records from which the cross correlation functions are obtained and τ is the time interval between successive noted values;

$-1, 0, f_{11}, f_{21}, \dots, f_{1n}, f_{2n}$ correspond respectively with the weights applied to the successive time delayed signals from said given trace and from said corresponding trace; and

P_{11} and P_{12} are uniquely identified by the solution of said matrix equation.

5. Apparatus as set forth in Claim 4, wherein said first and second time domain filters f_1 and f_2 are included in an attenuation means; said apparatus further comprising a first delay means providing simultaneously a plurality of outputs each of which represents the value of a selected trace on said first

seismic record at predetermined different instants of time, and a second delay means providing simultaneously a plurality of outputs each of which represents the value of a selected trace on said second seismic record at predetermined different instants of time; said attenuation means being individual to said outputs for receiving said outputs and multiplying each by a predetermined individual constant as represented by the respective f values of said matrix equation, and means for registering the combined outputs as provided by said summation means as a function of the time scale on said seismic records.

6. A method according to claim 1, substantially as described herein with reference to the accompanying drawings.

7. Apparatus for stacking corresponding traces on first and second seismic records representing seismic waves detected at a receiving location, substantially as described herein and as shown in Figure 2 of the accompanying drawings.

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