

PATENT SPECIFICATION

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DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Space Averaged Dynamic Correlation Analysis of Seismic Signals

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 processing of electrical signal representations of records of seismic energy and more particularly, in one aspect, relates to the use of space averaging to obtain a unique dynamic correlation among seismic signals.

The present invention is particularly useful in connection with known common depth point (CDP) seismic exploration methods, such as disclosed in U.S. Patent No. 2,732,906 to Mayne. It is also useful in enhancement and analysis of seismic traces forming seismic section displays.

Data processing systems are now available which render useful the application of many advanced data processing methods to long-time series, particularly those methods which involve autocorrelation functions and crosscorrelation functions. Such functions have been described, for example, by Norbert Wiener in his publication entitled *Extrapolation, Interpolation, and Smoothing of Stationary Time Series*, John Wiley & Sons, Inc. (1950), page 5, Equation 0.424. An example of an application of Wiener's disclosure to seismic data processing is disclosed in U.S. Patent No. 2,927,656 to Feagin et al.

The present invention will be described first in connection with treatment of CDP seismograms corrected for normal moveout (NMO). As thus employed, the invention relates to generation and use of crosscorrelation functions in a new and unique manner for the analysis of seismograms produced in CDP seismic exploration and more particularly is directed to the production of dynamic correlations for sets of different CDP space lags to permit simple velocity filtering advantageously to be used to separate the various velocity components present in the set of seismic data.

The present invention provides a method of generating a space averaged correlation electrical signal from records of seismic energy obtained by generating seismic energy at a sending station and recording the seismic energy following common depth point reflection, which method comprises generating electrical seismic signal representations of said records; cross correlating commonly centered limited time gates of a first pair of said electrical signal representations to produce a first crosscorrelation electrical signal, which first pair of electrical signal representations is associated with seismic energy travel including reflections from the same reflecting horizon along two paths of different geometries; crosscorrelating corresponding commonly centered limited time gates of a second pair of said electrical signal representations to produce a second crosscorrelation electrical signal, which second pair of electrical signal representations is associated with seismic energy travel including reflection from the said reflecting horizon along two paths of different geometries and summing the first and second cross-

correlation electrical signals to produce a space averaged output correlation electrical signal.

In one embodiment, in which the difference between the geometries of the paths of travel associated with the first pair of electrical seismic signal representations is the same as the difference between the geometries of the paths of travel associated with the second pair of electrical seismic signal representations, the electrical seismic signal representations are derived from at least three common depth point seismic records, the first pair of electrical seismic signal representations being derived from a first pair of the records and the second pair of electrical seismic signal representation being derived from a second pair of the records, the travel paths associated with the first pair of electrical seismic signal representations including reflection from a common first point on the reflecting horizon and the travel paths associated with the second pair of electrical seismic signal representations including reflection from a second point on the reflecting horizon spaced from the first point.

The invention also provides a method of producing time and space averaged correlation electrical seismic signals from a suite of common depth point seismic energy records obtained by common depth point seismic exploration techniques, which comprises generating sets of primary crosscorrelation signals by selectively crosscorrelating limited time gates of a plurality of sets of pairs of electrical seismic signal representations generated from all the records; wherein each primary correlation signal is generated by crosscorrelation of commonly centered limited time gates of a particular pair of electrical seismic signal representations wherein each pair of electrical seismic signal representations in the sets includes components representing seismic energy which has travelled to and from subsurface reflecting points over a corresponding pair of paths of first and second geometries respectively; and wherein there are space lags between the first and second geometries for any one set and the first and second geometries of any other set, whereby the primary correlation signals in one set differ from those in another set in accordance with the said space lags, summing the primary correlation signals in each of the sets to produce a set of output correlation electrical signals, and in which the output correlation signals are stored as a visual display on a common correlation time lag scale in the order of increasing space lag.

Further, the invention provides apparatus for producing a space averaged correlation signal from at least three common depth point seismic trace records which include electrical signals representing seismic energy travel along paths having geometries including reflection from a reflecting horizon, which comprises, means operable simultaneously to reproduce pairs of the said records, means responsive to commonly centred limited time gates of a first pair of electrical seismic signals derived by the reproducing means from a first pair of the records and associated with travel paths including reflection from a first reflection point and having first and second geometries respectively to produce a first primary crosscorrelation electrical signal, means responsive to commonly centred limited time gates of a second pair of electrical seismic signals derived by the reproducing means from a second pair of the records and associated with travel paths having the said first and second geometries but reflected from a second reflection point to produce a second primary crosscorrelation electrical signal, and means operable to sum the first and second primary crosscorrelation electrical signals to produce an output correlation electrical signal.

By way of example, embodiments of the invention will be described in greater detail with reference to the accompanying drawings, in which:

FIGURE 1 illustrates an off-end common depth point seismic surveying operation;

FIGURE 2 illustrates a system for producing space and time averaged correlation functions from the common depth point signals produced in accordance with FIGURE 1;

FIGURE 3 illustrates the time and space averaged crosscorrelations produced in accordance with FIGURE 2;

FIGURE 4 illustrates selection of time gates for production of the crosscorrelation functions;

FIGURE 5 illustrates results of a rotating wide band velocity filter operation on the signals shown in FIGURE 3;

FIGURE 6 illustrates the division of a seismic trace into different time zones;

FIGURE 7 is a chart showing increasing space lag chartered against increasing record time for the zones of FIGURES 6; and

FIGURE 8 is a display involving a mixture of space lag correlations.

Dynamic Correlations

FIGURE 1 illustrates a seismic field operation or common depth point seismic surveying, and more particularly an off-end shot-spread geometry particularly useful for six-fold subsurface coverage.

Common depth point seismic exploration may be carried out using any one of a number of different surface geometries for the source and detectors. The operation represented by FIGURE 1 has been found to be desirable because it permits a continuous multiple coverage of the subsurface. Operations at the surface involve locating shots successively at stations 50, 52, . . . 60, etc. Each shot is located one detector interval from the end detector in the spread. More particularly, seismic waves generated by detonation of an explosive charge at a known depth directly below location 50 would be detected by seismometers located at stations 51—74. The seismometer outputs are recorded by unit 76 to produce a seismogram which is particularly related to the subsurface segment 75a.

Stated otherwise, with the seismometers at locations 51—74, seismic waves created at station 50 travel along ray path a1 to and from a subsurface reflection point 1 on the subsurface segment 75a. Seismic waves traveling along the ray path a24 are incident upon and reflected from reflection point 24 on subsurface segment 75a. Energy traveling along ray paths a2—a5 similarly is reflected from respective subsurface reflection points. Thus, the entire subsurface segment 75a is effectively scanned by the sensing of energy reflected from twenty-four subsurfaces reflecting points with the energy traveling to the surface stations 51—74.

A twenty-four trace seismogram A, FIGURE 2, is produced. In a similar manner, seismograms B, C, D, E, and F are produced with successive shots being denoted beneath stations 52, 54, 56, 58, and 60.

It will be noted that energy traveling along ray path b1 is reflected from the same subsurface point as energy traveling along ray path a5. Thus, every fourth subsurface location is characterized by the same geometry. Thus, trace 5 on record A will include, energy reflected from the same point as reflected energy appearing on trace 1 of record B, FIGURE 2. When the shot location and the spread have been moved along in the direction of arrow 30, such that the shot is at station 60, there will be one trace on each of the records A—F that may include reflections from the same subsurface reflection point. Thus, there is six-fold coverage of the subsurface beginning at the first trace on record F and continuing so long as the program is continued in the direction of arrow 30.

