REVERSIBLE SEISMIC DATA COMPRESSION

By

MEEMONG LEE

Bachelor of Science in Electronic Engineering
Sogang University
Seoul, Korea
1975

Master of Science
Oklahoma State University
Stillwater, Oklahoma
1979

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in Partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
December, 1981

REVERSIBLE SEISMIC DATA COMPRESSION

Thesis Approved:

Rao Yarlagadda
Thesis Adviser

J. Chandler

James R. Rowland

Bennett Basore

C. M. Bacon

Norman N. Durham
Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to express my deep appreciation to my thesis adviser, Dr. Rao Yarlaggada, who has encouraged, guided, and advised me throughout this research. I would also like to thank the committee members, Dr. B. L. Basore, Dr. J. P. Chandler, Dr. D. R. Gimlin, and Dr. J. R. Rowland, for their review and valuable criticism of my manuscript.

Financial support was received from AMOCO. Dr. J. L. Schanks and the geophysics research group of AMOCO have helped with this research. They are gratefully acknowledged for their interest in this work.

Finally, I would like to express my sincere thanks to the peopie who have been indispensable in my graduate study abroad: first, to my parents for their understanding and love, and second, to Dr. and Mrs. Walker for their kindness and friendship.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure | Page

Figure | Page

CHAPTER I

OVERVIEW OF DATA COMPRESSION

Introduction

At the present time, analysis of seismic data is based upon a bulk of data collected from the field, recorded onto tapes, and transported to the research center where it is analyzed for possible use. This procedure introduces a delay in the analysis and usually will not allow for on-line decision. With recent developments in telecommunications, it has been found to be desirable to transmit the data via satellite in order to reduce delay time. However, the bit rate for telecommunications is limited and the cost for transmitting a large amount of seismic data may be prohibitive. For these reasons, the seismic data need to be compressed before transmission over communication channels. This thesis is devoted to the development of a seismic data compression method for satellite transmission.

Data Compression

Data compression can be viewed as any method of representing source data in an efficient manner while maintaining the required information content. An efficient representation of the source data can be obtained first, by reducing the redundant information; second, by reducing the bandwidth; and third, by efficient coding techniques [1]. The usage of the term "data" in this thesis is to indicate any digitized signal to be transmitted or stored. In order to avoid confusion, "information" is defined as a measure of the full range of important features contained in a set of data. This definition differs from the information theoretic definition, where it is used as a quantitative measure of information content. Both definitions are used in this work and the difference will be apparent from context. Such data compression is required due to storage constraints, digital computer memory size, limited bandwidth in communication links, limited capacity in channels, or by the desire of extracting important attributes from the source data.

Data compression can be defined in mathematical terms using the concept of entropy which, in simple terms, is referred to as the average information content measured as a number of information units (bits). The mathematical derivation of data compression, alternatively entropy compression, is given below.

The entropy can be written as [2]

$$H = -\sum_{i=1}^{D} p_i \log_2 p_i \ \text{(bits/configuration)} \qquad D = N^K \tag{1.1}$$

where K is the number of data, N is the number of quantization levels of data, and p_i is the probability of the ith configuration. Also, the information content of the ith configuration is given by

$$I_i = -\log_2 p_i \ \text{(bits)}. \tag{1.2}$$

When there is no redundancy in the data or every configuration has the same probability, the entropy is maximum and it is expressed as

$$H_{max} = K \log_2 N \ \text{(bits/configuration)}. \tag{1.3}$$

The redundancy ratio (R) is defined by

$$R = \frac{H_{max} - H}{H_{max}} . \tag{1.4}$$

The entropy compression ratio (C) can be defined by

$$C = \frac{H_{max}}{H} = \frac{K \log_2 N}{\sum_{i=1}^{D} p_i \log_2 p_i} = \frac{1}{1 - R} . \tag{1.5}$$

Equation (1.5) shows that the maximum entropy of transformed data can approach their own entropy by reducing the redundancy of the data (K), and/or by reducing the redundancy from the quantization levels (N), both of which result in reducing the number of possible configurations (D).

Most of the present data compression methods are combinations of the following methods; these include: entropy reducing transform [2], prediction [3], interpolation [4], orthogonal transforms [5], and digital code representations [6]. The five general data compression techniques mentioned above are examined in relation to entropy compression below.

Some entropy reducing transforms achieve data compression by deleting a portion of information in source data. For example, filtering (low-pass, high-pass, or band-pass) is one form of an entropy reducing transformation. Usually this method is applied when intelligibility is the main objective, and a portion of the data in terms of either time or frequency is used in extracting the desired information.

The prediction method can be used to compress data when a system model is available. Assuming that the system model is incorporated in a prediction algorithm at the receiver and the transmitter has a way of acknowledging the predicted value with no channel errors, it is acceptable to omit data which can be predicted at the receiver [3]. It is clear that the number of data to be transmitted can be reduced, and thus maximum entropy is compressed. Another advantage of this method, for entropy compression, can be realized by transmitting the difference between the source data and the predicted value (prediction error). This advantage can be seen because the prediction error variance is less than the variance of the source data. The minimization of the prediction error variance can be achieved by various techniques. These will be discussed in detail later.

The interpolation method [4] estimates the values between a given transmitted value and the most distant possible point, such that the maximum interpolation error is below the preset threshold. One simple example of interpolation techniques in data compression would be approximation of the source data by polynomial segments.

Orthogonal transforms are used in data compression because of their properties in representing data with linearly independent eigenvectors, thus reducing the redundancies. Data compression can be achieved if fewer numbers of transformed vector coefficients can represent the source data. This depends on the statistical characteristics of the source data.

Finally, the digital code representation achieves data compression by reducing the number of quantization levels while maintaining tolerable quantization error. When sampling an analog signal, the original bit rate is determined by the number of quantization levels employing the maximum entropy (Equation (1.3)). Assuming that there is a high rate of redundancy, the original bit rate can be reduced with an efficient code representation, thus achieving entropy compression.

Common application of data compression are found in systems for communications, speech and image processing, and pattern recognition [1].

A Thesis Review

Chapter II examines seismic data acquisition and reviews previous efforts in seismic data compression. In this thesis vibroseis data and impulsive seismic data are used for the proposed data compression. In order to visualize the characteristics of seismic data, statistics are measured and displayed. The proposed approach for "reversible seismic data compression" is discussed in relation to the statistical characteristics of seismic data.

In Chapter III, the proposed techniques are compared with other candidates and their performances are evaluated. First, orthogonal transforms, such as the Karhunen-Loéve transform, the Walsh-Hadamard transform, the discrete Fourier transform, and the discrete cosine transform are briefly examined and their compression ratios on seismic data are compared. Second, digital coding techniques are discussed in two steps, quantization methods and cosine representations. Brief derivations of signal-to-noise ratios are discussed for each technique, and their performance on seismic data compression is compared.

Chapter IV discusses compression methods for vibroseis data and impulsive seismic data. The vibroseis data compression is examined in the following order. First, the hybrid technique is introduced with respect to its compression ratio and signal-to-noise ratio relations. Second, the selection method is examined in terms of threshold. Third, μ-law quantization is studied in detail. Fourth, the implementation considerations are discussed. The impulsive seismic data compression is examined in three stages: data slicing, predictive coding using an optimum linear predictor, and its implementation. Finally, the results are evaluated for both types of seismic data.

In Chapter V, the general applications of satellite communications are examined. Compressed seismic data transmission via satellite is studied with respect to its time and space configurations.

Finally, Chapter VI suggests possible future research areas for the "reversible seismic data compression."

Summary

The main interests in data compression techniques are the compression ratio (CPR) and the distortion rate, often called the "signal-to-noise ratio" (SNR) [1]. This study defines the CPR as the ratio between the bit rate of the original signal and the compressed signal. The SNR is defined as the ratio between energy of the original signal and the noise, where the noise indicates the difference between the original signal and the reconstructed signal.

Data compression techniques can be divided into two categories, irreversible and reversible compression. In order to distinguish one from the other, reversibility should be defined. In general, techniques which can reconstruct the original data with an adequate error fidelity criterion are defined as reversible data compression techniques. When the original data cannot be reconstructed due to compression techniques, they are called irreversible techniques [2].

The entropy reducing transforms are irreversible data compression techniques, since some parts of the original signal have been discarded. For irreversible techniques, SNR cannot be considered. Rather, subjective measurements, such as human intelligibility, are considered as a measure of their performances.

The prediction, interpolation, orthogonal transforms, and digital coding representation methods are all reversible. However, the reconstructed data include the process error. The process error is defined as all the errors involved in techniques of compression and decompression. They include prediction error, interpolation error, transformation error, and quantization error. For reversible techniques, SNR is the measure of their performance. However, it is hard to determine the threshold of error fidelity when the original data have involved large noise. For this reason, the original data are assumed to be ideal in this thesis.

The development of a "reversible seismic data compression" technique is pursued, where "reversible" indicates that the original seismic data can be reconstructed with approximately a 30 dB signal-to-noise ratio. Figure 1 gives the block diagram identifying the noise (E_i) introduced at various locations. In this study the processed noise, denoted by E_2, is of interest.

The next chapter deals with seismic data acquisition methods, previous work, the proposed approach for seismic data compression, and statistical characteristics of seismic data.

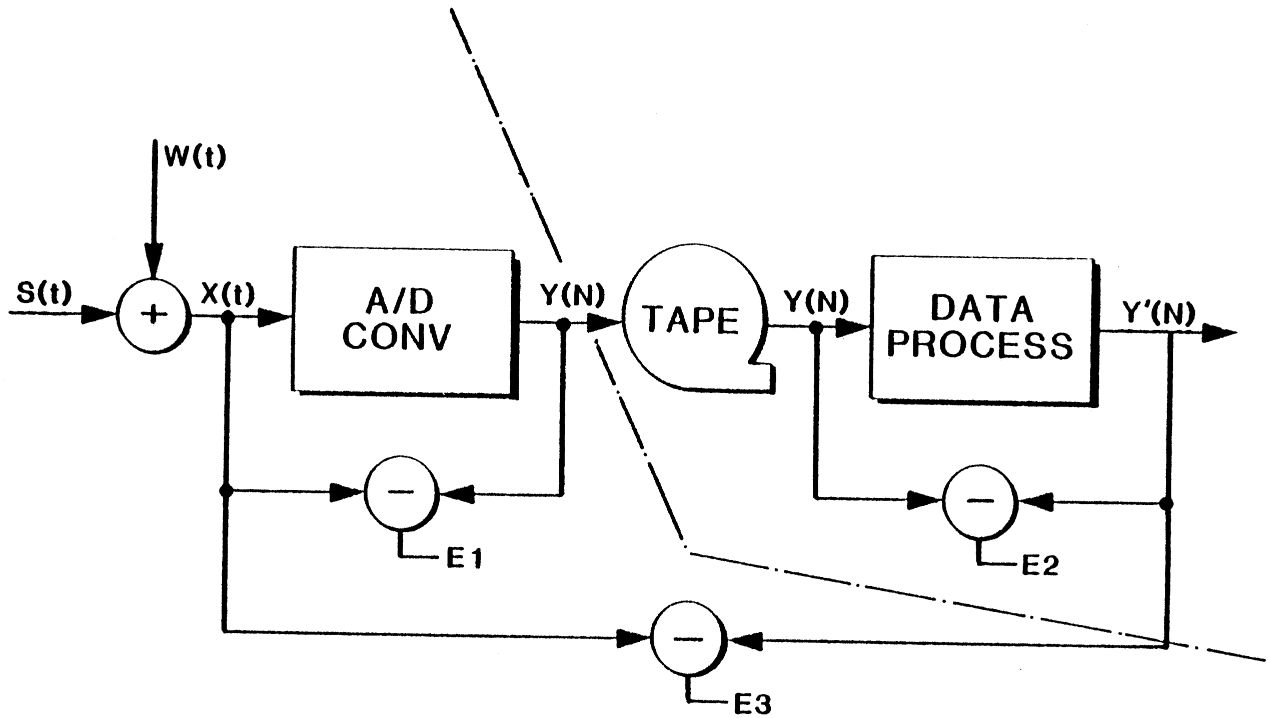


Figure 1. Simulation of Seismic Data Compression Techniques

CHAPTER II

GENERAL CONSIDERATIONS ON SEISMIC DATA COMPRESSION

Introduction

In Chapter I, a brief overview of data compression was introduced, with respect to general compression techniques in relation to entropy reduction.

This chapter focuses on several seismic data compression considerations. First, the basic concepts of seismic data acquisition are examined, with example cases of acquisition corresponding to vibroseis and impulsive inputs. Second, previous work on seismic data compression is reviewed and its performance is evaluated with respect to reversible considerations. Third, a reversible seismic data compression scheme is viewed and directions for this proposed approach are discussed. Finally, various statistical characteristics of seismic data are examined and some important results are displayed.

Seismic Data Acquisition

As mentioned earlier, seismic data are collected from the field and recorded onto digital tapes. The essence of such a data collection system is illustrated in Figure 2 [7]. Robinson and Treitel describe the seismic data acquisition procedures as follows:

Disturbances created by seismic energy sources propagate through the earth, where interfaces between geophysical strata reflect spreading wave fronts. The receivers shown in Figure 1-2 [Figure 2 in this thesis] actually represent a composite group of transducers (seismometers). These groups may consist of up to 100 individual geophones laid out in various linear and spatial patterns, with group intervals (between group distance) ranging from 50 to 900 ft. Each time a source is activated it is common practice to record either 24, 48, or 96 group traces on digital tape simultaneously as a single recording (p. 74).

