A SET OF PROGRAMS FOR PROCESSING DIGITAL SEISMIC DATA*

By

JOHN G. DAWSON**

INTRODUCTION

This paper deals with a set of programs to adjust, summarize, and refine seismic data used in Petroleum Exploration. Each program is a separate stand-alone program, although some of the programs are data dependent upon others. All the programs are written in Basic Assembler Language and are designed to run under the IBM Basic Operating System. The programs included in the set are:

1. Data Preparation

2. Normal Moveout Computation

3. Demultiplex

4. Normal Moveout Application

5. Stacking

6. Autocorrelation and the Power Density Spectrum

7. Band Pass Filtering

8. Point Sort

9. Multiplex

This set of programs and the documentation, which is the source material for this paper, were written by IBM employees. The programs were developed for a specific purpose in the hope that they might prove helpful to other members of the data processing community.

GENERAL

A schematic diagram of the computer configuration required to use these programs is shown on figure 1. The central processing unit must have 65,000 bytes of core storage, the decimal instruction set, the floating point instruction set and 2 selector channels. The input/output units required are a card render, a printer, 2-2311 disk storage drives and 2-2400 series magnetic tape units. A console typewriter is also required for communication with the operator.
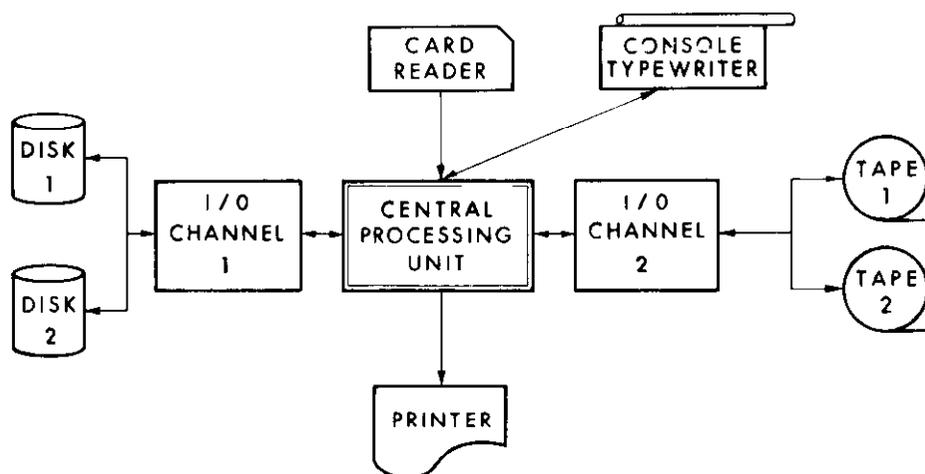

FIG. 1.—Computer configuration.

The possible processing sequences are shown in figure 2. The diamond shaped blocks represent decision points where the geophysicist can have one of the programs in the set operate upon the data or carry on to the next decision point.