The embodiment to be described is directed primarily to the utilization of the unique nature of common depth point operations wherein the signals are processed and combined to produce space and time averaged signals which lead to an analysis of the subsurface structure with a measure of certainty and accuracy that has not heretofore been possible. Dynamic correlation signals are generated, as between common depth traces. The correlation signals are averaged in the manner hereinafter described to obtain:

- (a) residual normal moveout vs. time and space,
- (b) residual multiple reflection moveout vs. time and space,
- (c) ratio of primary to multiple energy vs. time and space,
- (d) ratio of coherent energy to total energy vs. time and space.

The above are particularly useful in forming optimum space and time varying common depth point stacking filters. In addition, that portion of the dynamic correlation which reflects primary energy may be applied as space-time varying filters to the stacked records to provide the optimum frequency band pass for display and interpretation of the data.

Simplified Example

To illustrate the mode of operation embodied in this invention, consider the simplified example when only four common depth points and eight traces are involved. More particularly, trace F1 is crosscorrelated with trace E5 and trace G1 is crosscorrelated with trace F5. The resultant crosscorrelation signals or functions are then added or summed to produce a resultant correlation function which, by reason of the addition, is "space average". In a similar manner, trace F2 is crosscorrelated with trace E6 and trace G2 is crosscorrelated with trace F6. The resultant cross-correlation functions are summed to produce a second space averaged correlation function.

The above four reflection point example may be further understood by reference

to FIGURE 1 where the reflection wave paths leading from shot locations E, F, and G to four common depth points are shown in detail. Ray paths e5 and f1 both lead to and from a first point on the subsurface segment 75a. In a similar manner, ray paths g1 and f5 both lead to and from a second depth point which is four subsurface stations on down the segment 75a from the first point. Traces including the signals traveling along ray paths f1 and e5 are crosscorrelated. Similarly, traces including the signals traveling along g1 and f5 are crosscorrelated. The two resulting cross-correlation functions are summed and plotted or displayed on a scale having as its zero or origin the zero delay lag in the crosscorrelation scale.

Traces including signals traveling along ray paths f2 and e6 to and from a third point close to the first point are crosscorrelated. Similarly, traces including signals traveling along ray paths g2 and f6 to and from a fourth point close to the second point are crosscorrelated. The resultant crosscorrelation functions are then summed and preferably are then plotted or displayed contiguous to the first summed cross-correlation function with the same zero or origin generally as shown in FIGURE 3.

Full House Operations

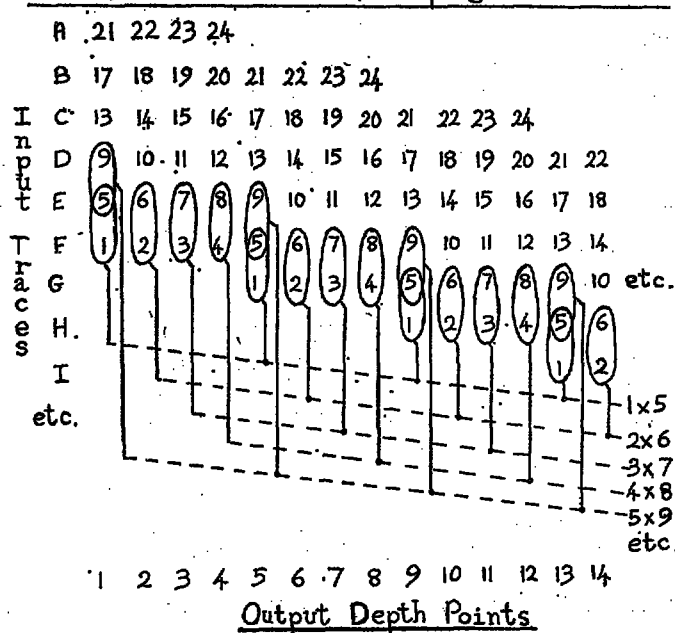
The description that follows illustrates the extension of the foregoing process to a six-fold coverage seismic operation. In the example that will be described now, a full suite of twenty-four averaged traces will be produced. In each case, averaging among correlation functions is accomplished by summing the crosscorrelation functions from one spread with crosscorrelation functions from all other spreads. This is done by combining correlation functions derived by crosscorrelating traces which include signals which follow paths of like geometry pairs.

Table I specifies the signals which are crosscorrelated and which resultant correlation functions are summed. In practice, the combinations shown in Table I preferably are extended so that about twenty or more space averaged correlation functions are produced where each such function is the sum of from twenty to thirty or more crosscorrelation functions. A full house set of such functions is represented in FIGURE 3 by traces 5—22.

Six-Fold Coverage Example

As noted above with reference to FIGURE 1, if the first shot is at station 50, the first full six-fold coverage starts with trace 1 of record F. Record F is produced with a shot located at station 60. Record F is illustrated in FIGURE 2 along with records A—E. For such common depth point arrays, the common depth point traces may then be regrouped in accordance with Table I.

TABLE I
CDP Trace Grouping



The grouping of Table I is convenient for obtaining dynamic correlations which are to be generated as between the traces within a common depth point set such as traces F1, E5, D9, C13, B17, and A21. The foregoing traces comprise the first full six-fold output traces for the array shown in FIGURE 1. In accordance with the invention, it has been found desirable to employ (i) short offset autocorrelations along with (ii) crosscorrelations between short and longer offsets from each common depth point set as will hereinafter be shown.

The signals detected at stations 51—74 of FIGURE 1 may be recorded in phonographically reproducible form as, for example, a multichannel digitized magnetic tape recording. This may be carried out in accordance with known methods and by means of known apparatus such as disclosed in U.S. Patent No. 3,134,957 to Foote et al. For the purpose of the present description, it will be understood that recording and playback systems such as are now well known in the art will be employed for the transfer of data once initially recorded by recorder 76 of FIGURE 1, for the operations hereinafter described.

Referring now to FIGURE 2, records A—F have been shown in an array which will be recognized as having a direct relationship to the trace grouping of Table I. The first record completing a six-fold coverage of a given reflection point along the subsurface segment 75a is the record F. More particularly, record A of FIGURE 2 covers the subsurface segment 75ai record B covers subsurface segment 75b; record C, segment 75c; record D, segment 75d; record E, segment 75e; and record F covers subsurface segment 75f.

The records A—F are arrayed in FIGURE 2 along with playback heads associated with each record symbolic of simultaneous playback of at least one trace from each of the records required in Table I for a given correlation function.

A signal channel 101 leads from a playback head for trace 1, record F, to both inputs of a first correlation unit 1×1 in a set 77 and to one input of unit $1 \times 5(77)$. Similarly, channels 102—104 lead to correlation units 2×2 — 4×4 , respectively, and to units 2×6 , 3×7 , and 4×8 of set 77. Channels 105—120 lead to one input of each of correlation units 9×13 — 20×24 , respectively. Channels 131—150 from the playback unit for record E lead to the second input in the units 1×5 — 20×24 , respectively.

Correlation units 1×1 — 4×4 and 1×5 — 20×24 in set 77 and units 1×5 — 8×12 in set 78 have been shown in block form. Such systems are in general well known both in the analog and digital form as, for example, described in analog form in connection with Figure 4 of U. S. Patent No. 2,794,965 to Yost, and as further described in U. S. Patent No. 3,131,375 to Watson. With such understanding, it will now be noted that channel 131 transmits the signal corresponding with trace 1 of record E to one input of a correlation unit 1×5 in the second set 78 of correlation units. Channels 132 and 133 similarly lead to one input of the correlation units 2×6 and 3×7 of set 78. Further, it will be noted that channels 175, 176, and 177 transmit signals from traces 5, 6, and 7 of record D to the second inputs on correlation units 1×5 , 2×6 , and 3×7 , respectively, of set 78. With the foregoing relationships, it will now be seen that autocorrelations from units 1×1 , 2×2 , 3×3 , and 4×4 of set 77 appear on channels 201—204. Two crosscorrelation functions appear on channels 205 and 206, i.e., from units $1 \times 5(77)$ and $1 \times 5(78)$. Similarly, two crosscorrelation functions appear on channels 207 and 208, i.e., from units $2 \times 6(77)$ and $2 \times 6(78)$.