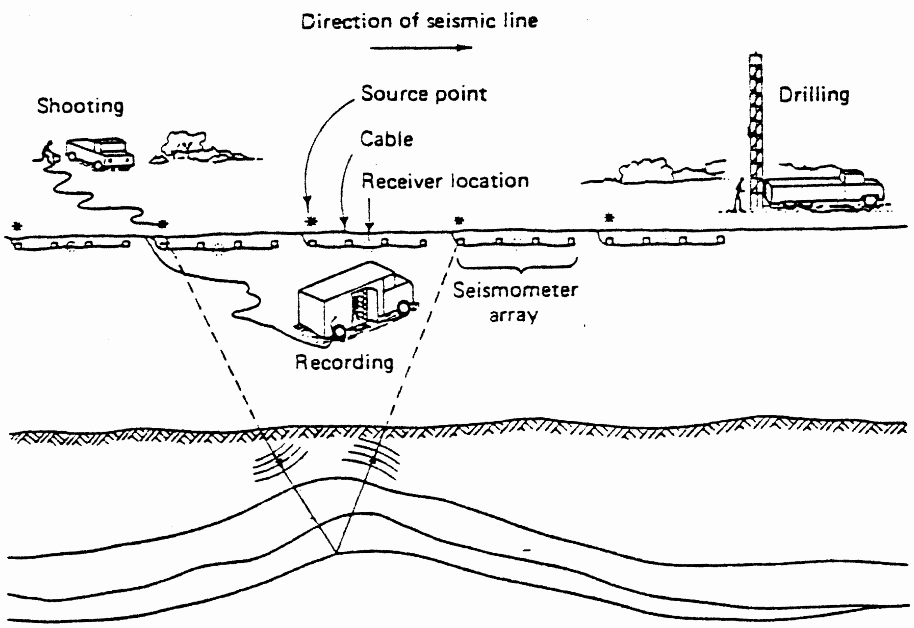


Figure 2. Seismic Data Acquisition (After Robinson and Treitel [7])

Robinson and Treitel state that many different types of energy sources are used to generate seismic waves. Dynamite and other high-energy explosive sources provide the simplest and most efficient means of releasing energy, but environmental considerations have led to the development of many alternative sources, such as explosive air guns, electrical sparks, vibrating chirp systems, and so on. The different types of energy sources require different compression techniques.

Seismic data compression will be investigated with vibroseis data and impulsive seismic data in this thesis, where vibroseis data refer to seismic data that are collected from the reflected wave generated by a vibrating chirp disturbance propagating through the earth, and impulsive seismic data refer to sesimic data that are collected from the reflected wave generated by a high-energy explosive source disturbance propagated through the earth. Examples of both types of seismic data acquisition environments are illustrated below.

In Appendix A, a set of vibroseis data is given. The data were sampled at 250 Hz for 19 seconds. Each time a vibrating chirp system was initiated, a group of 48 traces was simultaneously recorded onto a digital tape as a single recording, and is defined as a record. A 20 bit code consisting of 16 bits of mantissa and 4 bits of gain was used in this representation. The vibrating chirp system propagated a chirp signal ranging from 10 to 55 Hz for 14 seconds over the test interval.

Also, in Appendix A, a set of impulsive seismic data is given. The data were sampled at 1000 Hz for 1 second. Each time an explosion was initiated, a group of 198 traces was simultaneously recorded onto digital tape in a single recording. The same digital coding representation technique was used as in the vibroseis data case.

Due to the constraints in the bandwidth of communication links, and in storage, the bit rate (bits/second) and the block size (bits/block) are two important parameters for data compression considerations. A block is a number of seismic source initiations. In the following, the values of these parameters for the seismic data shown in Appendix A are given.

The bit rate (B) is

$$B = N_s \cdot F_s \cdot b \text{ (bits/second)} \tag{2.1}$$

where N_s is the number of traces in a record, F_s is the sampling rate, and b is the number of bits per sample. The block size (K) of the seismic data is

$$K = B \cdot N_t \cdot T \text{ (bits/block)} \tag{2.2}$$

where N_t is the number of tests performed and T is the sampling duration.

Using Equation (2.1), the bit rate of the vibroseis data (B_v) in Appendix A is

$$B_v = 48 \cdot 250 \cdot 20 = 192 \text{ k (bits/second)}$$

where $N_s = 48$, $F_s = 250$ H_z and b = 20 bits/sample. The bit rate of the impulsive seismic data (B_i) in Appendix A is

$$B_i = 198 \cdot 1000 \cdot 20 = 3920 \text{ k (bits/second)}$$

where $N_s = 198$, $F_s = 1000$ H_z and b = 20 bits/sample. Thus, the block size of the vibroseis data (K_v) is

$$K_v = 192\text{k} \cdot 16 \cdot 19 = 73 \text{ M (bits/block)}$$

where $B_v = 192$k, $N_t = 16$, and T = 19 seconds. The block size of the impulsive seismic data (K_i) is

$$K_i = 3960\text{k} \cdot 9 \cdot 1 = 1.8 \text{ M (bits/block)}$$

where $B_i = 3960$k, $N_t = 9$, and T = 1 second.

In general, 2400, 4800, 9600, and/or 56k baud rate (bits/second) are available for most communication links. Also most small computers have less than 256 k byte (2048 k bits) of memory size. Considering the above figures, the values of bit rate and block size for seismic data indicate that data compression is necessary in order to utilize a modern telecommunication system for transmission and for processing with mini- or microcomputers.

Data compression techniques have been investigated in many areas, such as speech and image processing. However, seismic data compression has not been investigated as thoroughly as the others. A review of one previous effort on seismic data compression is discussed in the next section.

Previous Work

A survey of previous seismic data compression yields one notable work by Wood [8], in which he used bandwidth limiting and efficient digital coding techniques. The results were obtained using two methods on a set of vibroseis data sampled at 500 Hz. These are data resampling and interpolation in the time domain and the Walsh transform, and sequency limiting and the Walsh inverse transform in the Walsh domain. These techniques are examined and evaluated below. In his paper, the resampling technique is a time domain compression technique described as follows.

From sampling theory [9], if a signal is bandlimited and sampled with anti-aliasing considerations, no information is lost through proper resampling and interpolation. Based on this statement, resampling (with averaging) is applied at 1/2, 1/4, and 1/8 of the original sampling rate at the transmitter. Then interpolation is performed at the receiver.

In the second method, the seismic data are transformed using the Walsh transform. Then sequency limiting is performed, by windowing the first major sequency range that contains 80 to 85 percent of the total energy. At the receiver, the data are buffered to their original size and then the inverse Walsh transform is applied. It has been found that resampling in the time domain amounts to sequency limiting in the Walsh domain and interpolation in the time domain amounts to the inverse Walsh transform. Flow charts corresponding to the above two methods are shown in Figure 3.

In the second stage, nonuniform quantization was applied with variable code word lengths for both methods. As illustrated in Figure 4, the step sizes are computed according to the probability densities of the data. The code word lengths are determined by the information rate of the quantization levels. For example, the first step size was illustrated to be 25.1, where 50 percent of the data could be represented. As shown in Equation (1.2), the information rate was computed as 1 bit; thus the code length was determined to be 1 bit.

In Wood's work [8], visible degradation in the final plotted seismic data was the measure of performance. Reversibility was not considered, since teleprocessing of the plot data was the major interest in his compression. In order to evaluate the applicability on reversible seismic data compression, the signal-to-noise ratios of the compression method given by Wood was estimated according to the percentage of the total energy he claimed to maintain in the Walsh domain. It was found to be approximately 7 dB without considering the processing error.

Wood pursued further compression by applying nonuniform quantization using an average of 3 bits per sample. This quantization introduces significant error. Though he claimed to achieve a 16:1 compression ratio, the signal-to-noise ratio (<7 dB) is too small to be of use for reversible seismic data compression. Also, it should be pointed out that the

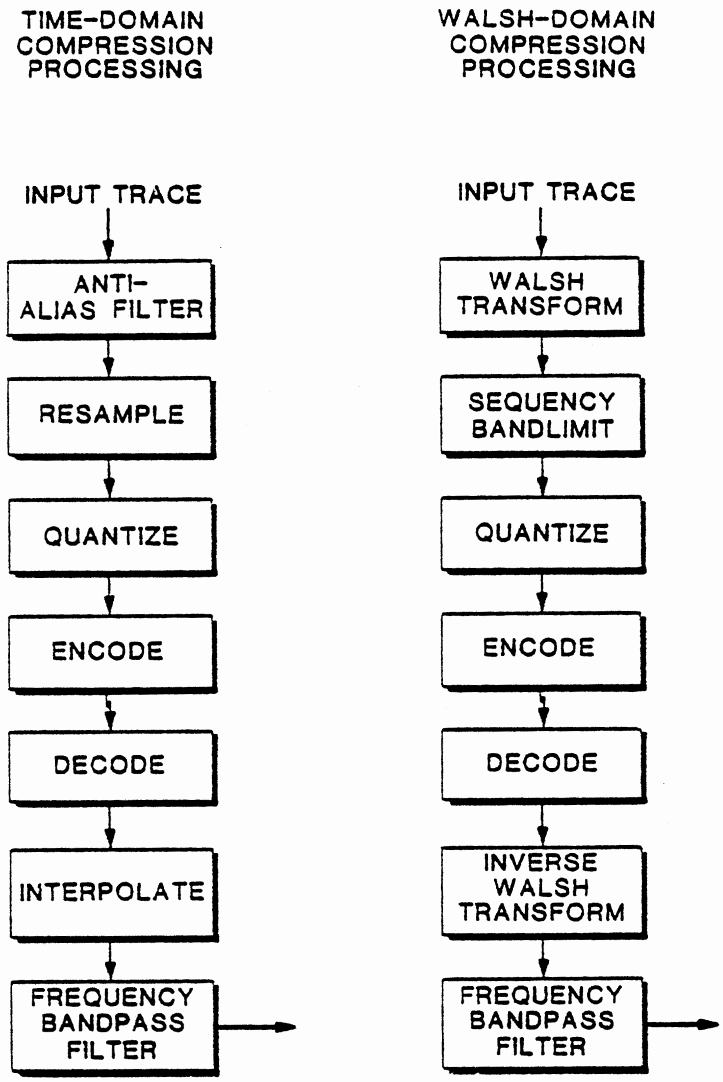


Figure 3. Data Compression Procedures
(After Wood [8])

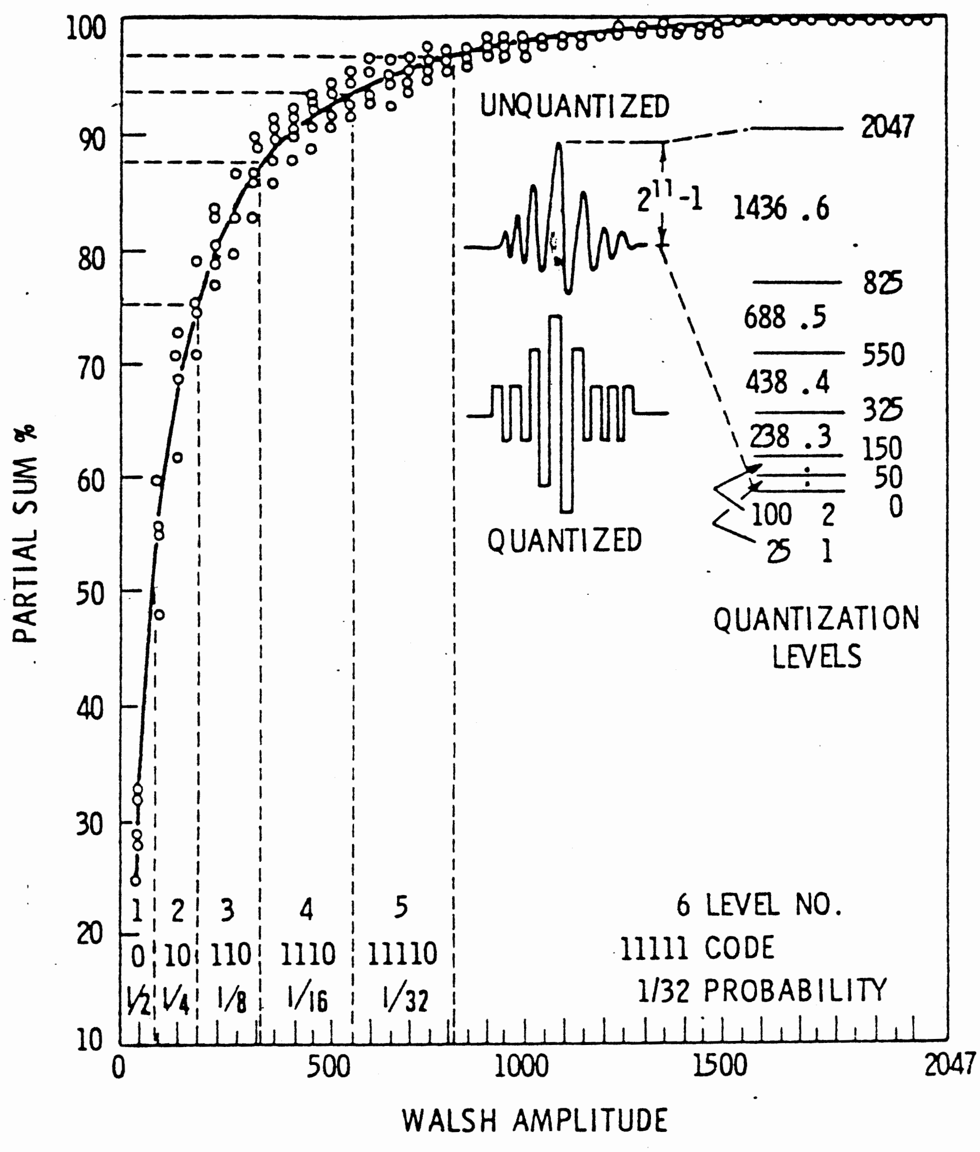


Figure 4. Non-Uniform Quantization (After Wood [8])

compression ratio is directly related to the sampling rate. This indicated that an 8:1 compression ratio is expected for the vibroseis data, because the sampling rate Wood used was 500 Hz instead of 250 Hz for the sample given in Appendix A. The proposed study examines alternative approaches for achieving seismic data compression with significant improvement in signal-to-noise ratio.

