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RECENT TRENDS IN SEISMIC DATA PROCESSING

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SUMMARY

The record is a summary of recent trends in the commercial processing of seismic data as seen during a study tour in Europe and the United Kingdom between February and June 1975. The study was made possible by a scholarship from l'Agence pour la Coopération Technique, Industrielle, et Economique (ACTIM), Paris.

The most important single aspect of seismic data processing at present is the velocity analysis, both for data enhancement and for data interpretation. Following this in importance are the determination of residual statics for land data and the suppression of multiples, especially for marine data.

Future trends in data processing involve the use of large numbers of recording channels per cable length; three-dimensional techniques of profiling, modelling, and migration; high-frequency, high-resolution surveying methods at small sampling intervals; and the development of faster minicomputers and the use of Walsh function analysis methods to cope with the massive increase in data that the first three trends will produce.

INTRODUCTION

The following notes on various aspects of the digital processing of seismic data derive from studies made in Paris during an ACTIM (Agence pour la Coopération Technique, Industrielle, et Economique) Scholarship between March and May 1975 and during an official overseas visit to data processing companies in the United Kingdom, Holland, West Germany, and France in June 1975.

The ACTIM Scholarship consisted of a four-week French language course and eight weeks with the Bureau d'Etudes Industrielles et de Coopération de l'Institut Francais du Petrole (BEICIP). It was also to include three weeks of study with the Compagnie Générale de Géophysique (CGG) in Paris but sickness prevented my carrying out this part of the scholarship. In its place I was able to substitute one week of study with Seismograph Service Limited (SSL) in London.

At BEICIP I worked with a group of geophysicists engaged in the processing and interpretation of deepwater marine seismic data recorded by l'Institut Francais du Pétrole (IFP) in their boat "Florence" during the life-testing of their energy source "Flexichoc" in offshore West Africa. Apart from this practical work, I also studied the theory of distributions as applied to the digitization of data, the theory of digital filtering and several theoretical aspects associated with two-dimensional filtering, deconvolution, and Walsh functions. During my stay with BEICIP, I made one-day visits to SNPA in Pau, ELF in Chambourcy and CFP in Paris; I also visited IFP to see their mini-computer the "Geoprocesseur" which they are building.

At SSL I worked with a group of geophysicists engaged on the processing and interpretation of high-frequency, high-resolution land data recorded for the British Coal Board in England.

Companies visited during the official overseas visit included Seiscom, Digicon, GSI (Croydon), Western, BP, Phillips, GSI (Amstelveen), Prakla, and CGG.

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A complete itinerary is given in the Appendix.

It was very clear from the studies made that the most important single aspect of seismic data processing at present is the determination of stacking velocities primarily as a means of achieving the optimum stacking of common-depth-point data, but also for time-depth conversions, migration, and the determination of other parameters such as densities, porosities, sand-shale ratios, etc. The next most important aspects are the determination of residual statics for land data and the elimination of multiples, especially from deepwater marine data. The bulk of this report therefore will be devoted to short summary reviews of these three aspects of data processing followed by comments on some of the other more interesting topics covered during the study tour. Some of the topics studied are covered very well in text books and published articles and there is very little point in reproducing such matter in this report. In these cases I have included references in the bibliography and references section at the back of the report. There is also little point in trying to reproduce examples of processing displays. These and other company literature are available if anyone is interested to see them.

VELOCITY ANALYSIS

Definitions of velocities encountered in seismic processing

Stacking velocity V_s.

This is the velocity derived directly from velocity analyses of multifold CDP data, and the determination of accurate stacking velocities is the primary objective of velocity analyses in order to give an accurate and optimum stack of the multifold data.

Average velocity V_a.

This is the average velocity taken over the shortest distance travel paths, i.e. assuming straight ray paths. It is the velocity determined from well velocity surveys, and by its very definition, it is the velocity required for the depth conversion.

$$V_a = \sum_{1}^{n} V_j T_j / \sum_{1}^{n} T_j$$

Where V_j is the interval velocity within layer j,

and T_j is the one-way time within layer j.

RMS velocity $\bar{V}$.

This is the time weighted root mean square velocity, i.e. the average velocity taken over the shortest time travel paths. It can be derived in two ways:

(i) from an approximation of the infinite series given on page 8, which represents the case of curved ray paths, or,

(ii) Dix derives the same expression for root mean square velocity by assuming straight ray paths for each velocity layer.

It is the velocity that most nearly approximates to the stacking velocity for horizontal strata and is identical to the stacking velocity at zero offset, i.e. at normal incidence. At offsets greater than zero, the stacking velocity is greater than the RMS velocity. This discrepancy may increase or decrease with depth depending on the heterogeneity of the ground.

It is equivalent to the average velocity only in the case of uniform velocity, i.e. where you have a homogeneous ground. It progressively exceeds the average velocity as the ground becomes more heterogeneous.

$$\bar{V} = \sqrt{\sum_{1}^{n} Vj^2 \ Tj / \sum_{1}^{n} Tj}$$

Interval velocity VI.