The crosscorrelation functions on channels 205 and 206 are applied to a summation unit 250 having an output line on which there will appear the 1×5 crosscorrelation summation. The correlation functions on channels 207 and 208 are applied to a summation unit 251 having an output line on which there appears the summation of the 2×6 crosscorrelation functions. Similarly, on the output of the summing unit 252 appears the summation of the 3×7 crosscorrelation functions. The 4×8 summation signal appears at the output of adding unit 253. The signals on channels 201—204 and the outputs of the units 250—253 may then be stored or registered in non-visible form or they may be recorded as illustrated in FIGURE 3.

In FIGURE 3, a set of autocorrelation functions and stacked crosscorrelation functions have been plotted. The waveforms plotted are representative of results of processing of actual seismic records. The traces are positioned as to correspond with the output of the system shown in FIGURE 2. The output traces include auto correlation functions 1×1 — 4×4 , respectively. The bottom eighteen traces 1×5 — 18×22 are the stacked crosscorrelation functions for successively increasing shot-detector spacing. It is to be noted that the last two traces corresponding to the

last two outputs from FIGURE 2 are not included in FIGURE 3. Otherwise, the set of output correlation functions as shown in FIGURE 3 would correspond with the operations indicated in FIGURE 2 with the following understanding. Only two crosscorrelation functions have been described for stacking in FIGURE 2, as, for example, in the summing unit 250. In contrast, in actual practice a great many crosscorrelation functions would be stacked to produce the 1×5 trace of FIGURE 3. Connections completed by way of cable 209 so indicate. Each of the other stacked crosscorrelation functions similarly are made up of a like number of crosscorrelation functions. In the example illustrated, twenty-four crosscorrelation functions were stacked to form each of the traces 1×5 — 18×22 .

In FIGURE 3 it will be noted that the primary reflection peaks 37 fall substantially uniformly along the zero axis of the crosscorrelation scale. The lag time scale for the correlation display of FIGURE 3 is in terms of "seconds lag" employed for the various points on the autocorrelation and crosscorrelation functions.

The legend at the top of FIGURE 3 indicates that the crosscorrelation and autocorrelation functions were formed for a time gate centred at RECORD TIME=1.550 SECONDS. This record time may be understood by referring to FIGURE 4 wherein it is indicated that traces F5 and E1 are to be crosscorrelated. The record time 1.550 of FIGURE 3 may correspond with the center time T1 of the record interval 32. That is, the time gate having a center T_K of trace F5 has limits $T_K - L/2$ to $T_K + L/2$. Time gate 32 from trace F5 is then crosscorrelated with a time gate from trace E1 defined by $(T_K + L/2 + t_{max}) - (T_K - L/2 - t_{min})$.

In the production of the primary crosscorrelation function from unit $1 \times 5(77)$, FIGURE 2, where $T1=1.550$ seconds, the trace F5, would be shifted to the left so that the left extremities of the two gates are in time alignment which from FIGURE 3 would be a lag time of -0.140 second. The trace F5 is then shifted progressively towards the right until the right hand limits of the two gates are in alignment at a time which corresponds with the limit shown in FIGURE 3, i.e., a lag time of $+0.265$ second. At each delay interval, one point on the crosscorrelation function is produced. The delay interval τ employed in obtaining the function shown in FIGURE 3 was 0.002 second. Thus, the time gate from trace E1 would be the length gate $32 + 0.140 + 0.265$ second.

A dynamic correlation display of the type shown in FIGURE 3 is produced for each of a plurality of time gates selected at spaced points along the length of the seismograms involved. As indicated in FIGURE 4 a first time gate 31 having a center at time T0 is followed by the time gate 32 having a center at time T1. Time gates 33—36, etc. are located at times T2—T5, respectively. A display of the type shown in FIGURE 3 is produced for each of the time gates 31—36 so that the character of the earth at successively deeper horizons is accurately depicted by the dynamic correlation display.

In FIGURE 4, it will be noted that the time gates 31—36 are selected to have an overlapping relation. This particular relationship is not critical. Rather than overlap, the time gates can be merely contiguous one to another to form a continuous coverage of the entire seismic record time scale. Alternatively, they may be spaced apart so that there is no overlapping or no continuity between the time gates. In actual practice, it has been found desirable, for convenience in processing, to select the time gates such that there is neither overlapping nor space between the time gates.

The display itself may be an oscillographic recording in the form of a wiggle trace record of the type shown in FIGURE 3. The display may be of a cathode ray type presentation of variable area, variable density or wiggle trace. The method is not limited to the particular form of apparatus indicated in FIGURE 2 nor to the production of the particular display of FIGURE 3. Rather, the operation permits the use of a wide variety of instrumentation. It may involve a fairly simple operation of only three common depth point seismograms with the production of two crosscorrelation signals applied to unit 250 so that only one stacked crosscorrelation trace would be registered, plotted or displayed or otherwise used for analysis. The two-output correlation signal display above described is not as informative as displays of full house correlations such as shown in FIGURE 3. In the latter case, the stacked correlation signals will comprise the sum of from twenty to thirty or more crosscorrelation signals.

It is important that the correlation signals employed to produce any one trace on the output display of FIGURE 3 involve the sum of correlation functions produced from signals having the same two shot-detector geometries for each of the twenty

to thirty different shot locations along the spread 51—74, FIGURE 1. Further, the shot-detector geometries for any one of the stacked crosscorrelation traces of FIGURE 3 differ from the geometries of every other one of the stacked crosscorrelation traces. By this means, both time and space averaging of the common depth point seismic data is utilized.

One result flowing from the invention is immediately apparent in FIGURE 3. FIGURE 3 shows that too much normal moveout correction was employed for the primary reflection 37. It is further apparent that there is a strong multiple reflection 38. With such a portrayal of seismic data, the exact correction for normal moveout for the primary 37 can be determined. Further, the nature of the filter necessary to select the primary reflection 37 occurring at record time 1.550 can be specified, as well as the nature of a filter which will eliminate the multiple 38, in accordance with the method disclosed in *Geophysics*, Volume 30, No. 3, June 1965, beginning at page 348.

With such a display for each of a plurality of time gates along the entire seismic record, the precise nature of the operation necessary to best emphasize the desired data and to attenuate undesired or unwanted noise is available throughout the entire record length of each reflection horizon.

The display of FIGURE 3 may be employed as an input signal to a wide band velocity filter process of the type known in the art and described by Embree et al. in *Geophysics*, December 1963, pages 948—974. The axis of such filter as applied to the stacked correlation functions of FIGURE 3 is rotated so that the nature of the primary and multiple reflections can be precisely identified and separated one from another.

More particularly, FIGURE 5 illustrates the results of an alternate trace rotating wide band velocity filter operation on the data of FIGURE 3. More particularly, the top trace 400 in FIGURE 5 represents the output of filter operation with the traces 1×5 , 3×7 , 5×9 , 7×11 , 9×13 , 11×15 , 13×17 , 15×19 , and 17×21 of FIGURE 3 as the input to the filter and with the filter axis tilted at a rate of -0.002 second per trace. Trace 401 is the filter output on the remaining set of alternate traces of FIGURE 3 with the same tilt.