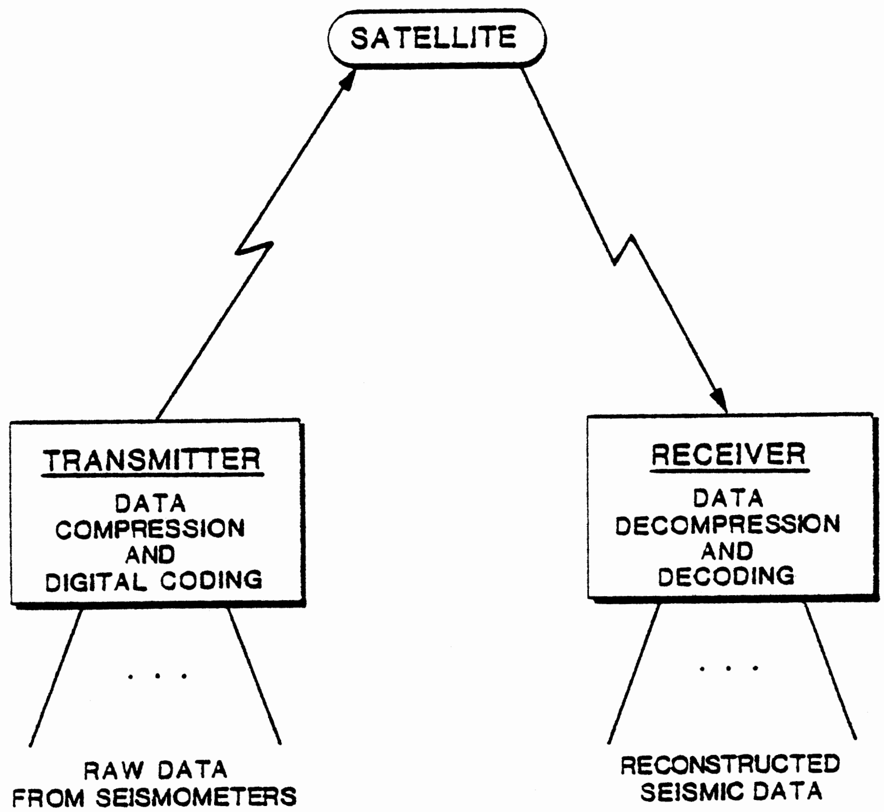
Proposed Approach

The proposed method of compression and decompression and satellite transmission is shown in Figure 5. The seismic data collected from the field are compressed and coded at the transmitter, and transmitted via satellite. The receiver performs decoding and decompression for reconstructing the original seismic data. The entire procedure involves data acquisition, data compression, satellite communication, and data reconstruction. This work will concentrate on the data compression and reconstruction for two types of seismic data, namely the vibroseis data and the impulsive seismic data. In Chapter V, the mechanics associated with satellite transmission and real-time implementation, such as time and space configurations and throughput considerations, will be discussed.

Before the compression methods are discussed, the statistical aspects of vibroseis data and impulsive seismic data need to be investigated. These are presented in the next section. The compression methods will be discussed in Chapters III and IV.

Statistical Analysis of the Seismic Data

It can be observed that signal processing techniques have been often developed based on a statistical model of signals [6]. For example, some



Available Baud Rate - 2400, 4800, 9600 and/or 56k bps
Reversible Data Compression - above 30 dB of SNR

Figure 5. Seismic Data Transmission via Satellite

digital coding methods for speech signals have been developed and evaluated under the assumption that the probability density function of speech signals can be modeled statistically as Laplace or Gamma probability densities. Similarly, it is necessary to obtain statistical models of seismic signals or to describe their statistical behaviors, so that an efficient compression technique can be chosen accordingly [10].

Statistical characteristics of seismic signals are examined with respect to several aspects. Such aspects would be statistical parameters, time-varying characteristics, the probability density functions, and correlation considerations in adjacent samples as well as in traces and tests. The term test indicates a source initiation in this thesis.

The statistical parameters include mean, variance, and peak-to-peak range. The examination of such parameters shows that the mean values are approximately zero for all traces and that the seismic data have nonuniform energy distribution among sensors. Amplitude distributions of several traces shown in Figure 6 illustrate symmetricity of seismic data. Figures 7a and 7b give a comparison of the peak values among traces and among tests. Figures 8a and 8b similarly compare the ratios between the peak value and the standard deviation.

For testing the stationarity of the seismic data, the time-varying characteristics are analyzed. This analysis has been performed on the seismic data trace by trace by dividing the sampling duration into time unit segments. For vibroseis data, one second is used as a time unit while 100 milliseconds are used for impulsive seismic data. The results are obtained by examining the statistical parameters mentioned above for each time unit interval. Figures 9a and 9b illustrate the time-varying characteristics for the peak values and the ratios between the peak value

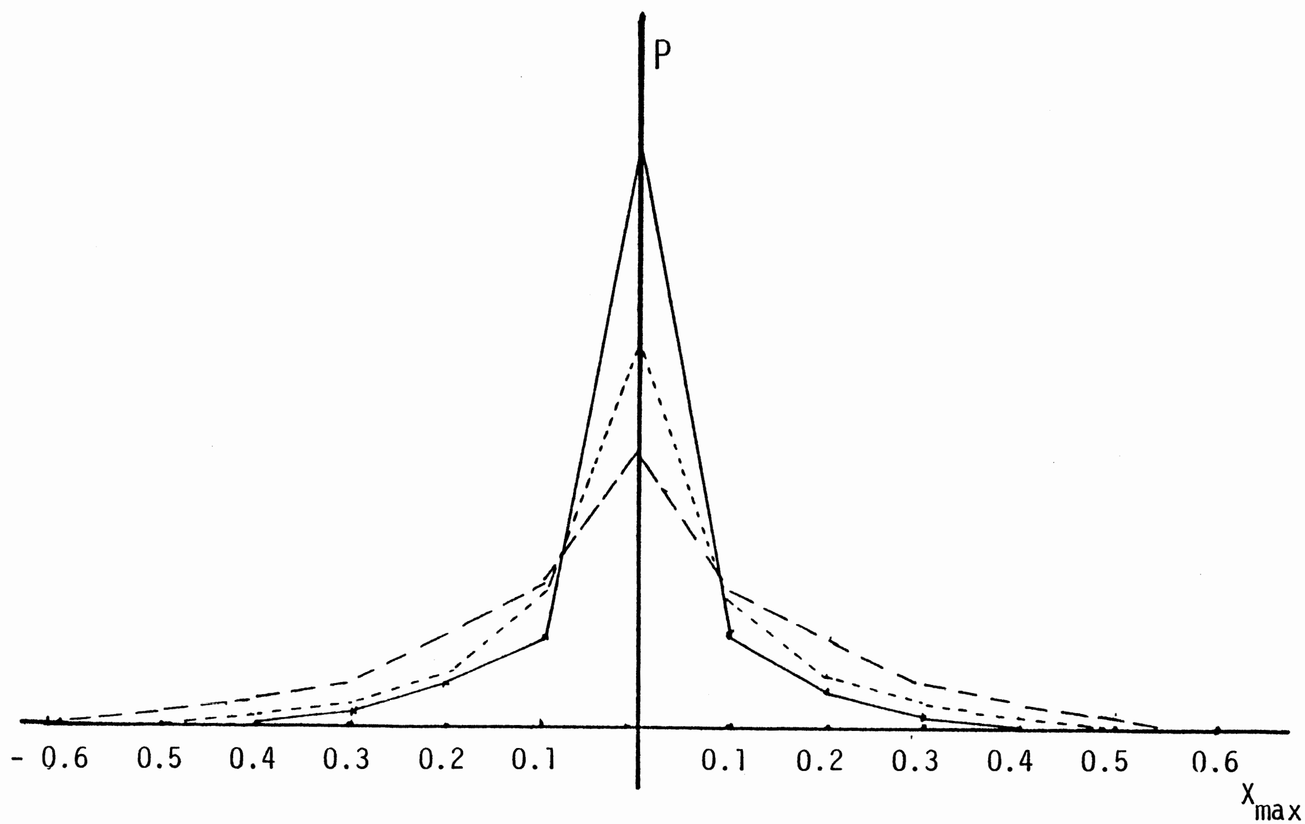
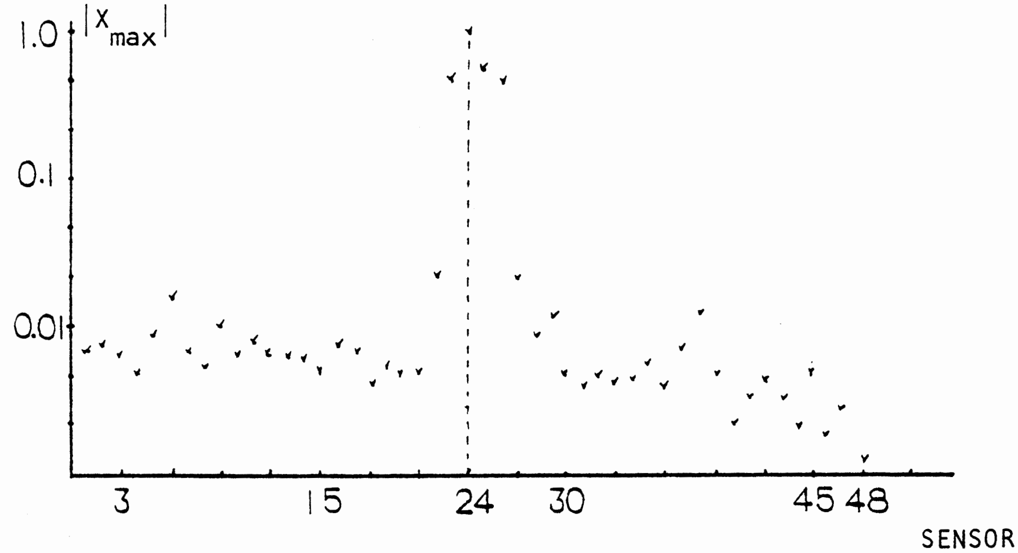
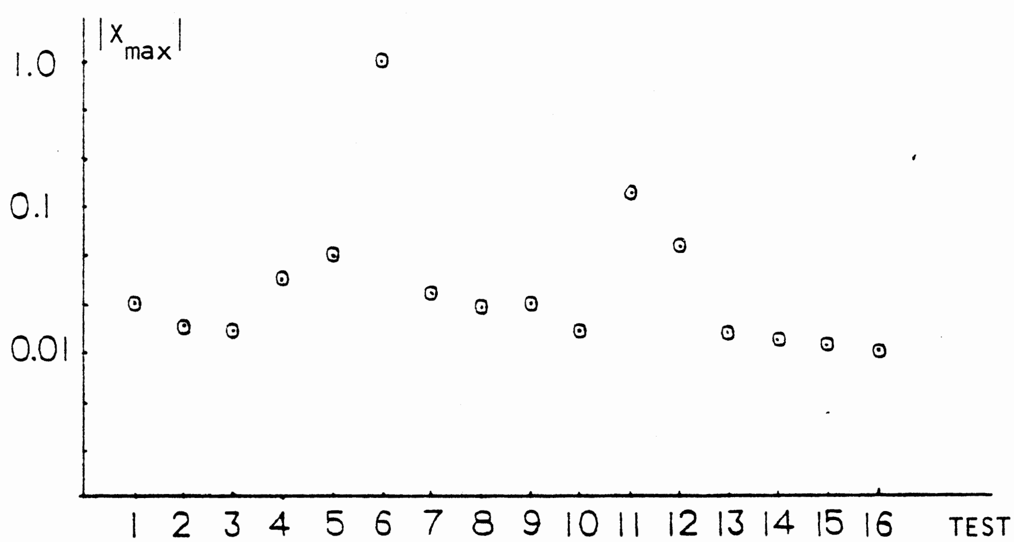