This depends on the method by which it is calculated. If it is computed from RMS velocities it will be an RMS interval velocity; if from average velocities, it will be an average interval velocity, and the former will always exceed the latter. In either case it is determined from Dix's formulae.

Instantaneous velocity Vi.

This is the interval velocity measured over a very small time or depth interval.

Migration velocity VM.

This is the velocity derived from an optimum migration stack. It approximates closely to the average velocity (12). The velocity is determined by generating migrated traces with a sequence of constant velocities, computing coherency of the energy that migrates into identical positions of the migrated traces, and then plotting the coherencies in terms of vertical travel time and velocity. The method is thus analogous to the conventional velocity analysis.

Normal Moveout

Velocity determinations from seismic data depend on the normal moveout or increase in reflection time due to offset of the receivers in respect to the source. It is ideally assumed that when we apply dynamic corrections with the correct velocity distribution, then all offset traces from a common-depth-point gather become identical to the zero-offset trace. However, there are several factors that cause distortion of the wavelet in the offset traces in relation to the zero-offset trace. First of all then let us consider these factors that result in a dynamically-corrected offset trace not being equivalent to a zero-offset trace.

As all velocity analyses are now made on common-depth-point data, only those factors affecting traces within a CDP gather will be considered.

1. Amplitude attenuation due to spherical divergence. The effect due to spherical divergence is a purely spatial one, and the attenuation is directly proportional to the average velocity and time. A correction is usually made for this effect before velocity analysis by assuming an average velocity distribution.

2. Filtering effect of the earth. The filtering effect of the earth is a complex of several causes, the main ones, however, being absorption (inelastic attenuation), transmission losses, dispersion, thin-layer multiple effects, and scattering. The overall effect is generally a lowering of the frequency of the signal with an increase in offset due to the selective attenuation of the high-frequency components; there is also a frequency-dependent phase-shifting effect resulting in signal distortion with respect to the zero-offset signal. O'Doherty and Anstey (1) have shown that filtering effects can also be influenced by the type of sedimentary deposition: cyclic deposition results in low-frequency attenuation whereas a transitional type of deposition will result in high-frequency attenuation.

3. Distortion due to variable transmission path effects. These effects may arise where there are local horizontal variations in geology, so that all the offset trace paths do not traverse the same geological sequence. The effects are most severe and most common within the sub-weathering zone.

4. Source and receiver variations. In land work there will, unavoidably, be variations in signal strength and spectrum within a CDP gather due to differences in the shot conditions, and similarly there will be variations in the geophone response. The amplitude variations due to these effects can be compensated for in the processing, but any signal distortions will remain.

In marine work variations in the depth of the cable will result in variations in the wavelet shape owing to relative differences in the arrival times of the direct pulse and the reflection from the water surface. The interference of these two pulses affects the shape of the recorded signal considerably.

5. Change in reflection coefficient with angle of incidence. The change in reflection coefficient with angle of incidence is most rapid about the critical angle, which is dependent on the velocity and density contrasts above and below the reflecting boundary.

6. Cross-over of reflections at far offsets. Cross-over occurs mostly where there is a rapid increase in velocity. The reflection hyperbolae for the low and high velocity events intersect at far offsets (2). The longer the spread, the more likely are these cross-overs to occur. In the application of dynamic corrections the part of the reflections beyond the point of intersection fails to correct and spurious events and noise are generated. The simplest solution to this problem is to mute out the data beyond the intersection point. For this purpose it is very useful to have playouts of the uncorrected CDP gathers.

7. Compression of data at far offsets. This is the most serious of the factors affecting normal moveout. The sequence of reflection coefficients is compressed in the offset traces causing a mixing of wavelets. This results in two effects after the application of dynamic corrections: a time-variant stretching of the signal and a consequent stretching of the intervals between samples. To maintain a uniform sampling rate we have therefore to resample the traces by interpolating between two original data samples. This is necessary for the stacking of the data and for any multichannel processing. The problem can be handled in several ways, for example:

a) No interpolation. The computer uses the original data point values at new points either side of it.

b) Linear interpolation between original data points.

c) Interpolation through three original points using an x^2 curve.

d) Interpolation through four original points using an x^3 curve.

The first two methods are the ones most commonly used in routine processing. The interpolation produces distortion of the signal, the production of "NMO noise". The stretching of the signal itself results in a lowering of the frequency of the signal. The two effects both increase with increase in offset and are dependent on the velocity function; effects are worse for a lower velocity function. The most common solution applied at present is to mute out the badly affected data. Even so, small amounts of stretching do affect the resultant stacked trace by compressing its frequency spectrum and by reducing the expected signal-to-noise improvement at higher frequencies (3).