Traces 402 and 403 are filter outputs generally corresponding with traces 400 and 401 but with the filter axis tilted at -0.001 second per trace. Traces 404 and 405 were obtained by operation on the display of FIGURE 3 with zero tilt. Traces 406 and 407 were obtained using $+0.001$ second per trace; traces 408 and 409, $+0.002$ second per trace; traces 410 and 411, $+0.003$ second per trace; traces 412 and 413, $+0.004$ second per trace; and traces 414 and 415, $+0.005$ second per trace. In each case, the two traces for each tilt are obtained from completely independent data. The reliability of any time indication on the display is thus enhanced when it is found to occur on both traces.

From the relative amplitudes of the energy in the traces in FIGURE 5, it will be seen that a primary reflection has a stepout of between zero and -0.001 second per trace. This follows from the fact that the amplitudes of the largest peaks on traces 402 to 405 are about equal. This means that the primary 37 properly would be identified as having a stepout of about one-half millisecond per trace in FIGURE 3.

When the multiple 38 is considered, it produces the largest amplitude signals on traces 408 to 411. The multiple is equally developed on traces 408 to 411. Therefore, the stepout of the multiple as it appears in FIGURE 3 is properly identified as about $+0.025$ second per trace.

Full House

As is evident from Table I, the geometry of the input traces which make up the various output depth points repeats every fourth output for six-fold coverage. Full house crosscorrelations of FIGURE 5 are produced by summing the crosscorrelations of like geometries from many common depth point records. The invention, however, is not limited to a six-fold coverage program.

The repetition of geometry from record to record provides the basis for space averaging the dynamic correlations for each time gate to improve the data correlation statistically. It assumes that primary reflection and multiple reflection crosscorrelations between CDP pairs for a given time gate are slowly varying functions of space, thus averaging across the seismic traverse or line or part of the line can be performed to build up the primary correlation. Space averaging for each time gate will be over correlations of "like" geometry; that is, crosscorrelations $F1 \times E5$, $G1 \times F5$, $H1 \times G5$, are stacked to provide an average 1×5 CDP crosscorrelation for part or all of a line.

Automation

Having described one specific embodiment of the invention, it will be appreciated that the many computations involved suggest the use of digital machines to carry out all or part of the process. The following will specify the automation steps which may be employed.

Referring to FIGURE 4 for definitions,

T_k = center of k^{th} time gate (msec);

L = length of data gate (msec);

$t_{\text{max}} = p\Delta T$ maximum positive correlation lag (msec);

$t_{\text{min}} = q\Delta T$ maximum negative correlation lag (msec).

The crosscorrelation between CDP traces X_i and X_j over this time gate is defined by:

$$\phi_{ij}(n, k) = m = \frac{T_k + L/2}{\sum \Delta T} X_i(m) X_j(m+n) \quad (1)$$

$$m = T_k - L/2$$

$$\Delta T$$

for lag range of $-q\Delta T \leq n\Delta T \leq p\Delta T$ where m is the summation index and n represents the sample time location. The index k refers to the time gate of the correlation, $k=0, 1, \dots, K$. The maximum number of correlation gates needed per trace ($K+1$) preferably will be of the order of from 25 to 30. In Equation (1), the indices i and j refer to trace numbers. The range of i for the particular six-fold geometry under discussion is $i=1, 2, 3, 4$ and it always represents the short offset trace of the CDP set. The range of j is $j=1+4s$ where $s=0, 1, 2, 3, 4, 5$. Thus, for each value of i there are six dynamic correlations consisting of one auto and five crosses each computed for $K+1$ time gates. The superscript 1 is keyed to the output depth point of Table I and ranges in value from $l=1, 2, \dots, N$, where N is the last depth point in the line with six-fold coverage. Note that there are twenty depth points at the beginning and end of the line which are less than six-fold coverage. These generally will not be used in dynamic correlation generation. The index 1 also identifies implicitly which records or shots the traces come from through Table I. In computer operations, care is exercised to keep track of all the correlations computed.

Dynamic Correlation Parameter Specification

Two modes of operation are suggested as the most desirable. One employs equal gate separation or overlap and the other employs variable gate times.

1. *Equal Gate Mode.* This will be preferred for it has simpler input. In this mode, the gate centers T_k are equally spaced in time on the record. In use, the first gate center time T_0 , the number of time gates $K+1$, and the gate center separation ΔT are specified. This defines the remaining gate center times $T_k = T_0 + k\Delta T$ for $k=1, 2, \dots, K$. The gate length L may be automatically computed to give the desired overlap between successive gates. In FIGURE 4, a 25% overlap has been illustrated, i.e.:

$$L = \frac{4}{3} \Delta T. \quad (2)$$

This yields the interlocking correlation gates as indicated in FIGURE 4. Additional input specifications for this operation include: the maximum and minimum correlation lags t_{max} , t_{min} , data decimation ratio, and the number of depth points N for which the dynamic correlations are to be computed. A record or tabulation of specific trace and record identifications for the CDP groupings will be maintained in each operation for each dynamic correlation.

2. *Unequal Gate Mode.* This mode will allow the use of a schedule of gate center times T_k which are not equally spaced. Typically, they may be closely spaced at early record times, where signal-to-noise ratios are good and temporal variations occur rapidly. At late record times, coarse spacing will be satisfactory because signal-to-noise ratios are generally poor, because longer data gates needed, and temporal variations in primaries and multiples occur slowly. The gate length L_k may also vary with record time. The 25% overlap is described in Equation (3):

$$L_k = \frac{4}{3} \Delta T_k = \frac{4}{3} (T_{k+1} - T_k) \quad (3)$$

where: $k=0, 1, 2, \dots K-1$; and
the last gate length equals the preceding one $L_k=L_{k-1}$.

Where this overlap is employed, the correlation lag range, data decimation, and number of depth points will be selected and total data length needed from each input trace is given by:

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1. For the Equal Gate Mode:

Initial time = $T_0 - L/2 - t_{min}$
Final time = $T_K + L/2 + t_{max}$.

2. For the Unequal Gate Mode:

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Initial time = $T_0 - L_{0/2} - t_{min}$
Final time = $T_K + L_{K/2} + t_{max}$.

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By way of example, for a line of 305 input profiles, which yields 50 output profiles with full six-fold coverage, the following number of dynamic correlations are computed. Fifty output profiles contain $50 \times 24 = 1200$ output depth points. For each depth point six dynamic correlations are generated, i.e., one autocorrelation and five crosscorrelations, giving a total of:

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$$\text{Total Dynamic Correlations} = 1200 \times 6 = 7200.$$

Each dynamic correlation consists of $K+1$ individual correlations, that is, one for each time gate. Therefore, a grand total of $(K+1) 7200$ individual correlations are generated and stored for averaging in a variety of ways.

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Experience has suggested that 20-30 time gates are sufficient for most problems. Assuming $24 = (K+1)$, a grand total of individual correlations would be 172,800 per 50 output profile line or 3456 individual correlations per output profile.

Averaging and Display of Dynamic Correlations

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Several types of averages may be performed and displayed in several formats with the following key quantitative information:

For space averaging, the dynamic correlations for a given CDP geometry will be averaged over all or part of the line as specified on input. By reference to Table I and Equation (1), these averages can be described as:

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$$\bar{\phi}_{ij}(n, k) = \frac{\Delta T}{L_k Q} \sum \phi_{ij}(n, k) \quad (4)$$

where the summation $\sum$ is over all output points which contain the particular i, j trace combination, Q is the number of correlations being stacked, and $\frac{L_k}{\Delta T}$ is the number

of points in the k^{th} correlation time gate. Normalization by the gate length $\frac{L_k}{\Delta T}$ may be done when computing the dynamic correlations. However, that would

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require significantly more divisions than by forming one quantity $\left(\frac{\Delta T}{L_k Q} \right)$ to be applied to the stacked output. Furthermore, in order to preserve accuracy, the scaling should be done after input to the stacking operation rather than during input to stack.