Figure 6. Amplititude Distribution of Vibroseis Data

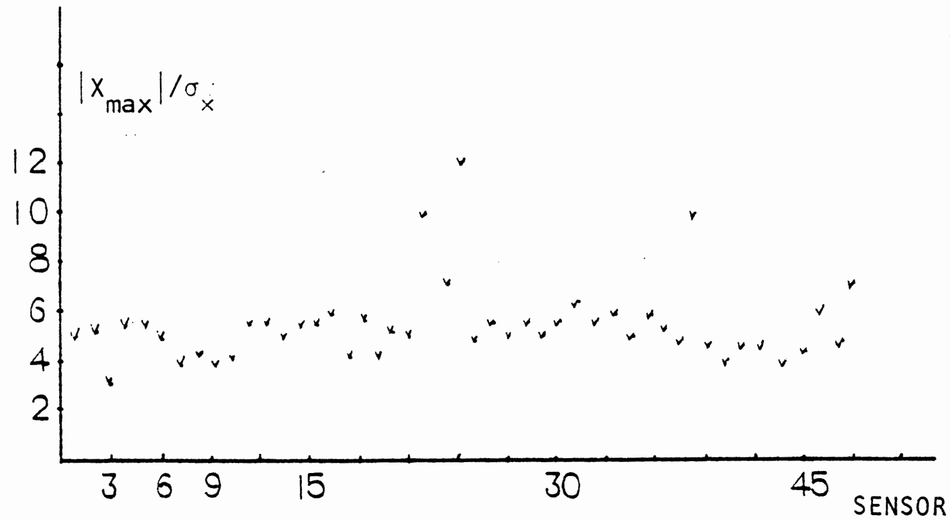


(a) Characteristics of $|X_{max}|$ among sensors

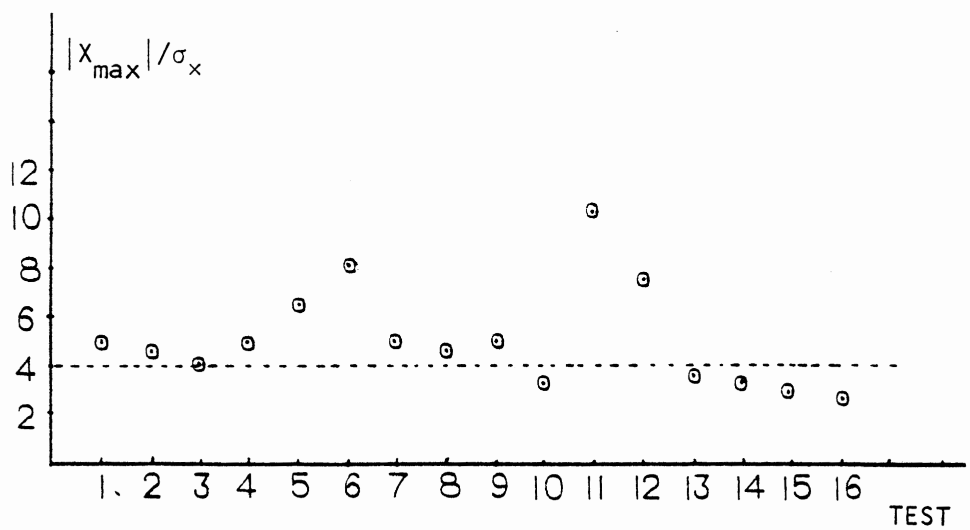


(b) Characteristics of $|X_{max}|$ among tests for one sensor

Figure 7. Illustrations of $|X_{max}|$ Characteristics of Vibroseis Data

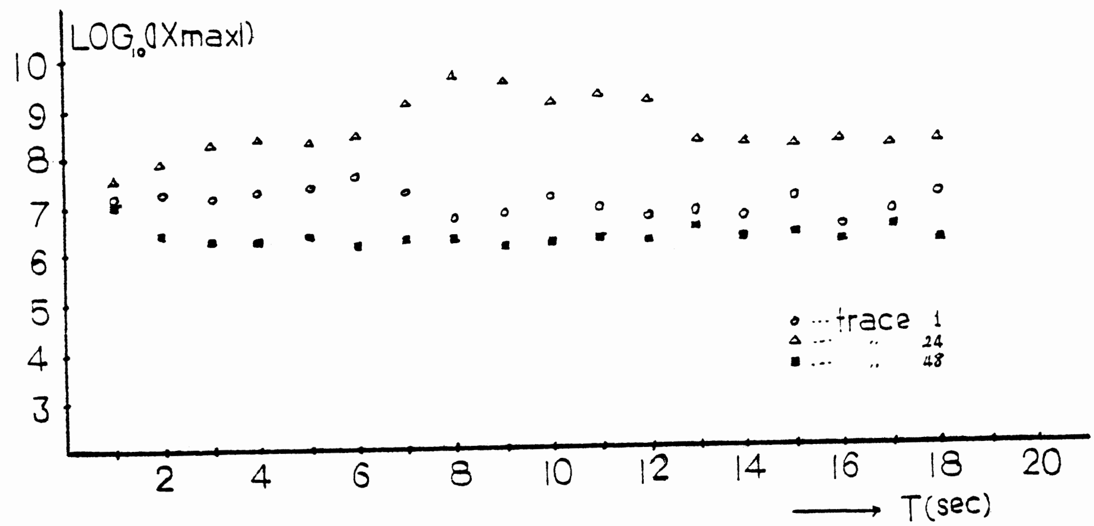


(a) Characteristics of $|X_{max}|/\sigma_x$ among sensors

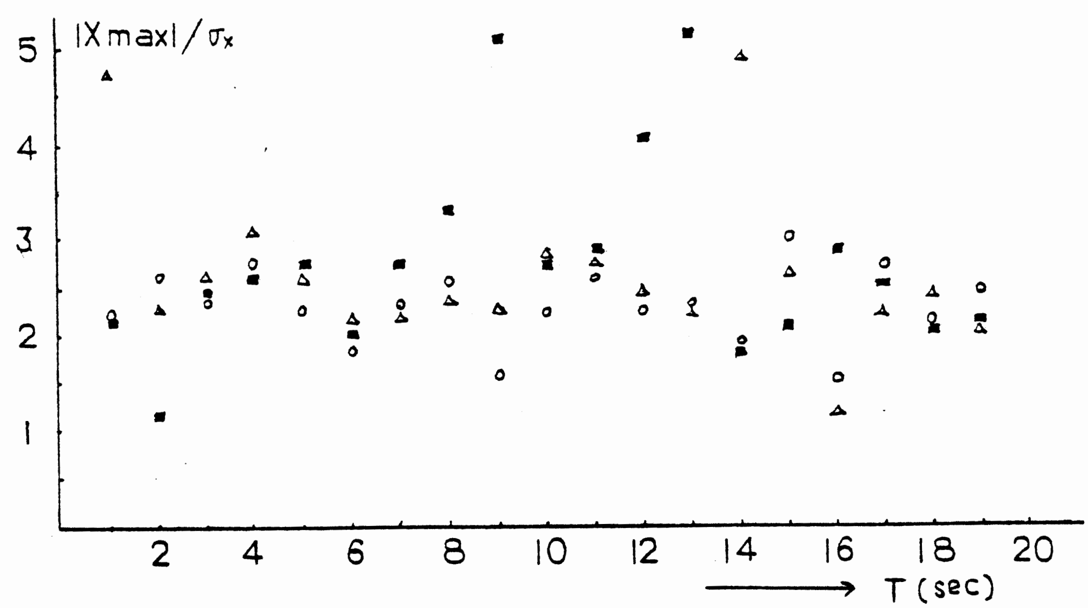


(b) Characteristics of $|X_{max}|/\sigma_x$ among tests for one sensor

Figure 8. Illustrations of $|X_{max}|/\sigma_x$ Characteristics of Vibroseis Data

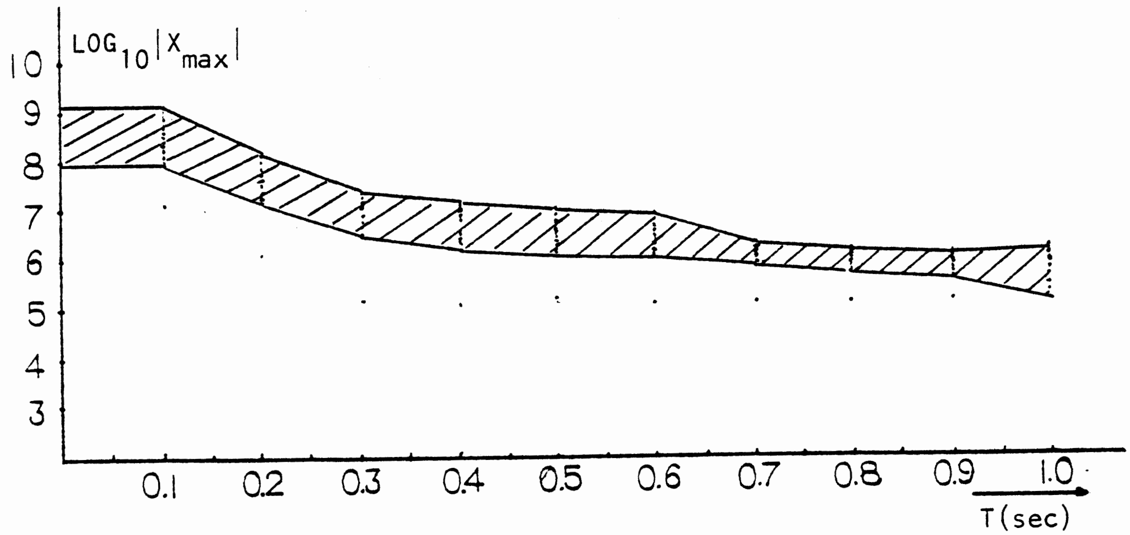


(a) Time Varying Characteristics of $|X_{max}|$ of Vibroseis Data

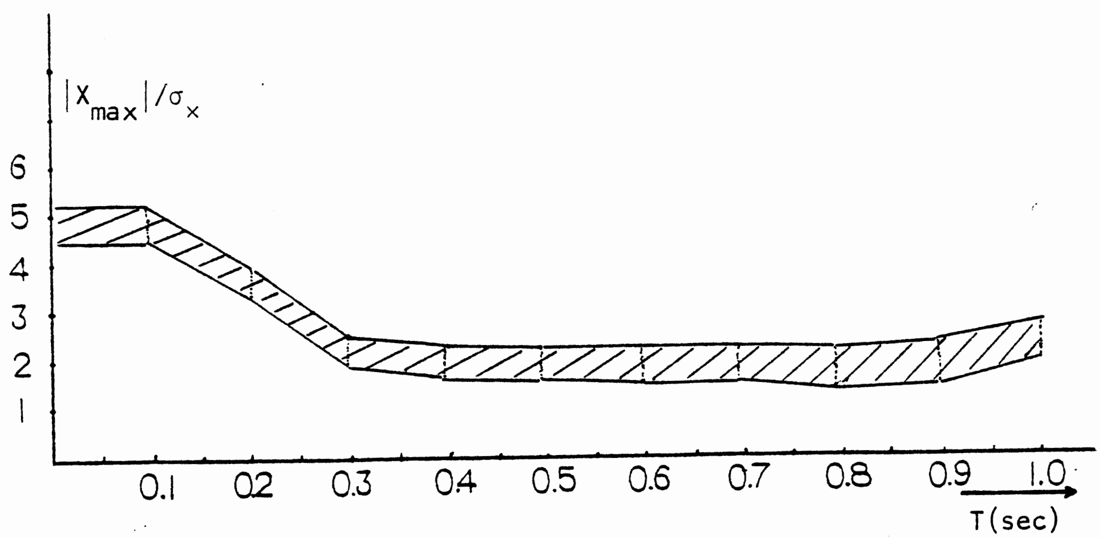


(b) Time Varying Characteristics of $|X_{max}|/\sigma_x$ of Vibroseis Data

Figure 9. Illustrations of Time Varying Characteristics of Seismic Data



(c) Time Varying Characteristics of $|X_{max}|$ of Impulsive Seismic Data



(d) Time Varying Characteristics of $|X_{max}|/\sigma_x$ of Impulsive Seismic Data

Figure 9. (Continued)

and the standard deviation of vibroseis data and of impulsive seismic data, respectively. It should be pointed out that three traces are displayed individually for vibroseis data and the ranges of 100 traces are displayed for impulsive seismic data. This is based on the fact that vibroseis data vary nonuniformly among traces, while impulsive seismic data vary uniformly among traces.

The probability density functions are obtained using the frequency histogram method. The frequency indicates the number of occurrences of data in a referenced range. The comparison of seismic data with well-known probability density functions, Laplace, Gamma, and speech signals, was performed in order to obtain a statistical model for seismic data. The results are shown in Figure 10. It can be observed that vibroseis data have a similar probability density function as speech signals. This indicates that it may be possible to use the results from speech processing. These results may include some performance measures of various digital speech coding methods. It can also be observed that the Laplace or Gamma density functions generally define the seismic data in a statistical sense.

The correlation between adjacent samples can be examined from the value of the autocorrelation function at the first lag. For example, the autocorrelation function of a partial trace of vibroseis data is shown in Figure 11. It can be seen that there is a relatively high correlation among sample points.