There are three basic ways of applying dynamic corrections:

i) Sample-by-sample moveout. Each data sample is moved according to the normal moveout equation, but the amount of movement is rounded to an integral number of samples.

ii) The block-move-stretch method. Data are moved and stretched in data blocks so as to occupy the same time interval as their zero-offset equivalents.

iii) The block-move-sum method. Data are moved in small data blocks equivalent in time to the length of the wavelet. Overlapping data blocks are used and data are summed and normalised within the overlap. There is no stretching of the data within the blocks. This method is a fairly recent development, and, although it appears to solve the problems associated with stretching and even those of cross-over theoretically, data so far processed with this method show only a marginal improvement in shallow reflection quality, over those processed with the first two methods. Digicon apply a form of this method, using blocks of 250 ms.

8. Approximation of NMO. It is assumed that the seismic wavefront is travelling along the shortest time path in accordance with Fermat's principle and Snell's Law. The arrival time T_x of a reflection at an offset X is therefore given (9) by the infinite series.

$$Tx^2 = C_1 + C_2X^2 + C_3X^4 + \ldots.$$

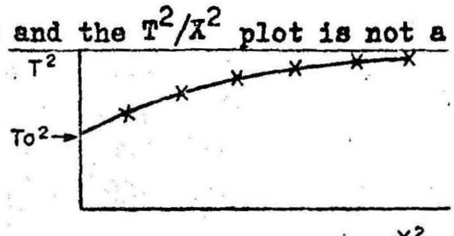
where $C_1 = T_o^{\ 2}$ (zero offset reflection time) and C_2, C_3... depend on the layer thicknesses and their interval velocities; C_2 can be written as $1/V^2$ where V is the RMS velocity. It is common practice to use only the first two terms of this equation in applying dynamic corrections. This leads to an expression for ΔT, the normal moveout: $\Delta T = \sqrt{\frac{X^2}{V_2} + T_o^{\ 2}} - T_o$

It has been found that there is very little advantage (and certain disadvantages) in using the three-term expression (4). The three-term expression is probably worthwhile on good data, but where there is "jitter" in the data due to incorrect static corrections or noise, the two-term expression is actually better in that it is statistically more reliable.

<u>Factors affecting stacking velocities</u>

Stacking velocities are the velocities that give the optimum stack of common-depth-point data and there are several factors that affect the optimum stack. There are also several other factors that affect the interpretation of the stacking velocities. First of all let us consider those factors that affect the optimum stack.

1. <u>Approximation of NMO</u>. The using of the two-term approximation mentioned previously implies an approximation of the seismic ray travel paths(refraction of the rays is not completely allowed for). Consequently, the travel times for the longer offsets are actually less than those allowed for in the equation, i.e. the actual travel-time velocities increase with increasing offset and the T^2/X^2 plot is not a straight line.



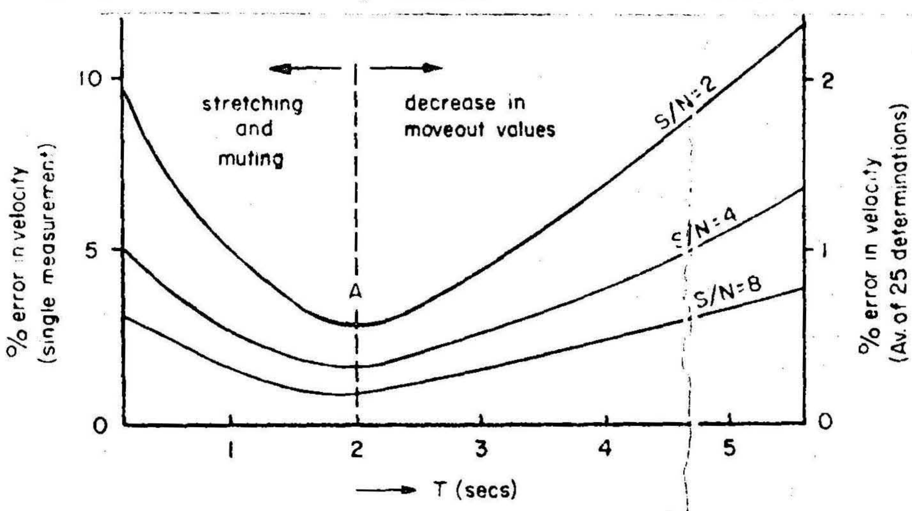
The true RMS velocity occurs only at To, i.e. at zero offset. In the velocity analysis process what one is effectively doing is drawing a least-squares straight-line through the T^2/X^2 plot. It can be seen that the ensuing velocity will always be higher than the true RMS velocity and that the discrepancy will increase with increasing spread-length. The stacking velocity that gives the optimum stack is therefore an average RMS velocity over the spread-length.