With space averaged dynamic correlation functions available, the display may then be selected. It may be of the form shown in FIGURE 3 which is a plot or display involving common time gates versus offset. The space averaged dynamic correlations for display and interpretation illustrated in FIGURE 3 shows the correlations for a particular time gate k arranged by offset.

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A different display, not shown, may involve common offset versus time gate. This display of the space averaged dynamic correlations is formed by arranging them in trace form for playback purposes in order of increasing time gate for each offset. There will be twenty-four such displays, for each portion of the line that is averaged, each one corresponding to a particular i, j combination, where

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$$i = 1, 2, 3, 4 \text{ and} \\ j = i + 4s, \quad s = 0, 1, 2, 3, 4, 5.$$

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The first of such displays would comprise the 1×1 correlation summations for each of the time gates 31—36, etc. of FIGURE 4. More particularly, in such displays, the top trace would represent the summations of the 1×1 correlations for the time gate 31. The second trace would be the summation of the 1×1 correlations for all records over time gate 32. The third trace would display the 1×1 summation for the time gate 33; the fourth trace, the 1×1 summation for time gate 34; the fifth trace, the 1×1 summation for time gate 35; the sixth trace, the 1×1 summation for time gate 36, etc.

The second display would be similar to the first except that it involves the summation of the 2×2 correlations. The third display would be similar to the first except that it involves the summation of the 3×3 correlations. The fourth display would be similar to the first except that it involves the summation of the 4×4 correlations.

The fifth display would involve the summation of the 1×5 correlations. Similar displays are formed through the 2×6 , 3×7 , . . . 20×24 sequence, such that the twenty-fourth display would involve the summation of the 20×24 correlations.

This display is not as readily interpreted as the common time gate versus offset display illustrated in FIGURE 3, but represents a useful display of a new and unique set of seismic data.

Increasing Space Lag Displays

In FIGURE 3, the display involves a common time gate versus offset with the space lag being maintained constant. More particularly, the stacked CDP dynamic correlations, as adjacent CDP traces, all have the same $1\Delta X$ space lag, i.e., four group intervals, as indicated in Table I.

This particular grouping results in primary and multiple residual moveout which increases linearly when the correlations are displayed in order of increasing mean offset for each time gate. The linear moveout relationships are advantageous for both interpretation and signal processing such as velocity filtering of the displays to quantitatively separate primary and multiple contribution as above described in connection with FIGURE 5.

In a display like that of FIGURE 3 but for late record times, a $1\Delta X$ (four group intervals) space lag may not provide sufficient resolution of the primary and multiple residual moveout. Therefore, the longer space lags preferably will be employed for increasing record time. The longer space lag dynamic correlations preferably will be displayed with selected short lag correlations while preserving the linear moveout relationships of the set.

For this purpose, it is satisfactory to divide the record into several time zones, four zones being shown along the trace 300 of FIGURE 6. For each zone a different set of dynamic correlations will be generated as indicated in the table of FIGURE 7.

In FIGURE 6, T_k represents the correlation gate limits $k=0, 1, \dots, K$. Record times t_1 , t_2 , and t_3 define the time zone boundaries. Within each zone a different set of dynamic correlations is generated in the following manner.

Zone 1: For this zone, the displays for all selected time gates will consist of the $1\Delta X$ space lag correlations with no alteration. One such display is shown in FIGURE 3. From such a display, residual moveout ($\Delta\Delta T$) would appear, plotted versus mean offset ($X_1 + X_2$) as a straight line passing through the origin. From the slope of such line the correction velocity of residual NMO correction can be determined.

Zone 2: This set of dynamic correlations may consist of $2\Delta X$ space lag correlations plus several $1\Delta X$ lag correlations which provide an extended range of linear moveout versus mean offset.

Zone 3: The third set of dynamic correlations may consist of a mixture of $1\Delta X$, $2\Delta X$, and $3\Delta X$ space lag correlations illustrated in FIGURE 8, where the top set of traces are short spacing autocorrelations and sets 2, 3, and 4 are cross-correlations of successively increasing space lag.

One selection of the time zones of FIGURE 6 and the space lags and mixtures thereof for the various time zones is indicated in FIGURE 7. Different geophysicists may make different selections than those in FIGURE 7. However, in accordance with FIGURE 7, during the early record times the displays would involve only the $1\Delta X$ space lags. FIGURE 3 is an example of such stacked space averaged dynamic correlations. The bottom eighteen traces represent the $1\Delta X$ or four-group interval crosscorrelations.

FIGURE 3 however was taken at a record time of 1.550 seconds. This record time might be within the second zone of FIGURE 7. Displays in zone 2 would

include 2ΔX space lags. Similarly, in zone 3, 3ΔX space lags would be employed, and in zone 4, 4ΔX space lags would be employed.

In FIGURE 8, a display record 301 produced by recorder 302 includes a combination of 1ΔX, 2ΔX, 3ΔX, 4ΔX, and 5ΔX crosscorrelations with the top four traces on record 301 being autocorrelation signals.

It will be noted that the greater the space lags employed for producing the crosscorrelation signals, the greater the separation between primary and multiple and the greater the step-out on the multiple.

More particularly, in FIGURE 8, the primary 303 has been aligned across the entire record. In the 1ΔX portion of the display, the step-out represented by line 304 for the multiple is not as readily defined as the line 305 which involves the 2ΔX correlations. The definition and separation of the multiple as indicated by the lines 306, 307, and 308 for the 3ΔX, 4ΔX, and 5ΔX portions, respectively, of the display illustrates the advantages that may be obtained by employing a combination of space lags in a given display. In any case, the use of larger space lags is desirable for time gates taken at late record times.

In FIGURE 8 channels 311—314 apply the four autocorrelation functions to the recorder 302. Units 315—319 and companion units (not shown) may be employed to generate and/or store the crosscorrelation functions for the 1ΔX space lags. The signal from unit 315 is applied directly to the summing unit 320. The signals from units 316—319 are applied to the summing unit 320 by way of delay units 321—324.

The delay units may be set for zero delay for the production of usable displays. The delay units 321—324 and companion delay units in other channels may be advantageously employed to enhance the quality of the display by removing static correction error prior to production of the summation of all the crosscorrelation signals for a given space lag.

Static Correction Error

The presence of both shot and group static correction errors will degrade the dynamic correlation stack. Static correction as employed herein refers to corrections involving shifting one trace as a whole relative to the other by a constant amount. Shot static correction requires shifting one trace relative to another in dependence upon the difference between elevations of the respective shots employed for producing the two records. Group static corrections involve a similar shift to correct for differences in the elevation of the seismic detector or group of detectors employed for producing the respective traces involved.

In contrast, normal moveout (NMO) earlier discussed refers to corrections introduced into a seismic record by non-linearly time shifting events on a given seismic trace to compensate for differences between the length of the travel paths from a point source to reflection points on a subsurface horizon and back to the earth's surface and a vertical path. NMO is generally understood in the art. Both analog and digital systems are known for carrying out such corrections. One system for accomplishing such correction is disclosed in U. S. Patent No. 3,092,805 to Koeijmans. Residual normal moveout (RNMO) is the moveout still present after application of procedures such as taught by the Koeijmans' patent.