Also, correlation characteristics among traces and among tests are examined via computing the correlation coefficients. These examinations are used for selecting traces or tests to be implemented for data compression techniques, so that statistically similar traces and tests can be

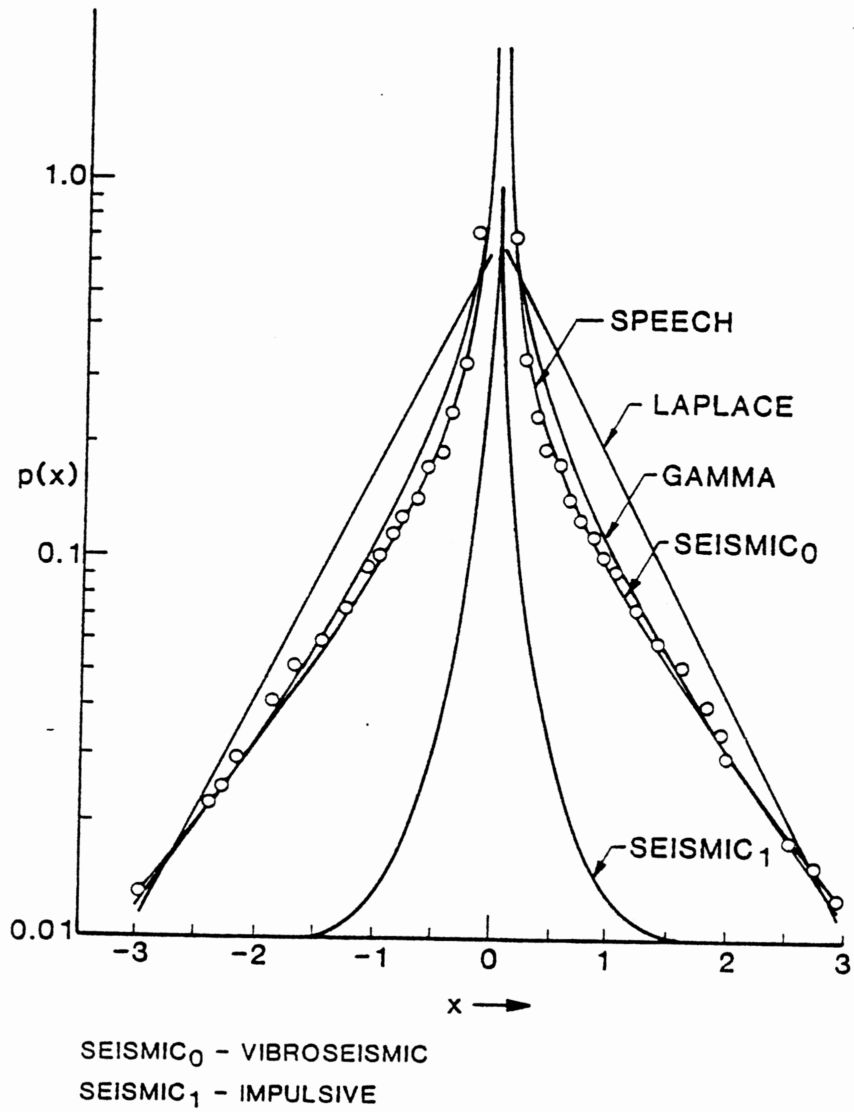


Figure 10. Probability Density Function of Seismic Data in Comparison of Laplace, Gamma and Speech (After Max and Paez [10])

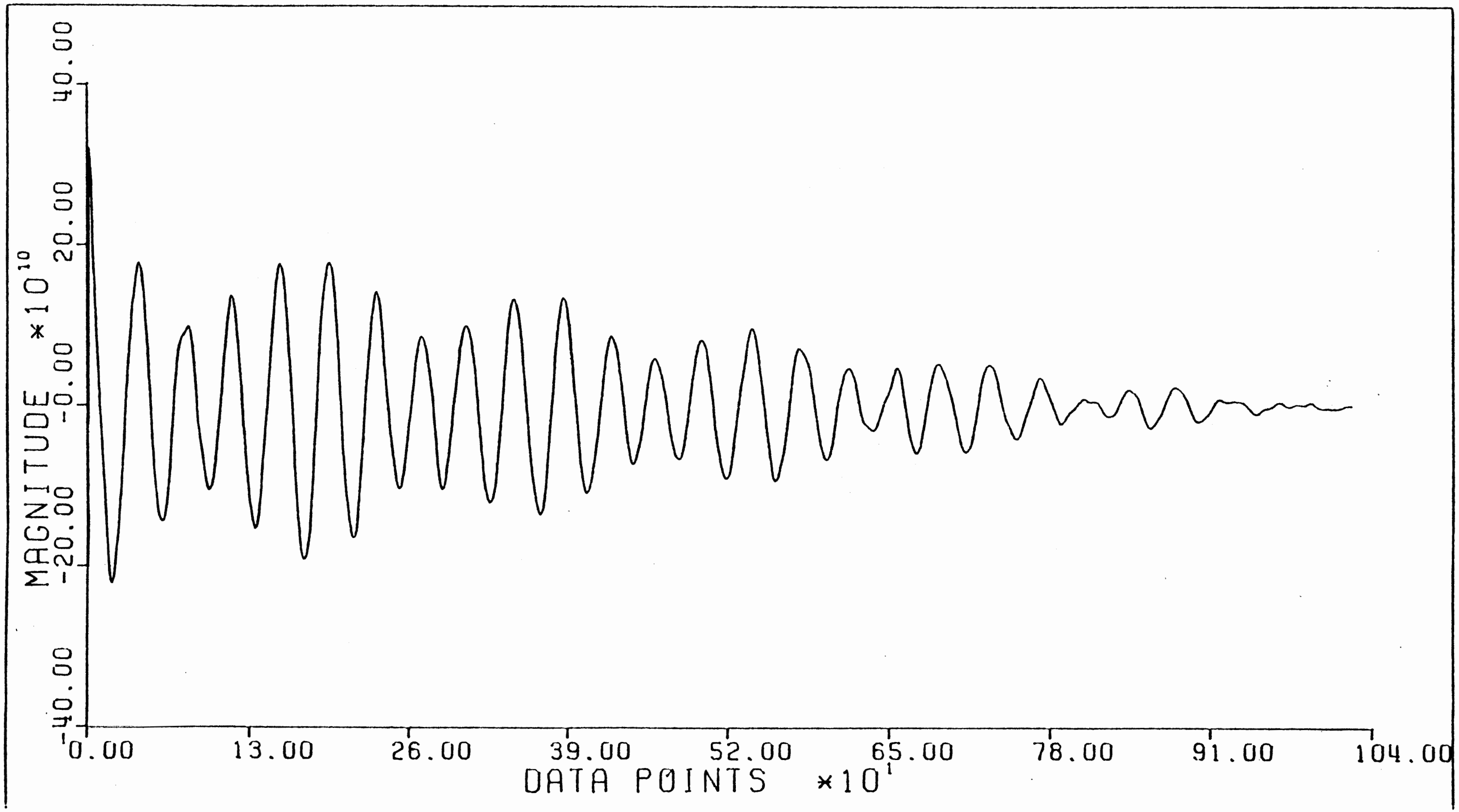


Figure 11. Auto-correlation Function of Vibroseis Data

grouped together. The correlation coefficients are ranged between +1 and -1, where +1 implies a complete linear relation and -1 implies a complete inversely linear relation [10]. Appendix B illustrates these coefficients of 16 traces of one sensor.

Further statistical analysis has been performed by applying the pre-emphasis method with low frequency and high frequency. The low-frequency pre-emphasized signal (D_n) can be computed from

$$D_n = X_n - a\, D_{n-1} \tag{2.3}$$

where $D_0 = X_0$ for $n = 1, 2, \ldots, N-1$, X_n is the original signal, and a is a gain factor. The high-frequency pre-emphasized signal (H_n) can be computed from

$$H_n = X_n - b\, X_{n-1} \tag{2.4}$$

where $H_0 = X_0$ for $n = 1, 2, \ldots, N-1$, and b is a gain factor.

The above pre-emphasis methods will be referred to as the first-order pre-emphasis. Also, the second-order pre-emphasis methods are investigated by applying the pre-emphasis on previously emphasized signals. For these first- and second-order pre-emphasized signals, the statistical characteristics mentioned above were examined. The important results obtained from these investigations are that the correlation coefficients increase (decrease) for low-frequency (high-frequency) pre-emphasized signals. In particular, for the second-order low-frequency pre-emphasized signals, the correlation coefficients are almost 1.0, as shown in Appendix B. The correlation considerations are not discussed for impulsive seismic data, since it is clearly seen from the plot in Appendix A that all of the traces are highly correlated.

The seismic data have been statistically analyzed in this section. The analysis results will be utilized for evaluating the utility of various data compression techniques for seismic data in Chapter III.

Summary

In this chapter, general considerations involved in seismic data compression, such as seismic data rate and size, reversibility of compression techniques, and statistical characteristics of seismic data, have been discussed. Data rate and size of vibroseis data were found to be 192k bps and 9M byte per block. Impulsive seismic data were shown to have 3960k bps of data rate and 230k byte of data size per block.

Due to bandwidth constraints of telecommunication channels and computer storage limits, data compression techniques are found to be necessary for seismic data transmission. One previous work by Wood [8], which is basically sequency limiting in the Walsh domain, was examined and it was determined to be improper since its signal-to-noise ratio is too small (less than 7 dB). For maintaining the desired quality of signal after reconstruction at the receiver, a SNR of 30 dB was considered essential for a compression method to be useful.

Analysis of statistical characteristics of vibroseis data showed that vibroseis data have a similar probability distributional characteristic as speech signals. Also, it was observed that vibroseis data traces are slightly correlated among each other, while impulsive seismic data traces are highly correlated. These characteristics will be used for evaluating performances of various compression techniques in the next chapter.

CHAPTER III

EVALUATION OF DATA COMPRESSION TECHNIQUES

Introduction

The statistical characteristics of vibroseis and impulsive seismic data were examined in Chapter II. Based on these characteristics, this chapter is devoted to evaluating techniques for reversible seismic data compression. The reversibility constraint is defined as 30 dB of SNR in this thesis, assuming that this constraint may provide the required quality for the signal to be reconstructed at the receiver.

In this chapter, five basic data compression techniques mentioned in Chapter I are discussed with respect to their use for reversible seismic data compression. First, it can be argued that the entropy reducing transforms can be neglected, since these methods extract the desired information from a portion of the data in terms of time and frequency, and thus lose the reversibility.

Second, prediction techniques are considered with respect to identifying an optimal predictor where the "linear prediction" algorithm is used for obtaining parameters for the predictor. For vibroseis data, these methods are ignored due to the computational complexities involved in obtaining the predictor parameters. However, these methods are implementable for impulsive seismic data since the predictor parameters can be obtained in a simple manner; these parameters can be used for designing a predictor for other traces. This is based on the characteristics of waveforms of the impulsive seismic data, which will be discussed later.

Third, interpolation techniques are discussed in relation to resampling techniques where some sample values can be reconstructed using a polynomial interpolator. The parameters associated with a polynomial interpolator should be generated at the transmitter and transmitted in place of the original data. This technique involves basically similar computational complexities as prediction techniques. For a seismic signal, the number of parameters associated with a polynomial interpolator is excessive and for these reasons, interpolation techniques are ignored.

Orthogonal transforms can be chosen for vibroseis data and for a nonimpulsive section of impulsive seismic data. These transforms remove redundancies and also they are simple implementation-wise. Energy conservation and the inversibility property of the orthogonal transforms allow for using other compression techniques in the transformed domain. Similarly, other compression techniques can be used prior to orthogonal transforms. These aspects will be examined in more detail in the next section.

Digital coding methods can be proposed for two reasons. First, digital coding is required for transmission over a digital communication channel. Second, data compression can be achieved by applying an efficient digital coding technique. Data compression consideration via digital coding is based on reducing the average number of bits (or bit rate) per symbol rather than reducing the number of messages. An efficient digital coding technique can be approached by various quantization techniques and encoding techniques. These various techniques will be discussed in a later part of this chapter.

Finally, the compression results of various compression techniques are compared and combinations of these techniques are proposed for vibroseis data and impulsive seismic data.

Orthogonal Transforms in Data Compression

Orthogonal transforms can be used for redundancy removal. This property is one of the key elements of data compression. The redundancy removal property is discussed below [5].

Let a sequence of N data points be represented by an N-dimensional vector $\underline{X}$. A transformed vector $\underline{Y}$ can be formed from $\underline{X}$ by

$$\underline{Y} = A\underline{X} \ , \tag{3.1}$$

where A is a unitary matrix. That is,

$$A^{*}A = 1 \ . \tag{3.2}$$

where * indicates a complex conjugate transpose. The objective is to select a subset of M components of $\underline{Y}$, where M is substantially less than N. The remaining (N - M) components can then be discarded without introducing objectionable error, where the error is, of course, the difference between the signal and the reconstructed signal using the retained M components of $\underline{Y}$. The error criterion often used for orthogonal transforms is the mean-square error criterion, and is discussed below.

From Equations (3.1) and (3.2),

$$\underline{X} = A^{*}\underline{Y} = \sum_{i=1}^{N} y_i \phi_i \ . \tag{3.3}$$

where

$$A^{*} = [\phi_1, \phi_2, \ldots, \phi_N] \ .$$

The reconstructed vector $\underline{X}'$ from the retained M components of $\underline{Y}$ can be given by

$$\underline{X}' = A^{*}\underline{Y}' , \tag{3.4}$$

where $\underline{Y}'$ contains M components of $\underline{Y}$ and a contant replaced for the discarded N-M components. It should be noted that M largest eigenvalues should be selected for the subset of Y'. The mean square error is usually defined as [5]

$$e = E[(X - X')^{*} (X - X')] = \sum_{i=M+1}^{N} \phi_i^{*} \Sigma_x \phi_i \tag{3.5}$$

where

$$\Sigma_x = E[(X - \bar{X})(X - \bar{X})^{*}]$$

with $\bar{X}$ being the mean value of $\underline{X}$. From the above relations, the minimum error is given by

$$e_{min} = \sum_{i=M+1}^{N} \lambda_i$$

with ϕ_i and λ_i being the eigenvector and the corresponding eigenvalue of the covariance matrix Σ_x.

The unitary transform A, composed of the eigenvectors of the covariance matrix of the given data, is called the Karhunen-Loéve transform. Also, it can be seen that the covariance matrix of the transformed vector $\underline{Y}$ is uncorrelated and it is expressed as [5]

$$\Sigma_y = \text{diag}\ (\lambda_1, \lambda_2, \ldots, \lambda_N) \ . \tag{3.7}$$

Equation (3.7) indicates that $\underline{Y}$ has no redundancy; thus $\underline{Y}$ is the most efficient representation of $\underline{X}$. However, there exists no general fast algorithm to compute the KLT, since the KLT depends upon the data covariance matrix. The computation involves $2N^2$ multiplications, and as N increases, the task of computing the transformed vector becomes a formidable one [11]. For this reason, several suboptimal orthogonal transforms are investigated, which include the Walsh-Hadamard, the discrete Fourier transform, and the discrete cosine transform. For illustrative purposes, vibroseis data shown in Figure 12 are used to compare these transforms.