The possible run sequence for a preliminary run is shown on figure 3. The first step would be to compute all the Normal Movement Charts for the particular area. These charts are based on the velocity information available and the spread configuration used in the area. The Data Preparation Program calculates and stores on the disk all the control information used by the other programs in the set. The Demultiplex Program rearranges the seismic data from a gapped multiplexed trace file into a record-by-trace file. The dynamic and static corrections are applied by the Normal Movement Application Program. The Autocorrelation and Power Density Spectrum Program can be run on some or all the traces to aid the interpreter in the design of the best filter for signal to noise improvement. The Point Sort Program will gather the traces from common depth points so they can be displayed side by side. The Multiplex Program creates a gapped multiplexed tape that can be converted back to an analog tape and used to produce the normal record section. This preliminary run can be used to insure the static and dynamic corrections are correct. The Point Sort gives the interpreter an opportunity to scan and edit the traces that are being stacked together before the production run.
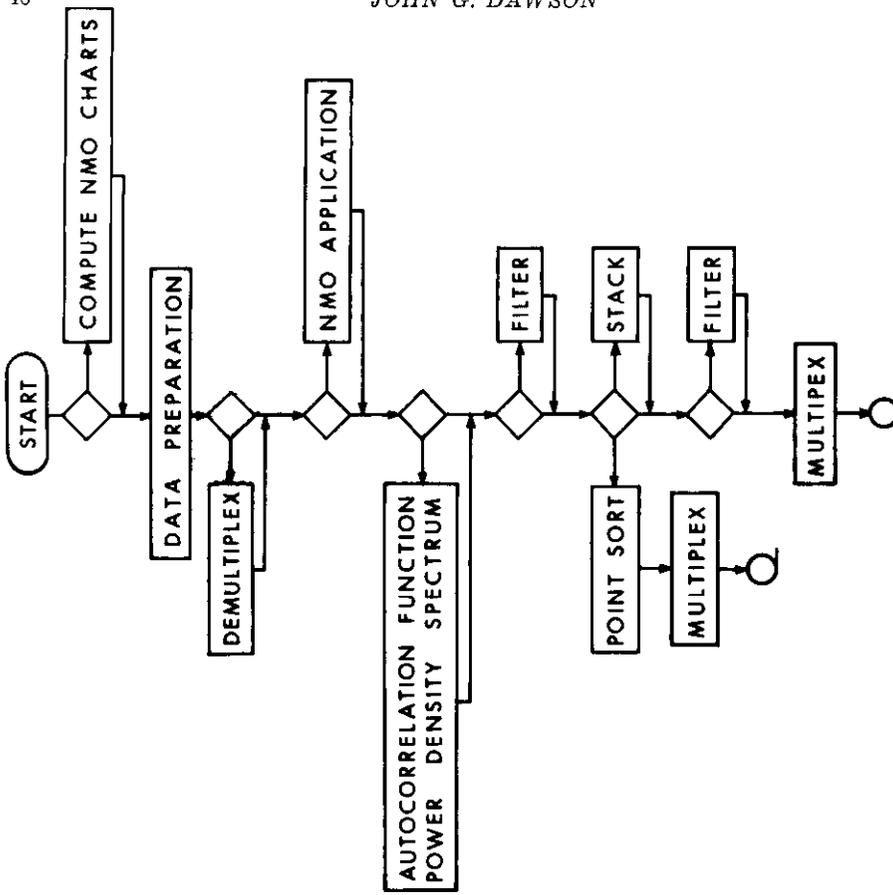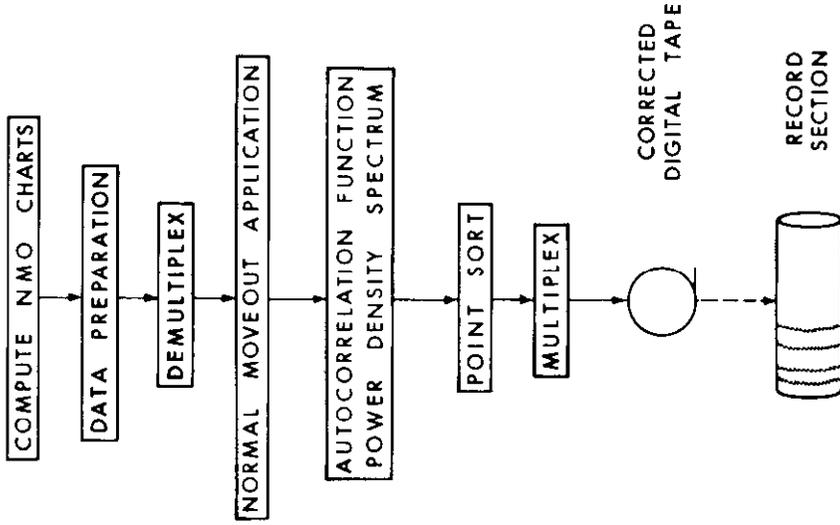
JOHN G. DAWSON

FIG. 2.—Processing sequence.

FIG. 3.—Possible run sequence. Preliminary run.

The production runs for an area as shown on figure 4 will not normally include the NMO Chart Computation as that only needs to be done once. The Demultiplex run could be eliminated if the Demultiplexed tape had been saved from the preliminary run. The stacking and Filtering Programs can be run in any sequence with the final program being the Multiplex Program. If a high speed digital photographic plotter is available, the multiplex operation, the digital to analog conversion and subsequent playback of the analog tape would not be required.
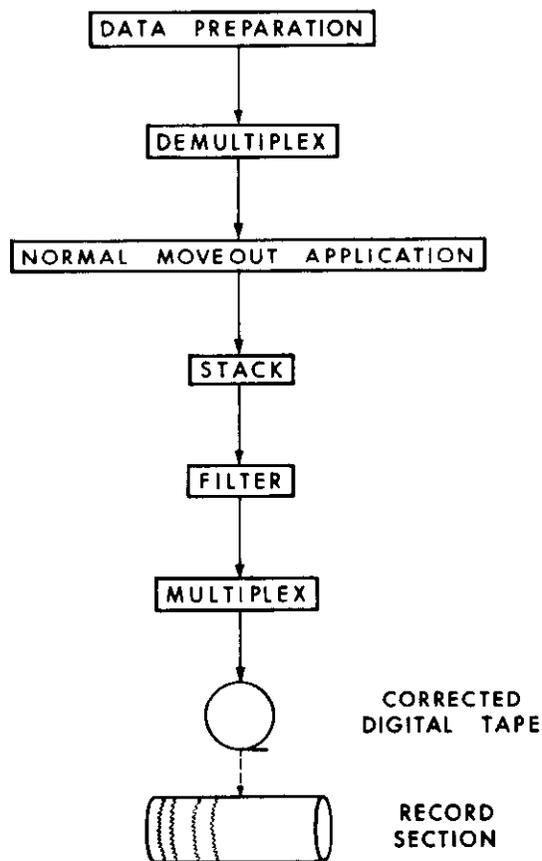

FIG. 4.—Possible run sequence. Production run.