The magnitude of static errors which can be tolerated in the stack will generally depend upon the signal to side lobe level of the individual correlations. In order to insure that the dynamic correlation averages provide adequate estimates of the residual normal moveout (RNMO) and primary versus multiple strength and time dependence, an automatic static correction operation is desired to insure that the dynamic correlations are added in phase. For this purpose, correlation between primary dynamic correlation records is performed, prior to stacking, to obtain the necessary static corrections. More particularly, the static correction to be applied to dynamic correlations $F1 \times E5 = \phi_{1,5}^1(n,k)$ and $G1 \times F5 = \phi_{1,5}^5(n,k)$ before stacking

may be obtained by correlating $\phi_{1,5}^1$ and $\phi_{1,5}^5$ for plus and minus five correlation lags of 0.002 second each or ± 20 msec. The time lag for the largest positive peak in this correlation lag range will be the static correction and will be applied to $G1 \times F5$ before adding to $F1 \times E5$. The next primary correlation signal in this set is $H1 \times G5$ (Table I). It will be correlated with $G1 \times F5$, and the static correction added to the previous one to get the net static correction relative to $F1 \times E5$. This is continued for the entire set of dynamic correlations contributing to the 1×5 geometry, and similarly for the other geometries, 1×9 , 1×13 , etc. If the individual dynamic correlations $\phi_{ij}^1(n,k)$ are in reproducible record form, these static correlations

may be performed as record correlations during the stacking operation. These short secondary correlations may be displayed in trace form for review by the geophysicist to assess the magnitude of the static problem prior to stacking the CDP data. One logical organization of these static correlations is the following. Reference to Table I shows that record correlations

$$\emptyset_{1,5}^1 \times \emptyset_{1,5}^5, \emptyset_{2,6}^2 \times \emptyset_{2,6}^6, \emptyset_{3,7}^3 \times \emptyset_{3,7}^7, \text{ and } \emptyset_{4,8}^4 \times \emptyset_{4,8}^8$$

all involve the same three shots E, F, and G. Thus, if only shot or record static correction errors are present, the above four secondary correlation signals will show the same static shift. Therefore, by displaying them as adjacent traces, they can easily be examined for consistency. If group statics are also present, then the statics should not show consistency between the above sets.

Secondary static correlation signals for the entire line may be conveniently displayed as one record with the grouping previously described. Each row or trace in such display gives the successive static correlations between nearest neighbor dynamic correlation with a given offset geometry. The relative static correction between neighbors $l=p$ and $l=p+4$ is read from the positive maximum of correlation indexed $l=p$. The net static correction applied to a given dynamic correlation signal, in the average, is the sum of statics in a given trace up to and including the one in question. In other words, the static corrections for averaging are referenced to the first primary correlation signal in the set. Each successive set of four primary correlation signals involves the same input records. They will show the same static error if only record statics are present.

Static corrections determined in the above manner from secondary correlation signals as between primary correlations do not yield directly shot correction or group static corrections to apply to the CDP data. The former are linear combinations of both shot and group statics, but represent an undetermined system of equations and cannot be solved for shot or group statics without additional independent data. Their value is nonetheless two fold: (a) they provide the correct statics to align the dynamic correlations before averaging, and (b) they assist in assessing the magnitude of the static problem before CDP stack. If static errors are significant, then the normal procedures can be used to estimate and incorporate static corrections in the CDP stack. Since the static errors determined from the secondary correlation signals will be combinations of shot and group statics, they will serve as a useful check on statics determined independently.

In FIGURE 8, it will be noted that the primary crosscorrelation signal $F1 \times E5$ from unit 315 and the $G1 \times F5$ signal from unit 316 are applied as inputs to the crosscorrelation unit 331. The secondary crosscorrelation signal 341 appears at the output of the unit 331. The time interval 351 represents the static correction necessary properly to align the primary crosscorrelation signal $F1 \times E5$ with the primary correlation signal $G1 \times F5$. By the linkage 361, the delay in unit 321 is adjusted in proportion to the interval 351. Units 332—334 are employed for production of correlation signals 342—344. Linkages 362—364 are employed for adjusting the delay in units 322—324, respectively. The adjustment produced by way of linkage 362 will be the sum of delay intervals 351 and 352. The delay introduced by linkage 363 will be the sum of the intervals 351, 352, and 353. The delay introduced by linkage 364 will be the sum of the intervals 351, 352, 353, and 354.

With the primary correlation signals $G1 \times F5$, $H1 \times G5$, $I1 \times H5$, and $J1 \times I5$ thus shifted, they are then applied to the summation unit 320 along with the rest of the $1\Delta X$ primary correlation signals similarly corrected for statics to produce the signal on the 1×5 trace of the display record 301. In a similar manner, the primary correlation signals, employed to produce the $2\Delta X$, $3\Delta X$, $4\Delta X$, and $5\Delta X$ traces, may be corrected for statics as above described.

The example used in connection with the foregoing description involves the use of an off-end CDP seismic field procedure. The display of FIGURE 3 involves full house correlations for six-fold coverage. Other combinations may be employed. Further, the field procedure need not be limited to the off-end shooting technique. Other selections, for example, four-fold subsurface coverage, twenty-fold subsurface coverage, etc., have been found to be useful.

The method and system above described produce time and space averaged displays of seismic signals from a suite of common depth point seismic records. The

operations may be summarized or characterized as follows. Primary crosscorrelation signals are generated by selectively crosscorrelating the commonly-centred limited time gate or a plurality of sets of pairs of traces from all the records. The pairs of traces in each of the sets each include energy thereon which travels to and from subsurface reflecting points over corresponding pairs of paths of first and second geometries, respectively. The first and second geometries for any one set differ from the first and second geometries of any other set by different space lags. By this means, a corresponding number of sets of primary correlation signals are produced, differing one from the other in accordance with the space lags. The primary correlation signals for each of the sets are summed to produce a set of output correlation signals. A display is formed of the output correlation signals on a common correlation scale in the order of increasing space lag.

Preferably, a plurality of time gates are selected along the time scale of the seismic records to produce one display for each of a plurality of successively later record times to delineate reflections from successively deeper reflection horizons.

When a time gate from an early record time is employed, the geometries are characterized by small shot-detector spacing differences. When a time gate from a late record time is employed, the geometries are characterized by large shot-detector spacing differences. When the output correlation signals are ordered in the display in the order of increasing space lag, they may be progressively filtered by a rotating wide band velocity filter to produce a set of velocity filtered traces for identification of primary and multiple reflections on each display. In some cases, static corrections may require crosscorrelating the primary crosscorrelation signals in each set in pairs to produce a suite of secondary crosscorrelation signals. The primary crosscorrelation signals are then shifted in time one relative to the other in amounts proportional to the time lags of the maximum peaks on the secondary crosscorrelation signals prior to summing of the primary crosscorrelation signals for eliminating degradation due to static errors.

While ordinarily a great many primary crosscorrelation signals will be combined for each space lag, a minimal operation would involve crosscorrelating limited time gates of a first pair of traces taken from a first pair of seismic records where the traces include energy traveling along paths of first and second geometries, respectively, for reflection from a first reflection point to produce a first crosscorrelation signal. In addition, the corresponding commonly-centred time gates of a second pair of traces taken from a second pair of the seismic records are crosscorrelated where the traces include energy traveling along paths of first and second geometries, respectively, for reflection from a second reflection point spaced from the first point to produce a second crosscorrelation signal. The first and second crosscorrelating signals are then summed to produce an output correlation signal uniquely definitive of primary and multiple content of the records within the selected time gate.

Signal Enhancement and/or Interpretation of Seismic Sections

Seismic record sections resulting either from common depth point operations as above described or from continuous or skip-continuous seismic field operations often are characterized by low energy seismic signals at or below the threshold at which the coherent data can be distinguished from noise. This condition can occur in early record times but generally is characteristic of late record times. The present invention may be applied to the enhancement of weak seismic signals and/or to the analysis of data in seismic record sections for an accurate evaluation of the dip of the subsurface reflecting horizon. The following description relates to space averaging seismic data obtained in continuous profiling.

Continuous seismic profiling operations for the production of seismic record sections generally are well known. One such section is illustrated in Figure 2 of U. S. Patent No. 3,105,220 to Groenendyke.