Walsh-Hadamard Transform (WHT)

The matrix A in Equation (3.1), in terms of the Hadamard matrices, is defined by [11]

$$A = A_{WHT} = H(\nu) \tag{3.8a}$$

$$H(\nu) = \begin{bmatrix} H(\nu-1) & H(\nu-1) \\ H(\nu-1) & -H(\nu-1) \end{bmatrix} \tag{3.8b}$$

where

$$H(0) = 1, \qquad N = 2^{\nu}$$

and

$$A_{WHT}^{-1} = \frac{1}{N} H_{\nu} .$$

Noting that $H(\nu)$ has only ± 1's, the WHT algorithm requires only $N \log_2 N$ summations [11]. This computational simplicity is the main reason for its wide usage.

Figure 13 illustrates the Walse-Hadamard transformed vector of the vibroseis data shown in Figure 12. As will be shown later, the WHT compression ratio is not as good as some of the other suboptimal transforms and, therefore, WHT is not used in the proposed compression methods.

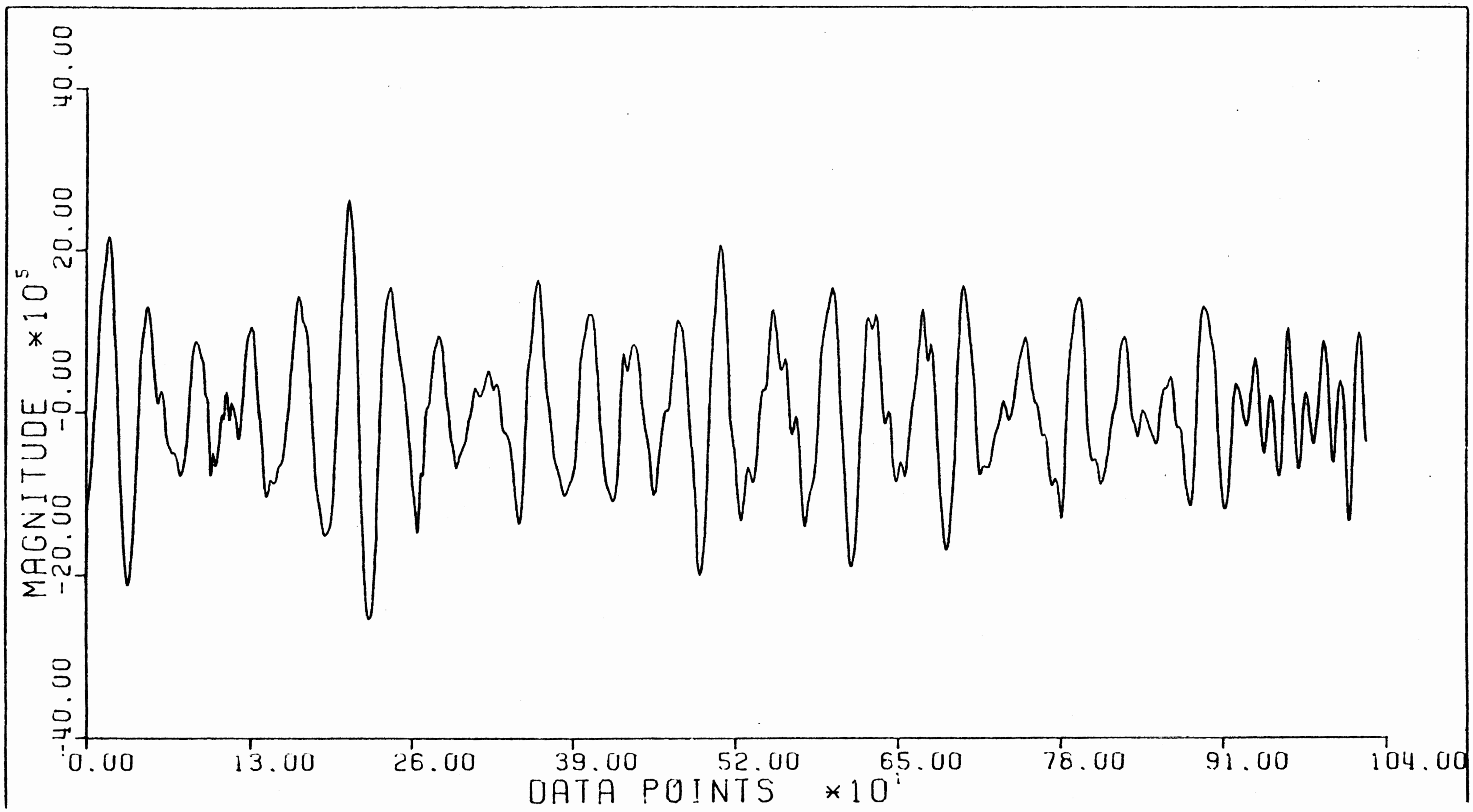


Figure 12. Partial Trace of Vibroseis Data

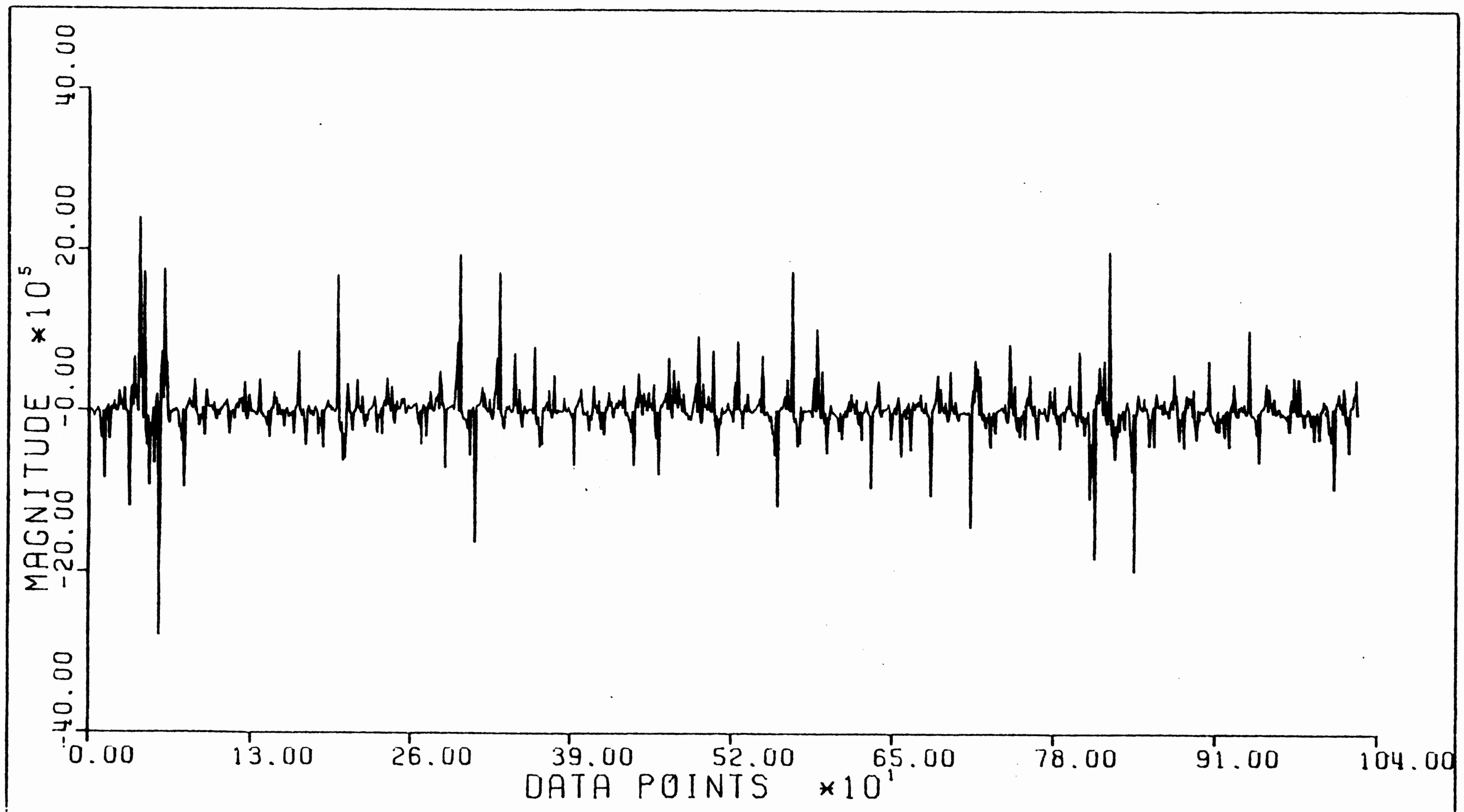


Figure 13. Walsh-Hadamard Transformed Vector Coefficients

Discrete Fourier Transform (DFT)

The matrix A in Equation (3.1), corresponding to the DFT, is defined by [5]

$$A = A_{DFT} = (a_{kj}) \tag{3.9}$$

where

$$a_{kj} = \exp[-i2\pi \frac{kj}{N}], \qquad 0 \leq k, j \leq N - 1$$

and

$$A_{DFT}^{-1} = \frac{1}{N} A^{*},$$

where A^{*} is the complex conjugate transpose of A. Note that $(1/\sqrt{N})$ can be incorporated into A to make it unitary and, of course, it has no important effect on the nature of the representation.

The DFT is of interest primarily because it approximates the continuous Fourier transform and fast algorithms are available. The basic FFT algorithm requires $2N \log_2 N$ multiplications for $N = 2^{\nu}$ to compute the transformed vector, and it is significantly simpler than the KLT computation [5].

Figure 14 shows the DFT transformed vector of the vibroseis data shown in Figure 12. The first half of the plot is the real part of the transformed vector components and the second half is the imaginary part of the transformed vector components. The DFT requires a complex components array and two threshold values are necessary for selecting the significant coefficients. Compared to the discrete cosine transform below, the DFT is not attractive.

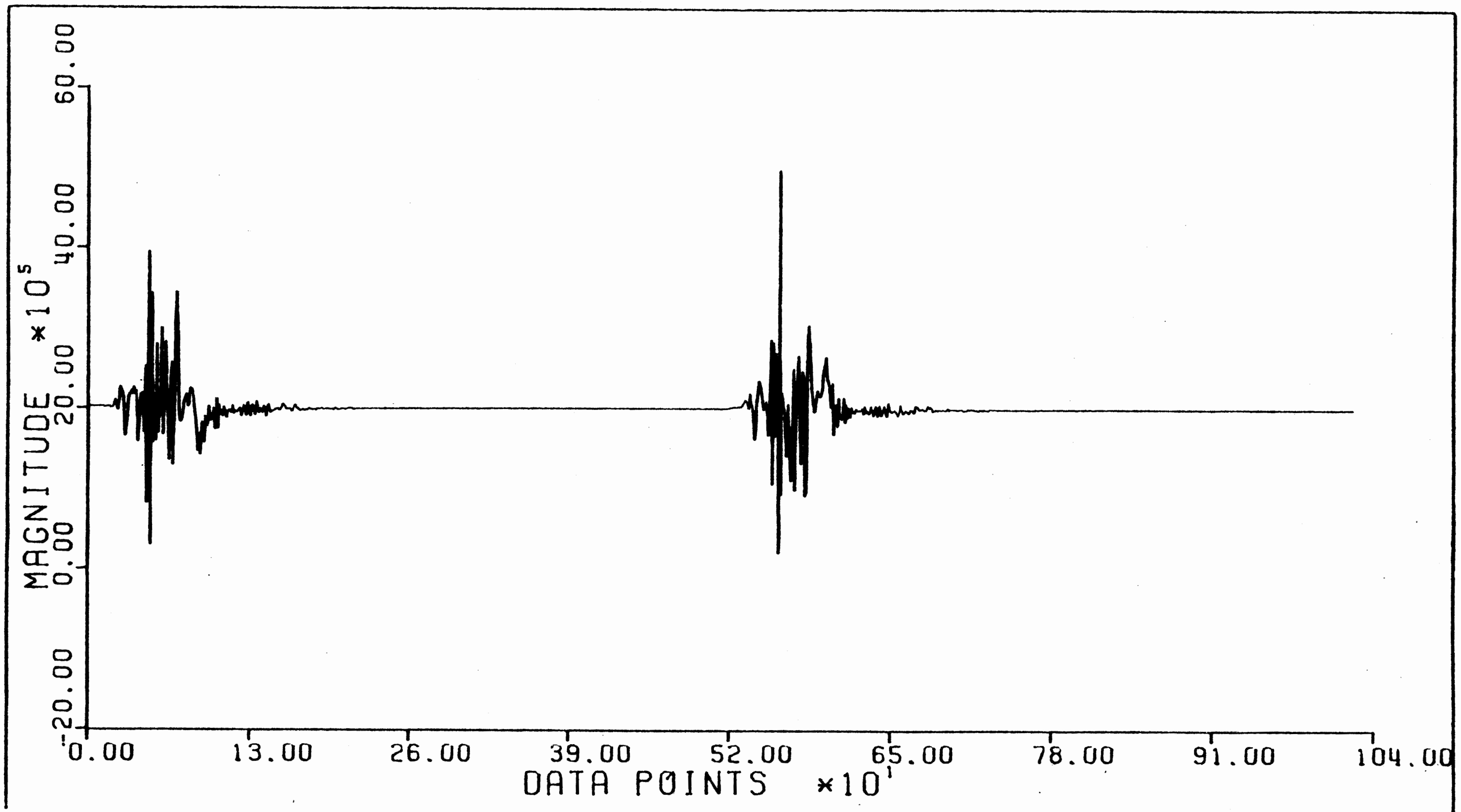


Figure 14. Discrete Fourier Transformed Vector Coefficients

Discrete Cosine Transform (DCT)

The DCT is similar to the DFT in that it uses sinusoidal waveforms as the basis of its orthogonal transform matrix. The matrix A in Equation (3.1) corresponding to the DCT is defined by [5]

$$A = A_{DCT} = (a_{kj}) \tag{3.10}$$

where

$$a_{kj} = \frac{2}{N} \cos \frac{2j+1}{2N} k\pi \qquad 0 \le j \le N-1; \; 1 \le k \le N-1$$

and

$$a_{0j} = \frac{1}{N} \qquad 0 \le j \le N-1$$

The inverse of A_{DCT} is given by

$$A_{DCT}^{-1} = (b_{jk})$$

where

$$b_{jk} = \frac{2}{N} \cos \left(\frac{2j+1}{2N} k\pi\right) + \frac{1}{N} \qquad 1 \le k \le N-1; \; 0 \le j \le N-1$$

and

$$b_{k0} = \frac{1}{N} \qquad 0 \le k \le N-1$$

The DCT can be computed using the FFT as follows [13]:

$$a_{kj} = \frac{2}{N} \text{Re } [\exp \frac{2j+1}{2N} k\pi] .$$

Similarly, it can be shown that the algorithm can be used to compute the inverse DCT coefficients. Also, it has been shown that the basis vectors of the DCT closely approximate the eigenvectors of a class of Toeplitz matrices and that the DCT approaches the KLT as far as optimality is concerned [11]. For these reasons, the DCT has been chosen as the orthogonal transformation technique for the vibroseis data compression.