NORMAL MOVEOUT COMPUTATION

The Normal Moveout Program translates velocity information into tables suitable for performing normal moveout corrections to digital traces. A set of tables representing up to 100 different shot point to geophone distances is prepared for each given velocity function. These tables are stored on the disk and each one is given a unique number for communication with the program that applies the normal moveout corrections. The input to the program is on cards that describe the shot point to geophone distances for which NMO tables are to be prepared and time-depth cards which describe the velocity function.

There are five functions the program will perform. These functions are create, add, replace, interpolate and modify. The create function starts a new set of NMO tables with the succeeding velocity function. Tables based on the succeeding velocity function are added to the file of tables. The replace function causes a specified set of tables to be replaced by the following set. By means of the interpolate function a new set of tables, representing different shot point to geophone distances, is created from an existing velocity function. The modify function creates a new set of NMO tables by applying empirical (vernier) corrections to an existing set of charts.

A curved ray path, based on Snell's Law, is used to calculate the arrival times at the specified distances from each of the depth levels
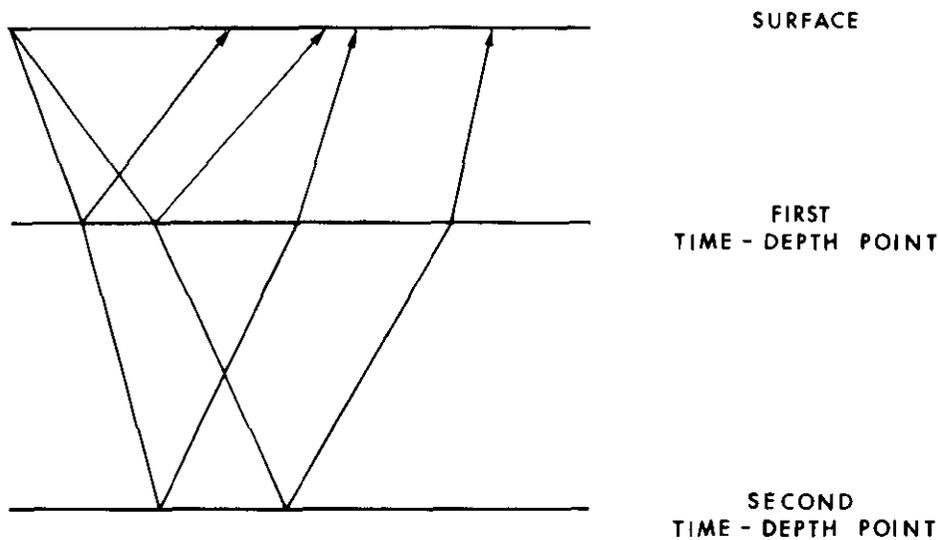

FIG. 5.—Velocity cross-section showing theoretical ray paths.

given in the velocity data.   The assumption of uniform velocity between adjacent depth levels is inherent in this method.

The first phase of the program tabulates surface distance and time of emergence of rays reflected from each of the given depth levels.   For each level up to 70 ray paths are tabulated representing initial angles that vary at one degree intervals from one to seventy degrees as shown in figure 5.   Data for a given level are terminated when refraction occurs or when one point of emergence is tabulated that is beyond the furthest distance for which the NMO table is to be calculated.   The results of these time-distance calculations are illustrated graphically as NMO Table 1 in figure 6.
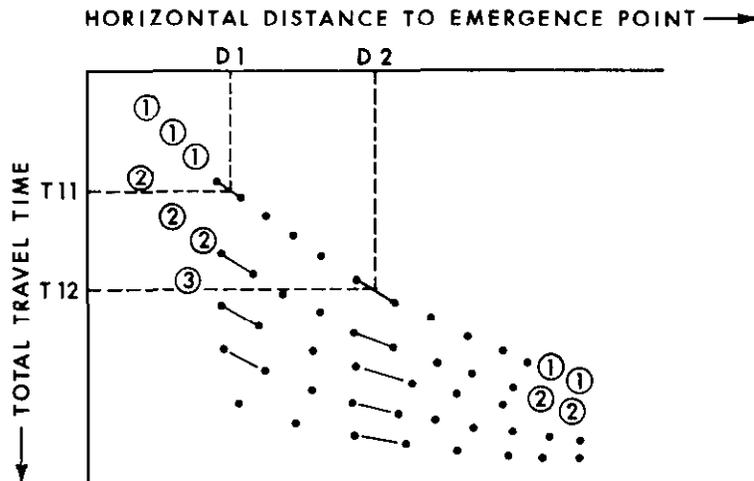

FIG. 6.—NMO table 1.

The next phase of the program evaluates arrival times from each level for given distances by linear interpolation between points of emergence as given in Table 1.   The results are placed in Table 2, which contains record times arranged by depth level within distance.   These results are checked for increasing time with increasing depth and/or distance. Figure 7 illustrates a portion of Table 2 and shows the graphic representation of the first column in Table 2.

The final phase of the program uses Table 2 together with the centre trace times to produce a NMO table for each of the specified distances. As shown in figure 8 the first entry in each table is the movement at the end of the first segment.   The next entry is the number of samples that must be moved intact to arrive at the time at which entry one applies. The subsequent entries are a series of segment lengths indicating the number of samples to be moved directly from the input trace to the output trace before an interpolated value is inserted in the output trace.