2. <u>Anisotropy</u>. Most formations are anisotropic in reality and the horizontal seismic velocities are normally greater than the vertical velocities. This effect will also tend to give higher travel-time velocities at far offsets because of the non-verticality of the travel path in the lower high-velocity layers.

3. <u>Reflection onset</u>. Velocity analysis techniques all work by the alignment of reflection peaks or troughs, i.e. they relate velocities to the times of the first reflection maxima. What we should really be trying to find are the velocities relative to the onset of the reflection, the alignment along A instead of that along B.

We have seen previously that there is a broadening of the wavelet with increasing offset due to the filtering effect of the earth and the NMO stretching. This will result in the optimum stacking velocity being lower than the correct velocity, and the timing of the velocity will be greater than the correct time. It has been suggested, however, that these two effects compensate for each other under certain conditions (5).

4. <u>Noise</u>. The presence of random noise reduces the statistical reliability of the stacking velocities obtained (6).



Point A is approximately where the spread-length (8000 ft in the example shown) is equal to depth, i.e. the point where optimum moveout data are available for the velocity determination. The diagram shows the danger of accepting velocities determined from single CDP gathers at isolated points. If single CDP gathers are to be used they should be used at every CDP point to provide continuous velocity measurements so that smoothing of the data can be carried out. If velocity analyses are to be made at isolated parts of a traverse, then more than one CDP point should be used. The amount of noise present on the seismic section is the main factor in deciding which type of analysis will be used. With low S/N ratios, velocity function stacks or constant velocity stacks are essential.

5. Statics. Incorrect static corrections are usually random and can be considered as noise. The determination of correct residual statics is very important in land data for good velocity determinations.

6. Feathering of marine cables. In the presence of strong cross-currents, marine cables are not straight along the traverse direction. This will affect the moveout on the far offset traces depending on the dip and cross-dip of the underlying strata.

7. Near-surface velocity anomalies. The problem occurs when horizontally-distributed velocity anomalies have dimensions roughly equal to the spread-length. Differential travel-time variations occur at different offsets and the moveout curve becomes non-hyperbolic. The velocity analysis process provides a best hyperbolic fit, however, and so gives a false velocity.

8. Spread length. Long spreads give a statistical improvement in the accuracy of the stacking velocities due to the relatively larger moveouts involved, but opposed to this improved accuracy is the increase in discrepancy between the stacking velocity and the true RMS velocity as pointed out above.

9. Dip. When the reflection horizon is dipping, the velocity analysis method assumes a horizontal bed and applies the best-fit hyperbola accordingly; consequently an optimum stack is not produced. The NMO is overcorrected but

can be reduced by multiplication by the term $\cos^2\theta$, where θ is the apparent dip in the line of the profile (7). If not corrected for dip, the velocities will be higher than they should be irrespective of whether the data are recorded up-dip or down-dip. When you have a dipping reflector, the reflecting points for the traces within a CDP gather do not actually occur at a single common point; there is a spread of reflecting points and the spreading of these points is always up-dip from the zero-offset point of normal incidence. Therefore apparent velocities are always higher whether actual shooting is up or down dip. Most velocity analysis methods now either allow for dip directly by performing the velocity scans for a range of dips, or compute the dip from adjacent velocity scans. The correct velocity is given by $V_s \cos\theta$.

10. Multiples. If a multiple occurs at the same time as a primary event, the resulting interference can give a false stacking velocity. Sometimes it is impossible to resolve the two events.

11. Aliasing. Sometimes one obtains false chance line-ups of data, especially at shallow times, and this is called aliasing of data.

Velocity analysis methods

There are four basic methods in use for the determination of stacking velocities.

1. Moveout scan. This is a simple summation of the traces of a single common-depth-point gather along a particular hyperbolic moveout curve (8). It is, for example, used by GSI in their 700 package.

2. Cross-correlation method. Instead of a simple summation of traces for a particular moveout curve, a cross-correlation of the traces is carried out. The cross-correlations are computed between all possible traces within a gather at numerous sequential, and sometimes overlapping, short time gates along the traces. The correlation values are then summed and all such summations normalised for display purposes. The normalising values are displayed as a separate "relative total energy" trace. It is, for example, used by Western in their Velan program.

3. Constant velocity stack. Common-depth-point gathers for several adjacent CDP points are used and the data are stacked for a series of constant RMS velocities. Where the correct velocity of a reflection occurs, the data are stacked in phase and reinforcement takes place giving the appearance of a strong reflection. As adjacent CDP points are utilised, the resultant sections exhibit dip. This is universally the favoured method and all companies use it either preferentially or as a supplement to their routine method.

Variations of the method include constant velocity gathers and velocity function gathers and velocity function stacks.

4. Multichannel filter method. a) For a particular value of To on the zero offset trace, the traces within a CDP gather are swept with various hyperbolas and passed through a multichannel semblance filter whose output is a measure of the coherent signal power. This power will be a maximum for the correct hyperbola. This is the method used by Seiscom in their velocity spectra (9) and by Digicon. b) By use of a modified fan filter one can allow for dip and produce a composite trace from the CDP gather for a particular hyperbola. This method is used by Geo Space Corp. (10).