Figure 15 shows the DCT transformed vector of the vibroseis data shown in Figure 13. For the three suboptimal transforms discussed above, the compression ratios (CPR) are tabulated in Table I corresponding to the vibriseis data in Figure 12. From these results it can be seen that the DCT gives the best compression among the three suboptimal transforms.

Digital Coding Techniques

It was pointed out earlier that efficient step-size to reduce the number of quantization levels and efficient bit allocation techniques to minimize the number of bits play an important role in digital coding for data compression. These ideas are implemented in various forms of quantization and encoding; some of these ideas are discussed below.

At the transmitter, the source signal is coded using the digital coding method, and the source signal is reconstructed at the receiver from the coded signal, subject to some error fidelity criteria. This is shown in Figure 16, where the input signal is denoted by $X(n)$, the quantized signal is denoted by $\hat{X}(n)$, and $C(n)$ is the code word for $\hat{X}(n)$. The received code $C'(n)$ is decoded and the decoded signal is denoted by $X'(n)$. Transmission error (or channel error) is not considered in this thesis for evaluating the compressed results of various techniques. Therefore, it is assumed that $C(n) = C'(n)$ and thus $\hat{X} = \hat{X}'(n)$. This implies the error $(X - X')$ is mainly quantization error.

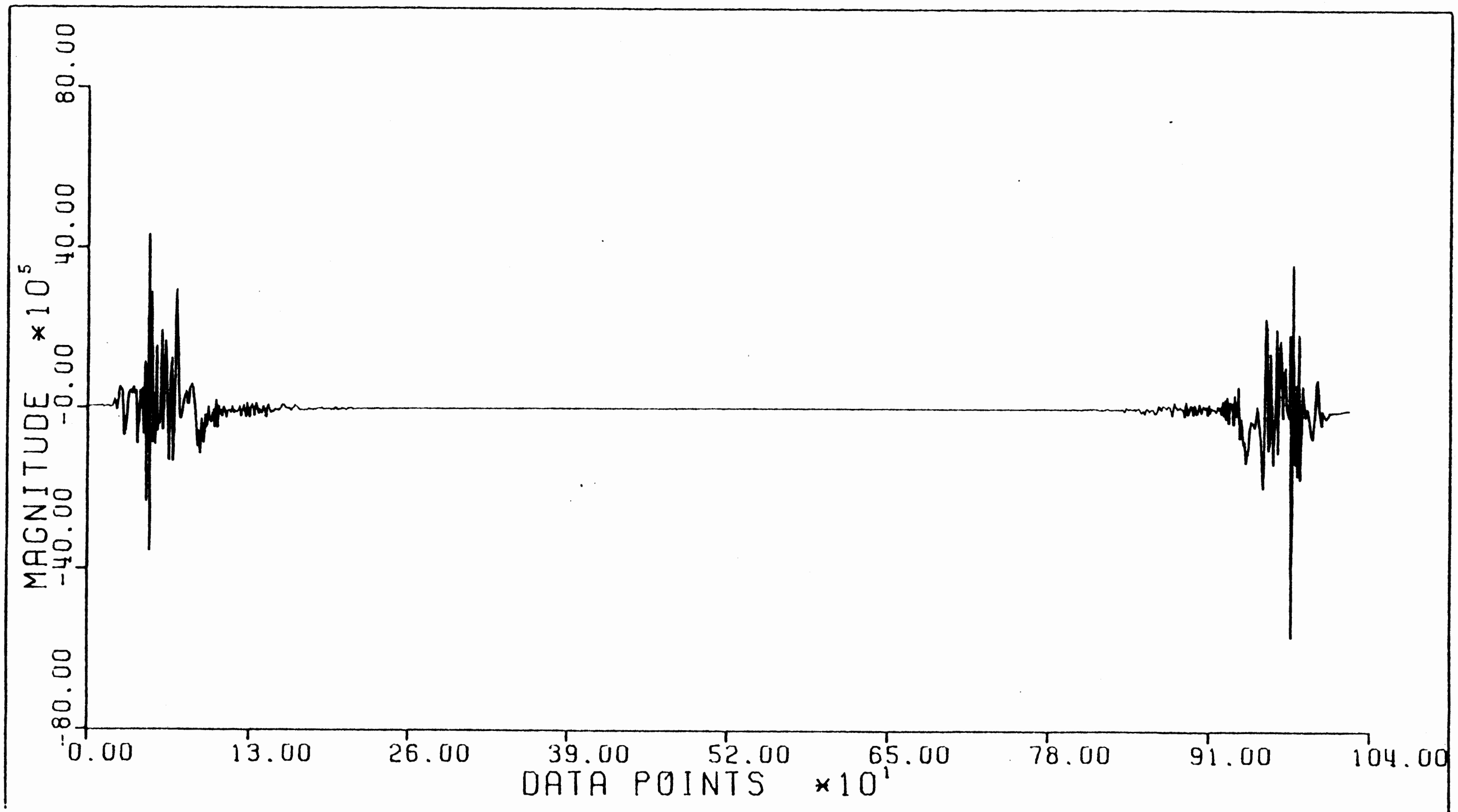


Figure 15. Discrete Cosine Transformed Vector Coefficients

TABLE I

CPR* OF ORTHOGONAL TRANSFORMS
ON VIBROSEIS DATA

TEST	WHT	DFT	DCT
1	1.19	1.44	2.41
2	1.17	1.24	1.70
3	1.21	2.74	3.02
4	1.21	1.17	1.40
5	1.21	2.59	2.96
6	1.19	1.37	2.17
7	1.19	2.99	3.32
8	1.15	2.68	2.88
9	1.10	1.82	2.73
10	1.16	1.20	1.35
11	1.16	1.30	1.66
12	1.15	1.22	1.62
13	1.14	2.24	2.50
14	1.12	2.73	2.88
15	1.13	1.27	1.60
16	1.21	2.31	2.52
AVG	1.17	1.89	2.29

*Threshold = $0.05\sigma_x$
SNR > 35 dB

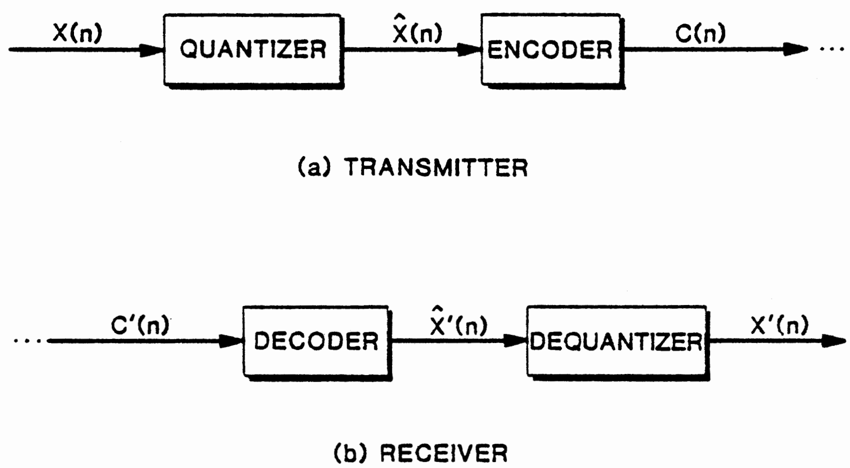


Figure 16. Digital Coding Techniques

For a given source and a given error fidelity criterion, the minimum transmission rate can be computed from the rate distortion function of Shannon [14], which will be discussed later. This optimum rate cannot readily be achieved because the coding technique is usually extremely complex or theoretically intractable. Most data compression techniques are suboptimal in the sense that they exceed the minimum possible transmission rate. It is not possible to choose the "best" way of coding for a given application, as the computational complexities and hardware design play important roles. The decision must be based on some vague factors, such as generality of the method relative to the source information and relative equipment complexities.

The following five sections are devoted to examining various coding techniques, which involve quantization and encoding for seismic data compression. Also, comparative merits and demerits are discussed in terms of quantization noise and compression ratio. The quantization noise or signal-to-noise ratio considerations are examined with four basic step-size algorithms: optimum, uniform, logarithmic, and adaptive algorithms. The compression ratio considerations are examined with two algorithms, fixed code word length and optimum code word length. The differential coding techniques are discussed with respect to their contributions on signal-to-noise ratio. First, the optimum quantizer is examined in the next section.

Optimum Step-Size Quantization

The optimum quantization technique is discussed to indicate the computational complexities and to obtain a standard result for comparing other quantization techniques.

The variance of the quantization error is given by

$$\sigma_e^2 = \int e^2 p_e(e)\ de \tag{3.11}$$

where e is the quantization error $(x - \hat{x})$, and $P_e(e)$ is the probability density function of the error signal and can be expressed in terms of the probability density function of X(n), $P_x(x)$ [10]. Equation (3.11) can thus be expressed as

$$\sigma_e^2 = 2 \sum_{i=1}^{M/2} \int_{x_{i-1}}^{x_i} (\hat{x}_i - x)^2\ P_x(x)\ dx \tag{3.12}$$

where M is the number of quantization levels, and $P_x(x)$ is assumed to be equal to $P_x(-x)$. Equation (3.12) indicates that it is possible to choose the quantization levels so as to minimize the quantization error variance, and thus maximize the SNR, when $P_x(x)$ is known. A brief discussion of selecting $\{x_i\}$ and $\{\hat{x}_i\}$ which minimize σ_e^2 is given below.

By using the minimization process, the optimum location of the quantization level $\hat{x}_i$ can be shown to be the centroid of the probability density interval x_{i-1} to x_i. Also, it has been found that the optimum boundary points lie halfway between the M/2 quantizer levels, $\hat{x}_i$. These nonlinearly related conditions must be met simultaneously, and iterative procedures are generally used to solve this problem. The parameter here is the step size.

As mentioned in Chapter II, the vibroseis data have a probability density function close to Laplace and Gamma density functions. For this reason, the optimal quantizer for signals with Laplace density and Gamma density developed by Max, Paez and Glisson [10] are examined and the optimum quantization step size for Laplace density is shown in Figure 17.

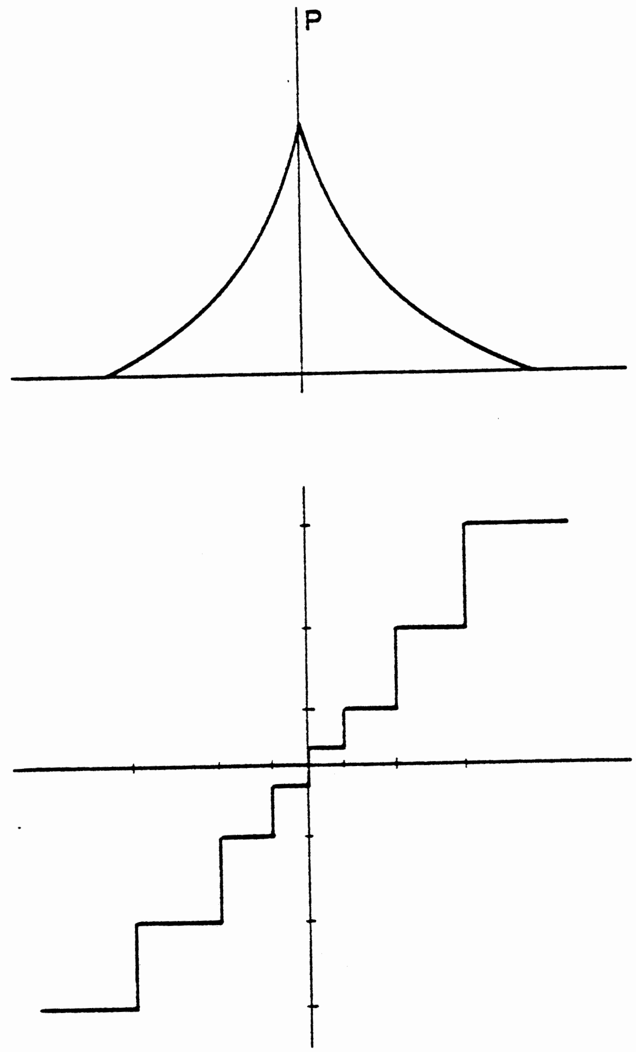


Figure 17. 3-bit Optimum Quantization
for Laplace Density
(After Max and Paez [10])

It can be easily seen from this figure that the quantization levels get farther apart as the probability density decreases. This indicates that large quantization errors should be reserved for the least frequently occurring samples.