The output from the program is a file of NMO tables recorded on the disk and if desired a listing of the tables on the printer.
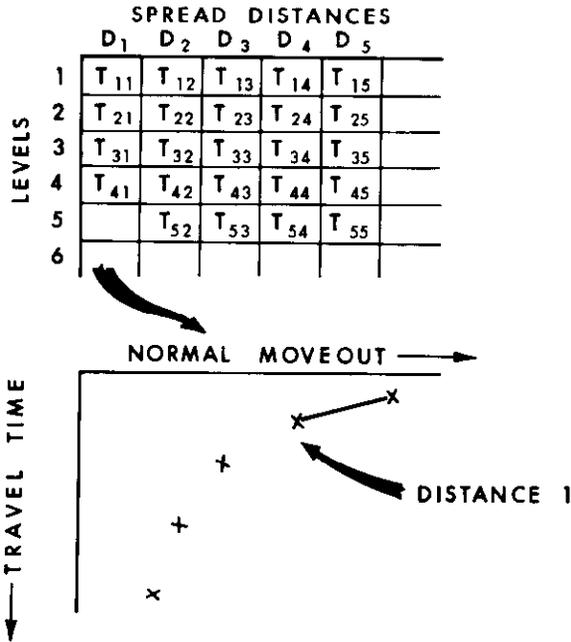
FIG. 7.—NMO Table 2. Table of interpolated total travel times.

DISTANCE 1

NMO FOR FIRST LEVEL	INITIAL MOVE	NO. OF SAMPLES	NO. OF SAMPLES	
25	100	3	3	

DISTANCE 2

NMO FOR FIRST LEVEL	INITIAL MOVE	NO. OF SAMPLES	NO. OF SAMPLES	
30	110	2	3	

DISTANCE 3

NMO FOR FIRST LEVEL	INITIAL MOVE	NO. OF SAMPLES	NO. OF SAMPLES	
35	120	2	2	

FIG. 8.—NMO Table 3.

DATA PREPARATION PROGRAM

The Data Preparation Program reads control cards and stores the control information used by the other programs on the disk. Surface distances from shot point to geophone are produced for the Normal Moveout Program. Stacking guides are produced for the Stacking Program and the Point Sort Program. The Data Preparation Program can process up to 255 shot points in one line and can produce up to 18 traces stacked at one depth point.
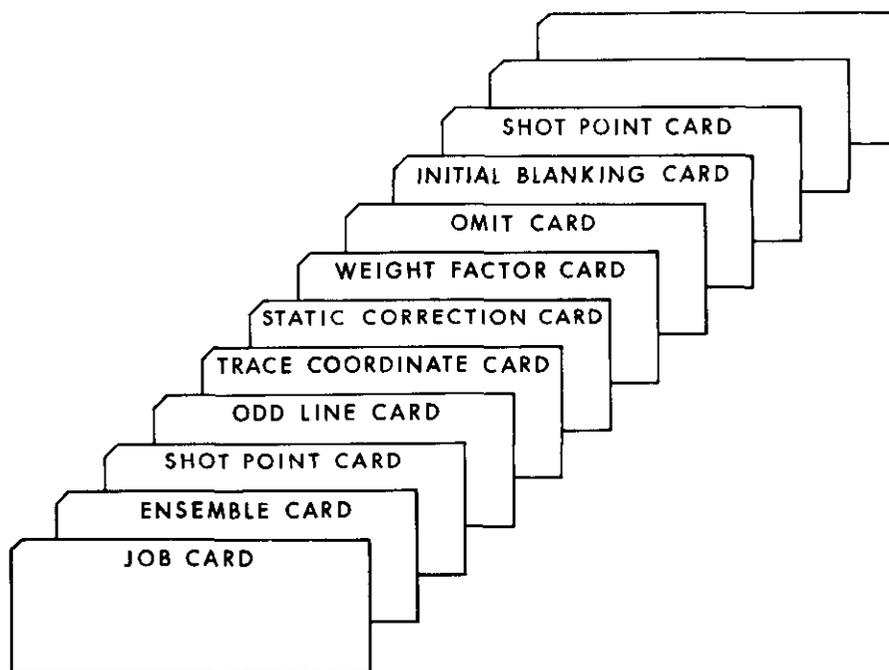

FIG. 9.—Data preparation control cards.

Figure 9 shows all of the possible control cards that are read by the Data Preparation Program. The Job Card specifies the job number, line number and number of shot-points. A number of control parameters such as whether or not stacking will be performed, the radius error for stacking and the input and output sampling rate. A base leveling switch is set and the beginning and ending sample number of the trace window to be used in computing base level and normalization factors is specified. Another logical program switch controls the amount of printed output produced by the Data Preparation Program.
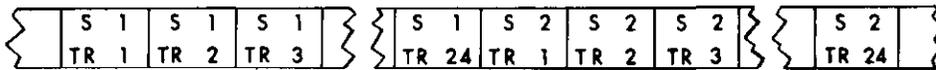
The Ensemble Card applies to 24 traces of each shot point and it indicates whether or not a particular trace is to be used in the Point Sort Program. If the Point Sort Program is not going to be used this card

may be omitted. The shot point card specifies the field tape identification and the X and Y co-ordinates of the shot point. The first trace distance and last trace distance in the direction of the line are specified along with the NMO table identification number and the time from the start of the recording to the time break. If the same static correction is to be used for all traces the value is specified on this card.