Comparison of methods. The method preferred by most geophysicists is the constant velocity stacks because of its similarity to the actual record sections. Selection depends also on S/N ratio. If this is low, you need some form of space averaging method as discussed earlier under "Noise". Also in cases of S/N less than 1, a cross-correlation technique must be used with caution as the S/N ratio is effectively being squared in the process (8).

Interpretation of velocity analyses

There are several factors that make an interpretation of the velocity analyses difficult:

1. Velocity inversions. These are difficult to detect and there are likely to be far more in fact than one suspects. Some events interpreted as multiples may in fact be inversions.

2. Multiples. These are usually easy to pick unless they occur near to primary events. They are always of lower velocity than a primary at the same time, although there may be some confusion if there are velocity inversions.

3. Dip. Dipping events give higher apparent velocities than horizontal events. Most methods nowadays, however, include dip compensation or determination and correction.

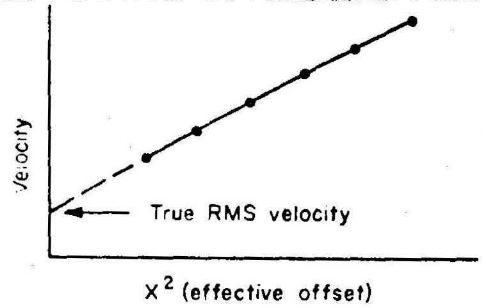
4. Diffractions. These can occur as spurious high velocity events.

5. Curvature of reflecting horizons. Differential dip can give two maxima points on velocity analyses displays at different times and velocities. The subsurface should be approximately linear over distances of the order of a spread length. Larger cables therefore make greater demands on subsurface continuity. Corrections can be applied for the effects of curvature (11).

Methods of deriving true RMS velocities from stacking velocities

There are two methods currently being used for this purpose:

1. The zero-offset method. This is a direct approach to the problem and involves extrapolating back to zero offset from a set of stacking velocities derived from a CDP gather by using different sets of offsets. Traces 1 to 14 are used to obtain a stacking velocity, then traces 3 to 16, 5 to 18, etc. giving a series of 7 stacking velocities increasing with effective offset. It is found in practice that a plot of Vs versus X^2 gives a straight line. It is a simple matter therefore to extrapolate back to zero offset to give the true RMS velocity.



An important feature of the method is that the evaluation of RMS velocity at one horizon is independent of errors at other horizons. The method can also be used in the case of dipping horizons.

2. <u>The iterative modelling method</u>. This is the method most commonly used at present. The stacking velocities (Vs_1) corresponding to all the major reflection horizons are picked, the interval velocities computed, and the thicknesses of the strata worked out to form a model of the ground. For each interface of the model, reflection travel-times are computed by a ray-tracing method for all offsets used in the stack. From these travel-times a new stacking velocity (Vs_2) is computed for each horizon. Vs_2 is then used to create a new model and the whole process is repeated until there is no change in the velocity. This is then taken to be the true RMS velocity.

AUTOMATIC RESIDUAL STATICS

Reliable residual static corrections are most important in the stacking of land seismic sections. All companies have their own individual programs for the automatic or semi-automatic determination of the corrections, but in spite of the large variability in these programs and their different degrees of reliability, nearly all of them utilise the same principles (13). However, whichever method is used it must satisfy the following three requirements:

1. Residual statics must be surface consistent, i.e., all traces from the same shot receives the same shot static correction and all traces from a particular geophone position will receive the same receiver correction.

2. They must be time invariant, i.e., all reflections down the record receive the same correction. This requirement necessitates the use of large time windows for the cross-correlations and also implies that enhancement of data occurs at all reflection horizons.

3. They must be independent of the frequency of the data. This means that the residual statics determinations are confined as far as possible to the near-offset traces.

Residual statics consist of time shifts due to four components:

a) Structure and dip of the reflection horizon.

b) Moveout or residual moveout.

c) Static correction at the source.

d) Static correction at the receiver.

The first two components are low-frequency effects and the last two are high-frequency random effects. Any reliable method of residual statics determination must separate out these four components. Brief summaries of the methods currently in use are given below.

1. The deterministic method. With CDP data one can group the data in such ways as to successively reduce the four time-shift variables to three. By taking traces within one CDP gather, the dip component reduces to zero; common-offset traces have no relative moveout component; and similarly with common-source traces and common-receiver traces. Thus one can establish four sets of equations with only four unknowns and these can be solved to give the required corrections. Aquitaine carry out this method where they have multi-coverage data of less than six-fold. With data of higher multiplicity they utilise the large redundancy of data and apply the statistical methods that most companies use.