In terms of FIGURE 1 of the drawings accompanying the present Specification, in continuous profiling, a first twenty-four trace record would be produced by detonating a charge at shot-point A and detecting the resultant seismic waves at detecting stations 51—74. A second record would be produced by detonating an explosive charge at shot-point G and detecting the resultant seismic waves at detecting locations 63—86. The last trace on the first record includes energy reflected from the same subsurface reflecting point as the first trace on the second record. Thus, the term "continuous profiling". Such an operation is then extended in the direction of arrow 30 to provide such continuous coverage of the subsurface reflecting horizon.

Where such seismic data is available in either reproducible or analog form, the present invention may be employed as follows. Signals detected at stations 51 and 52 after correction for normal moveout are crosscorrelated. Similarly, signals from stations 52 and 53 are crosscorrelated. In a similar manner, crosscorrelations are produced for each pair of traces over a length of the traverse which may be selected. For example, the last correlation between signals produced by a shot at shot-point A may be selected to be produced between traces detected at stations 62 and 63. The resulting set of twelve correlation functions would then be summed to provide space averaging over one-half the subsurface segment 75a.

A similar set of crosscorrelation functions would then be produced beginning with the signals detected at station 63 and ending with the signals detected at station 74. The second set of twelve crosscorrelation functions thus produced are then summed to provide a second space averaged crosscorrelation signal.

Similar space averaged crosscorrelation signals are produced for succeeding segments of the subsurface reflecting horizon. The resulting family of space averaged crosscorrelation functions preferably are then displayed in the same general manner as the space averaged display of FIGURE 3.

The crosscorrelations involved are taken for the commonly-centred selected time gates in each pair of traces. As above described, such gates generally will be during the late record times where signal enhancement is desired or where the attitude of the subsurface reflecting horizon cannot readily be discerned.

The spatial redundancy in either the common depth point seismograms or the continuous seismic profiling is such that where a reflecting plane is dipping at an angle, it will exhibit a time lag in the space averaged crosscorrelation display. Such a time lag increases with the space lag in a linear fashion. This means that a dipping primary reflection, otherwise buried in noise in a seismic record section, may be made to appear with prominence such as characterizes the PRIMARY reflection of FIGURE 3. If the subsurface reflecting horizon is horizontal, then the PRIMARY will line up, without step-out, across the space averaged display. If the subsurface reflecting horizon dips then the extent of the dip will be indicated on the display. The display is such that the wide band velocity filter can also be applied to automatically pick the dip of the subsurface reflecting horizon. In such case, a set of data of the class shown in FIGURE 5 will be produced.

In this embodiment of the invention, as well as in the CDP operation first described, a space averaged display may be produced for each of a plurality of time gates. Further, for any one time gate, it will be useful to produce space averaged displays for different space lags. More particularly, the example just described involves crosscorrelations between traces having space lags of one unit, that is, the unit distance between detecting stations 51 and 52. A second display would be produced for commonly-centred time gates by crosscorrelating trace 51 with 53, 52 with 54, 53 with 55, etc. wherein the space lag is of two units. A third display would involve crosscorrelating trace 51 with 54, 52 with 55, 53 with 56, etc. for a display based on a three unit space lag. This sequence can be carried forward to the extent necessary to achieve clear identification of the nature of the subsurface reflecting horizon. A dipping bed will be reflected by progressively increasing time lags across the display with increasing space lags between the correlations. Thus, the space averaging of seismic record sections has at least two desirable results. One is signal enhancement. The other is dip analysis.

The method thus applied is for structural interpretation of the subsurface by means of application of space average dynamic crosscorrelations to either CDP or continuous profiling traces. This application is particularly valuable for overcoming noise and/or unraveling interference between reflection events from different sets of subsurface reflectors.

WHAT WE CLAIM IS:—

1. A method of generating a space averaged correlation electrical signal from records of seismic energy obtained by generating seismic energy at a sending station, and recording the seismic energy following common depth point reflection, which method comprises generating electrical seismic signal representations of said records; crosscorrelating commonly centered limited time gates of a first pair of said electrical signal representations to produce a first crosscorrelation electrical signal, which first, pair of electrical signal representations is associated with seismic energy travel including reflections from the same reflecting horizon along two paths of different geometries; crosscorrelating corresponding commonly centered limited time gates of



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Where such seismic data is available in either reproducible or analog form, the present invention may be employed as follows. Signals detected at stations 51 and 52 after correction for normal moveout are crosscorrelated. Similarly, signals from stations 52 and 53 are crosscorrelated. In a similar manner, crosscorrelations are produced for each pair of traces over a length of the traverse which may be selected. For example, the last correlation between signals produced by a shot at shot-point A may be selected to be produced between traces detected at stations 62 and 63. The resulting set of twelve correlation functions would then be summed to provide space averaging over one-half the subsurface segment 75a.

A similar set of crosscorrelation functions would then be produced beginning with the signals detected at station 63 and ending with the signals detected at station 74. The second set of twelve crosscorrelation functions thus produced are then summed to provide a second space averaged crosscorrelation signal.

Similar space averaged crosscorrelation signals are produced for succeeding segments of the subsurface reflecting horizon. The resulting family of space averaged crosscorrelation functions preferably are then displayed in the same general manner as the space averaged display of FIGURE 3.

The crosscorrelations involved are taken for the commonly-centred selected time gates in each pair of traces. As above described, such gates generally will be during the late record times where signal enhancement is desired or where the attitude of the subsurface reflecting horizon cannot readily be discerned.

The spatial redundancy in either the common depth point seismograms or the continuous seismic profiling is such that where a reflecting plane is dipping at an angle, it will exhibit a time lag in the space averaged crosscorrelation display. Such a time lag increases with the space lag in a linear fashion. This means that a dipping primary reflection, otherwise buried in noise in a seismic record section, may be made to appear with prominence such as characterizes the PRIMARY reflection of FIGURE 3. If the subsurface reflecting horizon is horizontal, then the PRIMARY will line up, without step-out, across the space averaged display. If the subsurface reflecting horizon dips then the extent of the dip will be indicated on the display. The display is such that the wide band velocity filter can also be applied to automatically pick the dip of the subsurface reflecting horizon. In such case, a set of data of the class shown in FIGURE 5 will be produced.

In this embodiment of the invention, as well as in the CDP operation first described, a space averaged display may be produced for each of a plurality of time gates. Further, for any one time gate, it will be useful to produce space averaged displays for different space lags. More particularly, the example just described involves crosscorrelations between traces having space lags of one unit, that is, the unit distance between detecting stations 51 and 52. A second display would be produced for commonly-centred time gates by crosscorrelating trace 51 with 53, 52 with 54, 53 with 55, etc. wherein the space lag is of two units. A third display would involve crosscorrelating trace 51 with 54, 52 with 55, 53 with 56, etc. for a display based on a three unit space lag. This sequence can be carried forward to the extent necessary to achieve clear identification of the nature of the subsurface reflecting horizon. A dipping bed will be reflected by progressively increasing time lags across the display with increasing space lags between the correlations. Thus, the space averaging of seismic record sections has at least two desirable results. One is signal enhancement. The other is dip analysis.

The method thus applied is for structural interpretation of the subsurface by means of application of space average dynamic crosscorrelations to either CDP or continuous profiling traces. This application is particularly valuable for overcoming noise and/or unraveling interference between reflection events from different sets of subsurface reflectors.