The Odd Line Card specifies any deviation from the standard geophone station spacing for the line. The Trace Co-ordinate Card specifies the X and Y co-ordinates for five geophone stations. These cards are used to define crooked spreads. The Static Correction Card specifies the static corrections for each trace, 12 corrections per card. The Weight Factor Card specifies the weighting factor, from one to nine, for each trace pertaining to this shot point. The Initial Blanking Card species the number of traces to be omitted from the beginning of trace 1, trace 2, . . . trace 24. The number of samples for 12 traces can be punched in one card.

If printing has been specified in the Job Card a Distance Table listing will be produced by the Data Preparation Program. This listing consists of the shot point to subsurface incident point distance, the X and Y co-ordinates of the incident point and the shot point number and trace number of all traces common to this subsurface incident point.
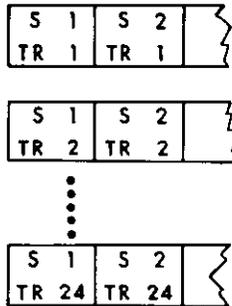

FIG. 10.—Demultiplex program.

DEMULTIPLEX PROGRAM

The Demultiplex Program rearranges seismic data from a gapped multiplexed trace file into a record-by-trace file. The program is written to process records composed of 100 time intervals from 30 data channels. Data channels 3-14 and 16-27 represent the seismic traces 1-24, the other channels are ignored. The general concept of the demultiplexing program is illustrated in figure 10. The program reads the input records into buffer areas and demultiplexes until a partial trace buffer is completed. These partial trace buffers are written on disk until a seismic record is completed. The partial traces are then read back into full *trace buffers and written on the record-by-trace tape file. The trace* buffer contains either two or three complete traces. Input and output files are double buffered in core to allow overlapping of disk reading and writing with tape reading and writing, and both with computing.

Program efficiency is dependent on buffer sizes in core and on the disk. For this reason different programs have been written for 65,000 byte storage machines and larger machines having 131,000 bytes of core storage. These programs also allot buffers differently depending on whether or not the trace requires more or less than 5,000 bytes. The tape record-by-trace file (demultiplexed file) has a 40 character line header record as its first record. The header record is produced by the Data Preparation Program and stored on the disk. All other records represent one trace of seismic data.

NORMAL MOVEOUT APPLICATION

This program applies time break, static and normal moveout corrections to digital traces and, upon request, calculates a base level factor so that all traces can be adjusted to an equivalent mean ampliture before stacking. For each shot point the appropriate shot point information record is read from the disk. The time break correction is applied first and the amount of useable information is adjusted accordingly.

If the proper normal moveout table is not already in core it is brought into core from the disk. The first entry is the total moveout at the first input level at which moveout can be calculated for this level. The next entry is the number of samples that must be moved intact to reach this level. As indicated in figure 11 all subsequent entries are segment lengths which indicate the number of samples to be moved directly from the uncorrected trace to the corrected trace before an interpolated sample is placed in the corrected trace. Within each segment the moveout is constant. Between adjacent segments the moveout differs by one sample interval. This table is used until the proper number of samples have been moved to the correct trace.

Static corrections are applied after moveout by moving the corrected trace the amount of the static. In the program this is actually done by adjusting a pointer to the output area rather than actually moving the trace. This method of static application is based on the assumption of the same velocity profile beneath each shot point. The program is writ-