2. The statistical method A. The method can be divided into five steps:

(a) Taking the common-source group of data, cross-correlate adjacent pairs of traces (e.g. there are 11 pairs in a 6-fold 24-channel case) and sum the correlations to reduce noise. However, you have to limit the number of pairs to the near-trace pairs to reduce the effect of moveout or residual moveout, and to limit the extent of the subsurface involved to avoid effects where the average dip from the section varies rapidly along the section.

(b) Similarly for common geophone data

(c) In each case you get a listing of:

i. Relative time shifts from one point to the next.

ii. Peak cross-correlation value.

iii. Cumulative time shift along the line.

iv. A plot of cumulative time shifts.

v. And plots of the cross-correlations.

These can be examined manually and any anomalous time shifts or doubtful correlations are excluded or amended.

(d) The data are filtered with a low-frequency rejection filter to remove effects of structure, dip, and moveout, and to give the true residual statics.

(e) The process can be iterated if necessary.

3. The statistical method B. This is a very quick method and not very reliable when carried out on its own. SSL, for instance, mostly use it in conjunction with method A. The first and third requirements listed above are not met by this method. Only traces within a CDP gather are used after moveout removal. This means that the time-shift components of moveout and dip are not involved. The method consists of three steps:

(a) A reference trace is chosen from within the group and is cross-correlated with each of the other traces.

(b) The time shifts are taken as the total residual static for the particular traces, if they lie within specified limits (usually about 10 ms maximum).

(c) These statics are applied to the data and processing continues.

4. The Prakla-Seismos method. Prakla-Seismos have a very sophisticated processing scheme called the Advanced Seismic Program System (ASP) in which reference traces are developed as processing proceeds along a traverse. From measurements of dip and coherency, a prediction trace is computed and compared with the next trace along the line. From the comparisons, new values of dip, coherency, velocity, and statics corrections are computed for the new trace. The method is very accurate and reliable (see Prakla-Seismos report No. 2/74).

MULTIPLES

The presence of multiples is the most serious problem in marine seismic exploration, especially in cold waters. There are several methods of suppression and elimination of multiples and, although some of them are extremely successful for shallow-water data, none of them to date gives a completely satisfactory solution to the problem of deeper-water multiples.

Basically there are three main methods of multiple attenuation:

1. Differential Moveout Methods

(a) CDP stacking. Multiple reflections generally have larger moveout (and lower velocity) than primary events at the same time. Consequently with multifold data they will tend to stack out of phase on application of dynamic corrections (14). In the case of ringing or reverberation, however, or in the case of strong interbed multiples, and in the case of deeper and long-period multiples where there is strong interference with primary events, or where the differential moveout is small, special methods of removal have to be adopted, as in methods 2 and 3 below.

Larger spreads give higher differentials and therefore better multiple attenuation.

(b) Two-dimensional filters. Velocity filters can be applied to the CDP gather traces, prior to stacking, to give optimum attenuation of multiples without distortion of the primaries.

2. Deconvolution Methods

Deconvolution methods are only applicable for periodic multiples. Once the periodicity is affected, as it is for instance with deeper-water multiples, the method becomes less effective. There have been four main developments in the application of deconvolution filters to the suppression of multiples since Backus first used them in 1959 (15).

(a) Backus-type filters. For the simple two-layer case of reverberation, simple three or four-point deconvolution operators can be used to provide effective elimination of the ringing (16). The operators are designed from a knowledge of the water depth and the reflection coefficient of the water bottom layer. The latter can be obtained directly from the autocorrelation function of the seismic trace, or can be found by trial and error. The operators become very long, e.g. 80 ms for 100 ft of water for the Backus 3-point filter.

(b) Predictive deconvolution. Predictive deconvolution makes use of least-squares prediction filters with prediction distances greater than unity, and leads to much shorter operators (17). It allows the selective attenuation of events which are periodic within given repetition ranges and is therefore effective in the suppression of rather complex reverberation patterns. The method also allows the control of the length of the desired output wavelet and so provides a specifiable degree of resolution. The prediction distance of the operator is made approximately equal to the two-way water time.

(c) Adaptive deconvolution. As water depths get larger the predictive deconvolution becomes less effective, and an adaptive deconvolution is used. This is also a prediction error filter, but it is continuously updated as a function of output. It is effectively a continuously time-varying prediction error filter and helps to compensate for relative amplitude distortions. It is utilised in the GSI "Dewater" and the CGG "Triton" programs.

(d) Multichannel deconvolution. As the periods of the multiples increase, the periods and amplitudes do not behave in a simple predictable manner and the normal single-channel deconvolution method performs less and less effectively and becomes useless. It can be shown (18) that long-period multiples behave in a stationary manner along radial directions on seismic sections and Seiscom have developed a multichannel predictive deconvolution method applied along the radial direction, which is quite effective in the suppression of long-period multiples.