WHAT WE CLAIM IS:—

1. A method of generating a space averaged correlation electrical signal from records of seismic energy obtained by generating seismic energy at a sending station, and recording the seismic energy following common depth point reflection, which method comprises generating electrical seismic signal representations of said records; crosscorrelating commonly centered limited time gates of a first pair of said electrical signal representations to produce a first crosscorrelation electrical signal, which first, pair of electrical signal representations is associated with seismic energy travel including reflections from the same reflecting horizon along two paths of different geometries; crosscorrelating corresponding commonly centered limited time gates of

5: a second pair of said electrical signal representations to produce a second cross-correlation electrical signal, which second pair of electrical signal representations is associated with seismic energy travel including reflection from the said reflecting horizon along two paths of different geometries; and summing the first and second crosscorrelation electrical signals to produce a space averaged output correlation electrical signal. 5

10 2. A method according to Claim 1, in which the difference between the geometries of the paths of travel associated with the first pair of electrical seismic signal representations is the same as the difference between the geometries of the paths of travel associated with the second pair of electrical seismic signal representations. 10

15 3. A method according to Claim 2, in which the electrical seismic signal representations are derived from at least three common depth point seismic records, the first pair of electrical seismic signal representations being derived from a first pair of the records and the second pair of electrical seismic signal representations being derived from a second pair of the records, and in which the travel paths associated with the first pair of electrical seismic signal representations include reflection from a common first point on the reflecting horizon and the travel paths associated with the second pair of electrical seismic signal representations include reflection from a second point on the reflecting horizon spaced from the first point. 15 20

20 4. A method according to Claim 3, the said records numbering twenty to thirty and wherein the output correlation signal is produced by summing cross-correlation signals which link all of the said seismic records with common depth point reflection energy which has travelled to and from reflection points spaced serially along the reflection horizon over paths having geometries consisting only of the geometries of the travel paths associated with the first and second pairs of electrical seismic signal representations. 20 25

25 5. A method according to Claim 3, in which the crosscorrelation signals are crosscorrelated to produce a secondary crosscorrelation signal and thereafter one of the first-mentioned crosscorrelation signals is time shifted relative to the other, by an amount equal to the correlation lag of the maximum peak in the secondary crosscorrelation signal, preparatory to the said summing to produce the output correlation signal. 25 30

30 6. A method according to Claim 3, further comprising crosscorrelating commonly centered time gates of a third pair of electrical seismic signal representations derived from the seismic records to produce a third crosscorrelation signal and crosscorrelating commonly centered time gates of a fourth pair of electrical seismic signal representations derived from the seismic records to produce a fourth crosscorrelation signal; the paths of travel associated with the third pair of electrical seismic signal representations including reflection from a third common reflection point on the reflecting horizon adjacent the said first reflecting point along respective paths of different geometries; and the paths of travel associated with the fourth pair of electrical seismic signal representations including reflection from a fourth common reflection point on the reflecting horizon adjacent the said second reflecting point along paths of different geometries; summing the third and fourth crosscorrelation signals to produce another space averaged output correlation electrical signal, and storing both output correlation electrical signals relative to the same correlation time lag scale. 30 35 40 45

50 7. A method according to Claim 6, in which the output correlation signals are stored as a visual side-by-side trace display with a common origin on the correlation time lag scale. 50

55 8. A method according to Claim 1, in which the first pair of electrical seismic signal representations are associated respectively with paths of seismic energy travel of first and second geometries including reflection from respective first and second points on the reflecting horizon, and the second pair of electrical seismic signal representations are associated with seismic energy paths of travel of third and fourth geometries including reflection from respective third and fourth points on the reflecting horizon. 55

60 9. A method according to Claim 8, the first and third points being coincident. 60

10. A method according to Claim 8, the first, second, third and fourth points being located at progressively increasing distances from the sending station.

11. A method of producing time and space averaged correlation electrical signals from a suite of common depth point seismic energy records obtained by



common depth point seismic exploration techniques, which comprises:

- 5 (a) generating sets of primary crosscorrelation signals by selectively crosscorrelating limited time gates of a plurality of sets of pairs of electrical seismic signals re-
presentations generated from all the records; wherein each primary correlation is
10 generated by crosscorrelation of commonly centered limited time gates of a particular pair of electrical seismic signal representations; wherein each pair of electrical seismic signal representations in the sets includes components representing seismic energy which has travelled to and from subsurface reflecting points over a corresponding pair of paths of first and second geometries respectively; and
15 wherein there are space lags between the first and second geometries for any one set and the first and second geometries of any other set, whereby the primary correlation signals in one set differ from those in another set in accordance with the said space lags,
- (b) summing the primary correlation signals in each of the sets to produce a set of output correlation electrical signals, and in which
- (c) the output correlation signals are stored as a visual display on a common correlation time lag scale in the order of increasing space lag.
12. A method according to Claim 11, wherein a plurality of time gates are selected along the time scale of the seismic records and a like plurality of displays are produced representing reflection points on successively deeper reflection horizons,
13. A method according to Claim 11, wherein the time gate is at an early record time and the geometries of the travel paths are characterized by small shot-detector spacing differences.
14. A method according to Claim 11, where the time gate is at a late record time and the geometries of the travel paths are characterized by large shot-detectors spacing differences.
15. A method according to Claim 11 or Claim 12, wherein the output correlation signals arranged in the or each display in the order of increasing space lag are progressively filtered by a rotating wide band velocity filter to produce a set of velocity filtered traces for identification of primary and multiple reflections on the display of the correlation signals which occur at record times within said time gate.
16. A method according to Claim 11, where for the or each time gate the primary crosscorrelation signals in each set are crosscorrelated in pairs to produce a suite of secondary crosscorrelation signals and wherein the primary crosscorrelation signals are shifted in time one relative to the other in amounts equal to the time lags of the maximum peaks on the secondary crosscorrelation signals prior to summing the primary crosscorrelation signals for production of the set of output correlation signals.
17. A method of producing a space averaged correlation electrical signal from records of seismic energy produced at a sending station, substantially as described herein with reference to and as illustrated by the accompanying drawings.
18. Apparatus for producing a space averaged correlation signal from at least three common depth point seismic trace records which include electrical signals representing seismic energy travel along paths having geometries including reflection from a reflecting horizon, which comprises, means operable simultaneously to reproduce pairs of the said records, means responsive to commonly centered limited time gates of a first pair of electrical seismic signals derived by the reproducing means from a first pair of the records and associated with travel paths including reflection from a first reflection point and having first and second geometries respectively to produce a first primary crosscorrelation electrical signal, means responsive to commonly centered limited time gates of a second pair of electrical seismic signals derived by the reproducing means from a second pair of the records and associated with travel paths having the said first and second geometries but reflected from a second reflection point to produce a second primary crosscorrelation electrical signal, and means operable to sum the first and second primary crosscorrelation electrical signals to produce an output correlation electrical signal.
19. Apparatus according to Claim 18 which includes:
means operable to crosscorrelate the first and second primary correlation signals to produce a secondary correlation electrical signal, and
means operable to shift one of the first and second primary crosscorrelation signals in time relative to the other by an amount equal to the time lag of the maximum amplitude of the secondary crosscorrelation signal to effect enhancement of the output correlation signal.



* C L H S *

- 5 20. Apparatus according to Claim 18, and also comprising means responsive to commonly centred limited time gates of a third pair of electrical seismic signals derived by the reproducing means from the records and associated with travel paths having third and fourth geometries respectively and including reflection from a third reflection point adjacent to said first reflection point to produce a third primary crosscorrelation electrical signal, means responsive to commonly centered limited time gates of a fourth pair seismic signals derived by the reproducing means from the records and associated with travel paths having the said third and fourth geometries respectively and including reflection from a fourth reflection point to produce a fourth primary crosscorrelation electrical signal, means operable to sum the first and second primary crosscorrelation signals and to sum the third and fourth primary crosscorrelation signals to produce a pair of output correlation electrical signals, and means connected to store the output correlation signals relative to a common correlation time lag scale.
- 10
- 15 21. Apparatus for producing a space averaged correlation electrical signal from at least three common depth point seismic trace records, substantially as described herein with reference to the accompanying drawings:
- 15

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