NMO FOR FIRST LEVEL	INITIAL MOVE	NO. OF SAMPLES	NO. OF SAMPLES	⋯	NO. OF SAMPLES	NO. OF SAMPLES
2 5	100	3	3		7	10

NMO = 3

INPUT AREA

| 1990 | 1992 | 1994 | 1996 | 1998 | 2000 | 2002 |

OUTPUT AREA

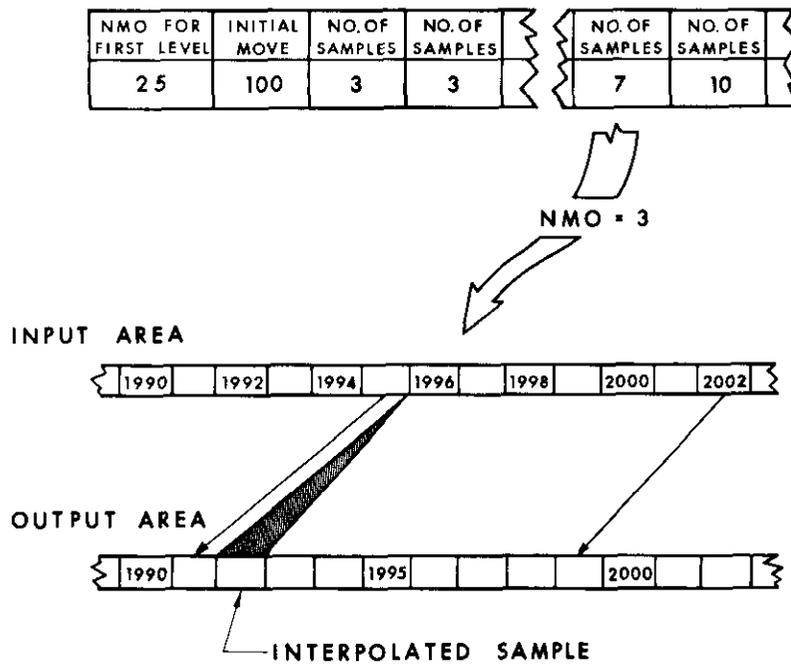| 1990 | | | | 1995 | | | | 2000 | | |

INTERPOLATED SAMPLE

FIG. 11.—NMO Table 3. Table for distance 1.

ten to overlap input with computing. Core requirements based on 65,000 bytes do not allow overlap of the output thus the program operates at approximately tape speed. The output consists of a corrected record-by-trace file on tape suitable for filtering, point sorting, stacking or multiplexing. The first 8 bytes of each trace are appropriated for identifying information such as the shot point sequence number, the trace number, the point sort sequence number and the base level factor.

AUTOCORRELATION FUNCTION AND THE POWER DENSITY SPECTRUM

Frequently a seismic interpreter requires more detailed information about the frequency-energy relationship of a seismogram in order to specify the best filter for signal to noise improvement. The progarm accepts the digitized amplitude values of an interval of up to 2500 sample points. The sample spacing (ΔT) and the frequency increment (Δw) at which the power density spectrum is to be calculated are entered as input information along with the number of time lags (maximhm of 225), the number of sample points to use and the sample number of the

starting point. The program computes the autocorrelation function and the power density spectrum and prints the values one per line.

Figure 12 illustrates the mathematical methods used for the calculation. The reference for these programs is:

$$1. \ X \text{ AVERAGE} = \frac{1}{N} \sum X_{(I)} \quad I \text{ FROM 1 TO N}$$

$$2. \ X'_{(I)} = X_{(I)} - X \text{ AVERAGE}$$

$$3. \ R_{(K\Delta T)} = \frac{1}{N-K} \sum (X'_{(I)} X'_{(I+K)}) \quad I \text{ FROM 1 TO N-K}$$

$$X_{(I)} = \text{THE } I^{TH} \text{ SAMPLE}$$

$$N = \text{NUMBER OF SAMPLES}$$

$$\Delta T = \text{SAMPLE SPACING}$$

K GOES FROM 0 TO THE NUMBER OF LAGS

**THE ESTIMATE
OF THE
POWER DENSITY SPECTRUM**

$$F_{(P\Delta W)} = 2\Delta T \left(R_0 + 2 \sum R_{(K\Delta T)} \cos(2\pi P\Delta W K\Delta T) \right)$$

$$P \text{ GOES FROM 1 TO } \frac{1}{2\Delta T \Delta W}$$

$$\frac{2}{TN} \leq w \leq \frac{1}{2\Delta T}$$

K GOES FROM 1 TO THE NUMBER OF LAGS

TN = LENGTH OF THE SERIES INTERVAL

FIG. 12.—Approximation to the autocorrelation function.

• RWAC2F, Autocorrelation Function Generation

• PWDS2F, Power Spectral Density Function
These two programs were written in 704-SAP by TRW Systems, 1 Space Park, Redondo Beach, California.

The autocorrelation program examines the normal moveout done bit in the line header record to determine if normal moveout has been done. If normal moveout has been done, the record number and trace number are taken from the first 8 bytes of each trace record. If normal moveout has not been done the seismic data start at the beginning of the trace record and the trace results are numbered sequentially.

JOHN G. DAWSON

BAND PASS FILTERING

Filtering is the process of removing undesirable components from a signal. In most cases, this is done by attenuating the amplitude contribution of selected frequencies from the seismic trace. The Band Pass Filtering Program performs two basic functions. The first is to compute the coefficients for a filter operator based on input parameters which describe the transfer function of the desired filter. The program will also read coefficients from cards should the user want to use other coefficients. The second function is the application of the filter operator to one or more traces by convolving the operator with the trace. The technique used to compute this operator is described in a paper entitled "Design of Numerical Filters With Applications to Missile Data Processing" by Joseph F. A. Ormsby. This paper appeared in the Journal of the Association for Computing Machinery, July 1961.

The method for the calculation of the low pass coefficients is illustrated in figure 13. The high pass coefficients are computed in terms of the
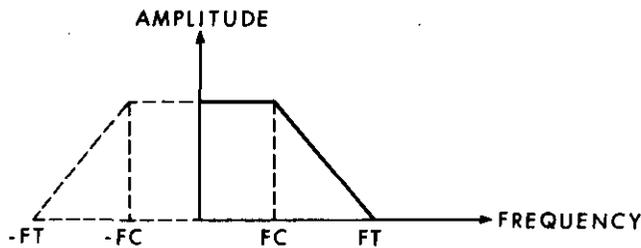
$$H_{(N)} = \frac{\cos(2\pi N \, FC/SF) - \cos(2\pi N \, FT/SF)}{2\pi N^2 (FT - FC/SF)}$$

FC = CUTOFF FREQUENCY IN CYCLES / SEC.