3. Subtraction Methods

This is the most direct and logical approach to the suppression of multiples, and the methods used generally give good results. The methods depend first of all on the identification of the multiples, and it is in this respect that the methods vary the most, and secondly in subtracting them from the seismic section.

(a) The "Souston" method. This method (19) is used by CGG and is carried out in three steps:

i. Produce a multiple-enhanced section by stacking with the NMO function corresponding to the multiples only. The primaries will be stacked out.

ii. Apply reverse NMO corrections to give an uncorrected record of each CDP gather which will contain only multiples. Each trace of this model is then cross-correlated with its original field trace to identify the multiples. Each multiple on the model trace is then weighted in amplitude to equal the amplitude of the corresponding multiple on the field trace, so that subtraction is complete.

iii. Subtract the model traces from the field traces, eliminating all multiples.

iv. Process the cleaned field traces as normal.

(b) BEICIP method. This is applicable for simple deepwater multiples, where you only have the first multiple within the section of interest, i.e., where you get the initial seismic section superimposed on the lower half of the section as a simple multiple section. For each trace, the time delay for the water-bottom multiple is calculated from the geometry - water depth and trace offset. This delay is then applied to the trace and the delayed trace is cross-correlated with original trace to identify the multiples in the lower part of the section. Amplitude weightings are then determined as in the

Souston method and the two traces are then subtracted, eliminating the multiples. Processing then proceeds as usual.

(c) Autoconvolution method. The inverted autoconvolution of a seismic trace consists only of multiples - the primaries all disappear (20). The multiples appear at the correct times and with correct polarities but with distorted amplitudes. The amplitudes can be corrected as in the Souston method and the modified inverted autoconvolution subtracted from the field trace. Prakla's "long-leg multiple attack" method utilises a modification of this method (21). They found difficulties of time shifts between the autoconvolved trace and the original trace, so they apply a short to medium deconvolution operator to the original trace and then find the autocorrelation of the deconvolved trace. They then convolve this autocorrelation function with the original trace to obtain the multiples-only trace.

(d) Wave equation method. This is a method being developed by Digicon, but not yet applied in production processing (22). The approach is to propagate the original unstacked seismic data, recorded at the surface, down and then back up through the water layer. Each event in the original data is then transformed into its associated water bottom multiple. This gives a means of identification of the multiples and hence a possibility of subtracting them.

MINI COMPUTERS

Since the success of the Phoenix and Command minicomputer systems, several other companies have developed similar systems and have tried to update the capabilities of the minicomputer. SSL themselves have updated the Phoenix system to include floating point processing. Other updated models I saw during my tour were:

1. Texas Instruments' TIMAP
2. Western Geophysical's COBA III/FAST
3. Prakla-Seismos's SSP-11
4. L'Institut Francais du Pétrole "Geoprocesseur"

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The Geoprocesseur is without doubt the most advanced of the minicomputers, but unfortunately is not yet out of the laboratory stage. It has been designed specifically for geophysical use and is much faster than its predecessors. It utilises emitter-coupled logic technology and microprogrammation. If it can be put into production in 1976 it could be very successful. It will be able to cope with the massive increase of data expected from the eventual increase in the number of traces per spread length to 512. The cost of the Geoprocesseur will be in the region of 700 to 800 thousand dollars.

3-D PROFILING

The main exploration contractors such as GSI, CGG, and Prakla all offer methods of three-dimensional profiling both on land and offshore. The method was initiated by CGG in 1971 (23). The method now favoured for land work is to use a straight cable layout, and offset the shots from the traverse line in a random manner between 50 and 500 feet. For distances below 50 ft events are difficult to sort out. CGG use a maximum offset of 200 feet as they find that correlations become difficult for larger offsets. For marine work, three to six separate cables are towed in parallel and spaced about 120 feet apart. Prakla, however, use a single cable and two sets of airgun arrays each offset 120 feet to the port and starboard of the boat (24).

CGG display their data in colour, different colours for events coming from the rear, front and vertically. The data are usually migrated three-dimensionally and contoured along the profile.

The 3-D profiling stack sometimes gives enhancement over the conventionally recorded single-line stack. It gives continuous values of cross-dip and enables meaningful migration to be made.

GSI, CGG, and Prakla also have programs for crooked line processing, which are similar to their 3-D profiling programs.

HIGH-FREQUENCY SURVEYS

In 1972, British Petroleum and Seismic Explorations International (now Digicon) carried out a high-frequency, high-resolution marine survey over part of the Forties Field in the North Sea in order to map a shallow high-pressure gas sand that was a serious drilling hazard (25). The survey was so successful that Digicon, realising the wider applications of the method to oil and gas exploration, have developed the method using more powerful sparker sources, and now have two boats working full time in off-shore Louisiana and one about to commence work in the North Sea.