FT = TERMINAL FREQUENCY IN CYCLES/SEC.

SF = SAMPLING FREQUENCY IN CYCLES/SEC.

N = NUMBER OF COEFFICIENTS : 1, 2, 3, ··· N

FIG. 13.—Calculation of the filter operator. Low-pass filter.

low pass coefficients by using FC=F1 and FT=F2 as illustrated in figure 14. The notch filter coefficients can be computed from a low pass and a high pass filter. Compute the low pass coefficients using FC=F1 and FT=F2. Compute the high pass coefficients using FC=F3 and FT=F4.

AMPLITUDE

FREQUENCY

$-F2$ $-F1$ $F1$ $F2$
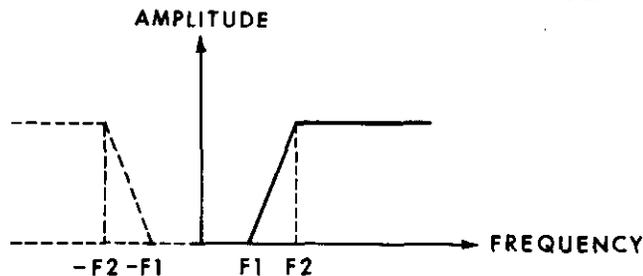
SET FC $=$ F1

FT $=$ F2

USE LOW PASS EQUATION TO CALCULATE $H_{(N)}$

HIGH PASS		LOW PASS
$H_{(0)}$	$=$	$1 - H_{(0)}$
$H_{(N)}$	$=$	$-H_{(N)}$

WHERE N $=$ 1, 2, ..., N

FIG. 14.—Calculation of filter operator. High-pass filter.

AMPLITUDE

NOTCH
FILTER

FREQUENCY

F1 F2 F3 F4

AMPLITUDE

BAND PASS
FILTER

FREQUENCY

F1 F2   F3 F4

AMPLITUDE

MATCHED
FILTER

FREQUENCY
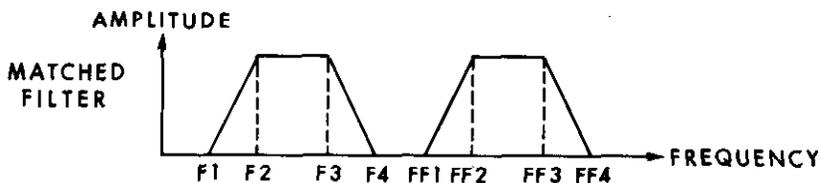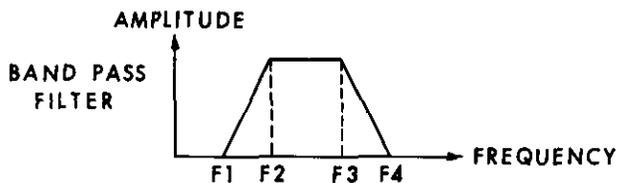
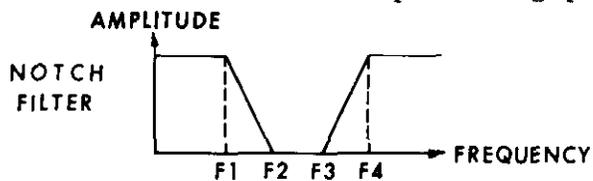F1 F2   F3 F4 FF1 FF2   FF3 FF4

FIG. 15.—Calculation of filter operator. a) Notch filter, b) Band-pass filter, c) Matched filter.

The values for F1 to F4 are illustrated in figure 15. The notch filter coefficients are then calculated using the following formula:

Notch		Low Pass		High Pass
$H(N)$	$=$	$H(N)$	$-$	$H(N)$

$$\text{Where } N = 0, 1, 2, \ldots, N$$

A Band Pass Filter as shown in figure 15 can be calculated by constructing a notch filter as before and using the following:

Band Pass		Notch
$H(O)$	$=$	$1 - H(O)$
$H(N)$	$=$	$-H(N)$

$$\text{Where } N = 0, 1, 2, \ldots, N$$

Similarly the Matched Filter, alo shown in figure 15, can be produced from two band pass filters. Construct a band pass filter for F1, F2, F3, F4 and for FF1, FF2, FF3, FF4 then the matched filter is given by:

Matched		Band Pass (F)		Band Pass (FF)
$M(N)$	$=$	$H(N)$	$+$	$H(N)$

$$\text{Where } N - 0, 1, 2, \ldots, N$$

To apply the filter, the following formula is used for all filters:

$$SF(M) = H(O) * S(M) + \overset{N}{\underset{N-1}{\text{SUM}}} H(N) \, (S[M] + N) + S(M - N)$$

$SF(M) = $ Filtered output at the Mth sample interval

$S(M) = $ Input value of the Mth sample interval

$H(N) = $ N the weighting factor of the linear filter operator

POINT SORT PROGRAM

The purpose of the point sort program is to gather traces from common depth points. The traces may then be displayed side by side and the alignment checked before stacking. The Data Preparation Program generates sequence numbers for the traces and these sequence numbers are then written in each trace header by the Normal Moveout Application Program. The Point Sort Program reads the trace, calculates a disk address based on the sequence number and writes the trace on the disk. When all traces have been written on disk the multiplex program is called and the traces are multiplexed and written on the output tape. A disk can hold up to 600 traces. If more than 600 traces are on the input file they will be processing in multiples of 600.