Digicon use a sparker source of 124 kilojoules energy in a multi-array to avoid bubbles. The large electric fields caused time-break problems at first, but these were overcome by using fibre optics to give an optically operated time break. The cable parameters are reduced about 5:1 compared with conventional geometry giving a 300 m cable length (including offset), 18 geophones per station, and station intervals of 10 m. The sparker signal response peaks at about 170 Hz and vertical resolution is about 5-10 ft. Good quality data can be obtained down to 1-1$\frac{1}{2}$ seconds, and down to 2 seconds in exceptional areas. Sampling was at 1 ms intervals. Digicon are experimenting with more powerful sources. I was shown several sections of data and the inprovement in resolution over conventionally-recorded data was phenomenal.

Both Western and SSL were carrying out high-frequency surveys on land. Western were recording on video tape in the field and then converting to digital in the processing centre at $\frac{1}{4}$ ms intervals.

WALSH FUNCTIONS

Walsh functions are square-wave functions that can be utilised for the analysis of seismic traces just as trigonometric functions have been utilised (26). However, they have advantages over trigonometric functions in that they are a better form of analysis for discrete data and because they involve only the summation of real numbers as against the multiplication and summation of complex numbers. They can therefore result in much faster processing (27). Most processing companies are playing around with Walsh functions and transforms, but none so far is using them in production processing. With the increase in the amount of data to be processed, however, they will certainly be used in the future.

Their main use at present is in the field of telecommunications for the compression of data before transmission. They have the facility of being able to reduce the amount of data from 10 to 30 times with very little degradation after reconstitution (20).

MIGRATION

All companies visited, except Digicon, use a method of migration similar to that proposed by Fontanel and Grau in 1969 (29). The programs used have many different names, but basically they are the same: holoseismic, impulsive holography, migration stack (30), digital migration, total migration, and seismic imaging.

Digicon are the first company to utilise the researches of Dr Claerbout of Stanford University on the application of the wave equation to the processing of seismic data (31), and their migration program is based on the wave equation (22). The method is still in the process of development to achieve optimum results. GSI intend to bring out a wave equation migration program later this year.

COLOUR DISPLAYS

All contractors now produce coloured seismic sections for the display of extra parameters such as velocity, frequency, reflection strength, and polarity, but Seiscom, the initiators of this type of display on a production basis, are still producing the best product. Their reproducibility of colour tones is very reliable and they now produce the displays on paper that can be folded as distinct from the usual photographic-type paper. Their "Isomet" displays show fence diagrams in colour.

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FUTURE TRENDS

1. The most important trend seems to be towards an increasing number of recording channels; 96 channels are already being used in some parts of the world and it is thought that the increase to 256 and 512 channels will take place within the next year or so. The reasons for wanting to use so many channels over practically the same cable lengths as used at present are to reduce random noise by increasing the statistics, to reduce coherent noise by grouping of channels within the computer, and to give an improved resolution horizontally. If noise can be reduced effectively this will lead to better deconvolution, which in turn will give better vertical resolution and more accurate and detailed velocity analyses. Improved velocity analysis will lead to an improvement in the determination of other parameters such as density and porosity. In other words, one will be closer to the ideal of determining the sequence of reflection coefficients within the section. The improved resolution will give a better definition of stratigraphic traps.

2. The massive increase in data that the increase in the number of recording channels will bring about will require fast and efficient computers to process the data. This is where the type of computer such as the IFP Geoprocesseur may be useful.

3. Most companies are playing around with Walsh functions as a means of speeding up processing and it is possible that they will be used more and more.

4. High-frequency, high-resolution surveys are being used in petroleum exploration, and Digicon's success in this direction will no doubt stimulate the development of more penetrative sources and a wider use of the method.

5. There is an obvious trend to three-dimensional techniques, such as 3-D profiling, 3-D modelling, and 3-D migration. It is quite possible that three-dimensional migration stacking will supersede the conventional CDP stacking and that velocity analyses will result directly from the optimum migration stack.

6. While at Seiscom I was told that they would be making an announcement of something revolutionary in the processing field before the end of the year but what this may be is open to speculation. I was assured that it would not be merely cosmetics, but something really big. This just illustrates that seismic data processing is now in a most exciting period of development.

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APPENDIX

Itinerary

ACTIM Scholarship

1 - 28 February	French language course, Paris
1 March - 27 April	Working with BEICIP
16 April	Visit to CFP, Paris
18 April	Visit to SNPA, Pau
24 April	Visit to ELF, Chambourcy

Private Study

19 - 23 May	Working with SSL, London

Official Overseas Visit

27 May	Visit to Western Geophysical, London
28 May	Visit to GSI, London
29 May	Visit to Digicon, London
30 May	Visit to Phillips and British Petroleum, London
2 June	Visit to Seiscom, London
3 - 4 June	Visit to Texas Instruments, Amsterdam
5 June	Visit to Prakla-Seismos, Hannover
6 June	Visit to ACTIM, Paris
9 - 10 June	Visit to CGG, Paris