Since the Point Sort and Multiplex Programs call each other, both must reside in the disk program library. The disk and tape read and write plus the compute time are overlapped so the program runs at tape speed.

STACKING PROGRAM

The stacking program performs the function of compositing traces according to the common depth point principle. The Data Preparation Program calculates a disk address for each trace corresponding to its common depth point. The Stacking Program reads the composite trace located at the specified disk address into core storage. The current trace is summed with it and the new composite trace replaces the original one on the disk. At any point during the processing the disk contains partially stacked traces which will become completely stacked when all the input traces have been processed. Setting the disk to zeros is a necessary prelude to this method of stacking.

Input to the Stacking Program consists of traces which have been processed by the Normal Moveout Application Program and the shot point information records stored on the disk by the Data Preparation Program. The Stacking Program applies base leveling to the input traces, creates normalizing constants and normalizes the stacked output. The polarity of any trace can be reversed, the initial portion of the traces can be blanked and a weighting factor may be applied to individual traces. The maximum length of any given line to be processed by this program is limited by the amount of output which is 600 stacked traces.

MULTIPLEX PROGRAM

The Multiplex Program rearranges seismic data from the record-by-trace file into a gapped multiplexed file as shown in figure 16. The
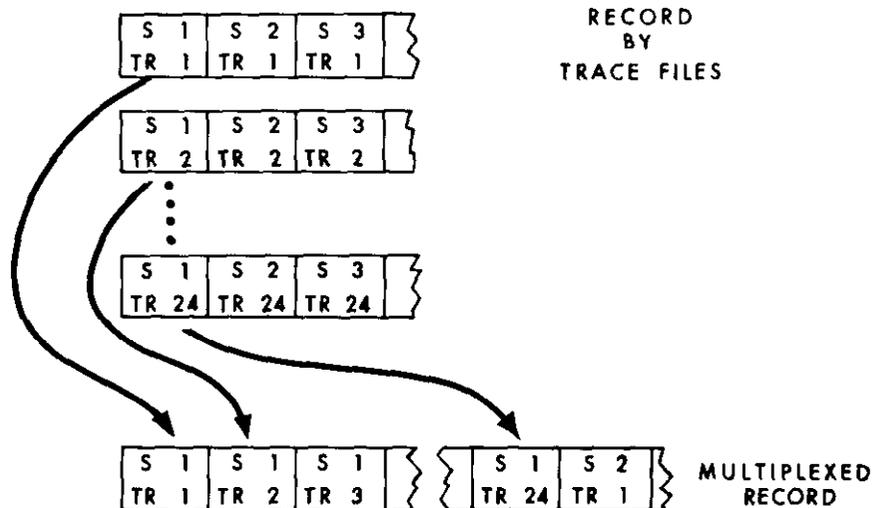

FIG. 16.—Multiplex program.

multiplexed file consists of records made up of 100 time intervals from 30 data channels. Data channels 3-14 and 16-27 represent seismic traces 1-24, the other channels are ignored.

The Multiplex Program reads into trace buffers from the record-by-trace tape and writes onto partial trace files on disk until a seismic record is complete. The partial trace files are then read into core and multiplexed. The gapped multiplexed tape file is written as records are completed. Both tapes and disk are double buffered in core to allow overlapping of disk reading and writing with tape reading and writing and both with computing.

TIMING FACTORS

Timing factors affecting the running time are based on experience with an IBM System/360 Model 40 Computer. The Normal Moveout Computation and the Data Preparation Program operate faster than the printer can output the results. The Data Preparation Program running time is also dependent upon the number of shot points in the line as is the Autocorrelation Function and Power Density Spectrum Program. The Demultiplex Program is dependent upon the number of samples and the magnetic tape speed. The Point Sort Program, the Stacking Program and the Multiplex Program have their running times largely dependent upon the transfer speed of the magnetic tape drives. The Normal Moveout Application Program is also dependent upon the tape speed unless base levelling is performed.

The Band Pass Filtering Program is completely dependent upon the internal speed of the computer. The time spent applying a digital operator to a 24 trace record can be much larger than the total time spent performing all the other operations. For this particular computer application there have been a number of special features produced to reduce the time spent in convolving the filter operator with the trace. The Band Pass Filtering Program makes use of one of these features if it is installed on the machine and will realize an increase in speed of about 4.5 to 1.