This technique will not be used due to the computational complexity and the lack of exact information on the $P_x(x)$ for the vibroseis data. For these reasons, several suboptimum quantization techniques are discussed, including the uniform step-size quantization, non-uniform step-size, and adaptive step-size quantization.

Uniform Step-Size Quantization

The uniform step-size quantizer is the simplest kind of all the quantizers. This quantizer involves only two parameters, the number of levels and the quantization step-size, denoted as Δ. For a b-bit uniform quantizer, there are 2^b levels. This is illustrated in Figure 18 for a 3-bit quantizer. It has been found that the quantization error of this technique approaches the optimum quantizer when the signal is described by Gaussian distribution [15].

For future use, the parameter Δ and the SNR for this method is given below. The step-size is

$$\Delta = \frac{\text{Peak-to-peak range}}{\text{Number of levels}} .$$

If a symmetrical probability density function can be assumed for X(n), the Δ can be expressed as

$$\Delta = \frac{2\,|X_{max}|}{2^b}$$

where $|X_{max}|$ is the absolute maximum of X(n).

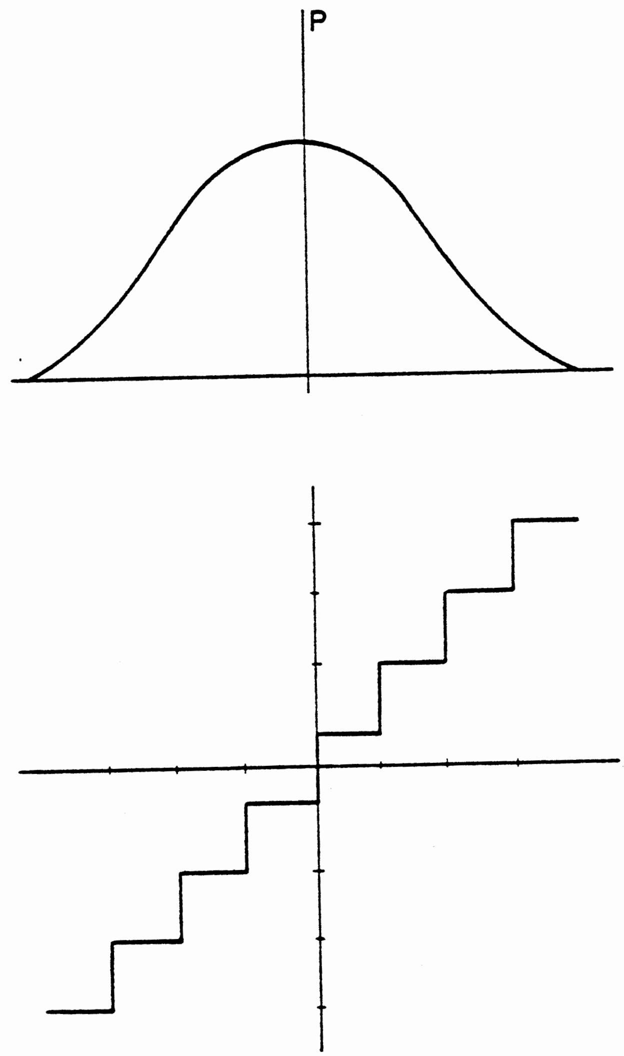


Figure 18. 3-bit Uniform Quantization for Gauss Density

The quantization error of the uniform step-size quantizer [16]

$$\text{SNR(dB)} = 6b + 4.77 - 20 \log (|X_{max}|/\sigma_x) \qquad (3.13)$$

which points out that each additional bit contributes a 6 dB to the signal-to-noise ratio. This derivation was based on the following assumptions. First, the quantization error is a stationary white noise process; second, the quantization error is uncorrelated with the input signal; and third, the distribution of quantization error is uniform over each quantization interval [17].

The first assumption is true when the input signal fluctuates in a complicated manner. The second assumption can be met if there are enough quantization levels available so that the step-size is properly small. The step-size can be determined empirically by applying various step sizes and examining the correlation between the quantization error and the input signal. The third assumption can be true if the range of the quantizer is set so as to match the peak-to-peak range of the signal, which is difficult to meet due to time varying characteristics of seismic signals. The time varying characteristics of seismic data are shown in Figure 9a and 9b indicating that the peak-to-peak range varies significantly from one time frame to another. Thus the number of quantization levels are not fully used in each frame, and the SNR in Equation (3.13) may not be achieved. Also, the uniform step-size quantization suffers from the dependence upon the signal variance. For example, the $(|X_{max}|/\sigma_x)$ for the vibroseis data may vary from four to twelve, which can be seen in Figures 8a and 8b. This indicates a significant reduction in SNR. For this reason, quantization techniques which are less sensitive to the signal variance are investigated in the following.

Logarithmic Step-Size Quantization

The logarithmic quantizer, often called the instantaneous compressor/expander or simply compander, resolves the dependence of the SNR upon the signal variance by logarithmically spaced quantization levels. This can be alternatively achieved by quantizing the logarithm of the input rather than the input itself. Also, the companding may be used to improve the signal-to-noise ratio by producing effectively non-uniform quantization so that the largest quantization errors should be reserved for the least probable samples.

The signal-to-noise of the logarithmic quantizer is [6]

$$SNR = \frac{1}{\sigma_e^2} \tag{3.14}$$

This equation shows that the SNR depends upon only the step-size. Since the logarithm of very small numbers can be very large, this type of quantizer in general needs infinite number of quantization levels and therefore is impractical.

For this reason, Smith [18] has developed the alternative compression characteristics called μ-law. The μ-law is expressed as

$$Y(n) = F[X(n)]$$

$$= X_{max} \frac{\log 1 + \mu \frac{|X_n|}{X_{max}}}{\log(1 + \mu)} \text{ sign } (X(n)) \tag{3.15}$$

The parameter μ controls the degree of compression and may be chosen that large changes in the input produce relatively small changes in the output. When μ is zero, it corresponds to uniform step-size quantization. The μ-law step-size with μ-value of 500 and several μ-curves with associated μ-values are illustrated in Figure 19. The signal-to-noise ratio of this quantizer for $\mu > 0$ is [18]

$$\mathrm{SNR(dB)} = 6b + 4.77 - 20 \log (\ln(1 + \mu)) - 10 \log \left(1 + \frac{X_{max}}{\mu\sigma_x}^2 + 2 \frac{X_{max}}{\mu\sigma_x}\right). \qquad (3.16)$$

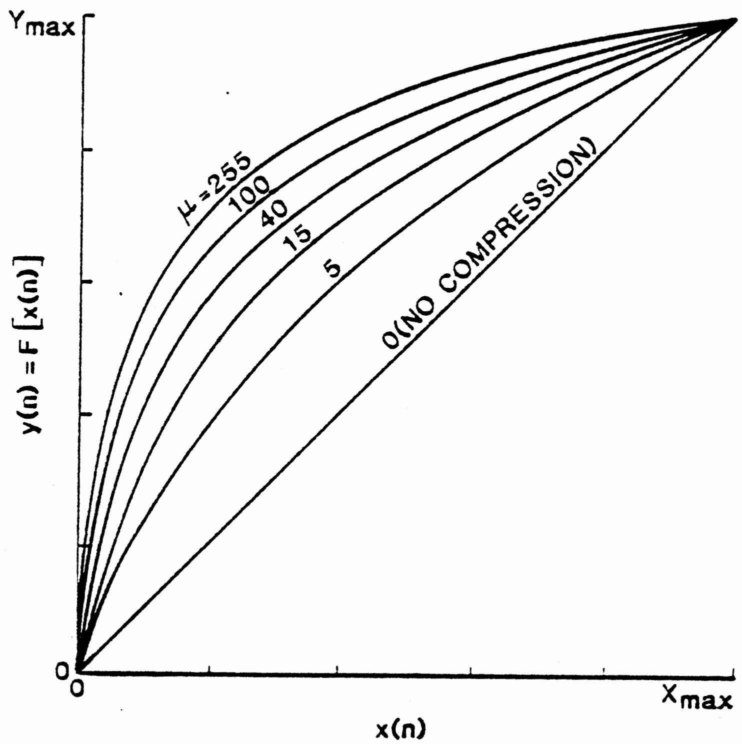
From this equation, it can be seen that the dependence of SNR upon the signal variance can be reduced by controlling the μ-value. This will be discussed in more detail later.

Both uniform and non-uniform step-size quantization has limitations when a signal has time-varying properties. For this reason, an adaptive step-size quantization technique is investigated in the next section.

Adaptive Step-Size Quantization

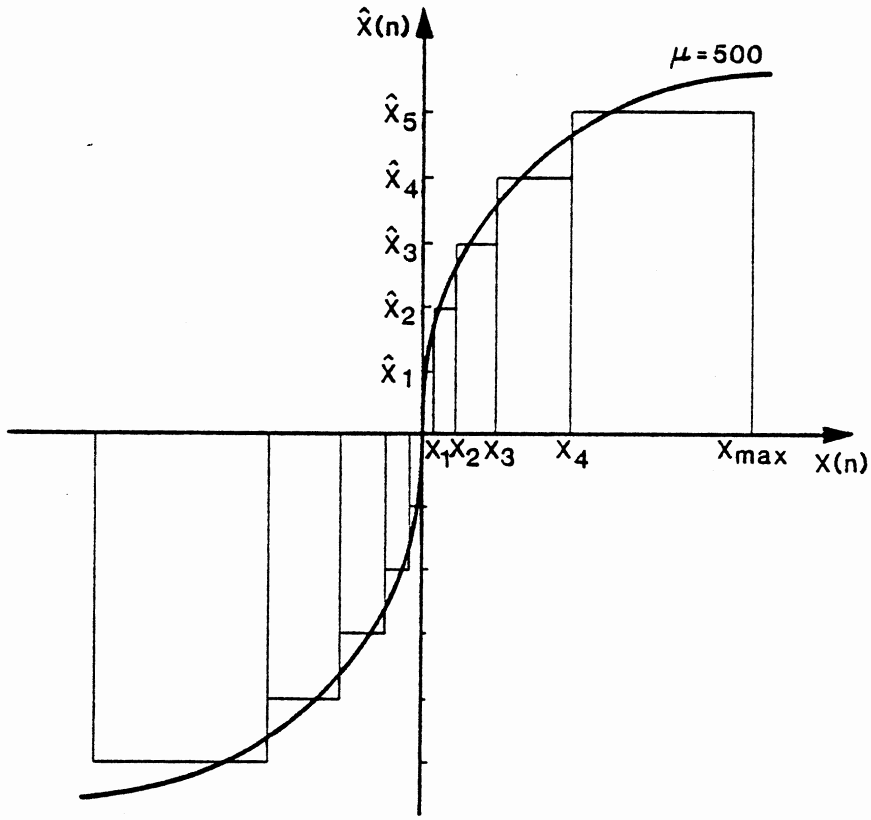
The basic idea of adaptive quantization is to let step-size vary so as to match the variance of the input signal. This implies that it is necessary to obtain an estimate of the time varying amplitude properties of the input signal. Sample-to-sample changes (or rapid changes within a few samples) and syllabic changes (or slowly varying) [6] need to be considered. For simplicity, the amplitude changes of sample-to-sample are used as the basis of the step-size adaptation for seismic data.

In general, there are two schemes in adaptive quantization, feed forward and feed backward quantization. When the step-size is adjusted according to the input itself, it is referred to as a feed-forward adaptive quantizer. When the step-size is adapted on the basis of the previous output of the quantizer, it is referred to as feed-backward quantizer. The feed-backward adaptation is based on the assumption that adjacent



(a) μ-curves (After Smith [18])

Figure 19. μ-curves and Distribution Levels



(b) Distribution Levels (μ = 500)

Figure 19. (Continued)

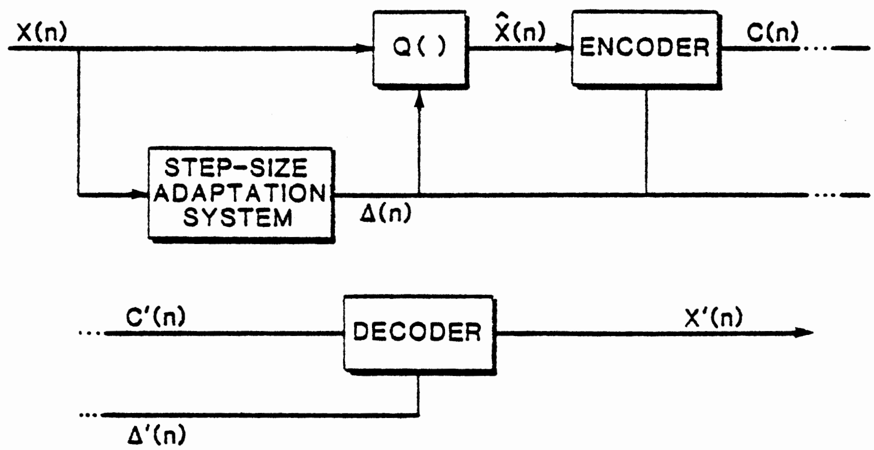
samples do not vary much, that is, sample-to-sample correlation is high. The feed forward and feed backward quantization schemes are shown in Figures 20a and 20b, respectively.

The feed-forward adaptation needs to transmit the step-size information for decoding, as the decoder cannot generate the step-size without current input data, while the feed-backward adaptation allows for the computation of step-size at the decoder in the absence of channel errors. This is a distinct advantage of feed-backward adaptation, especially when data compression is a critical issue. For this reason, feed-backward adaptation is used in this research and is discussed in detail in a later part of this section. It should be pointed out that the feed-backward adaptation has increased sensitivity to errors in the codewords, since such errors imply not only an error in the quantization level but also in the step-size [19].

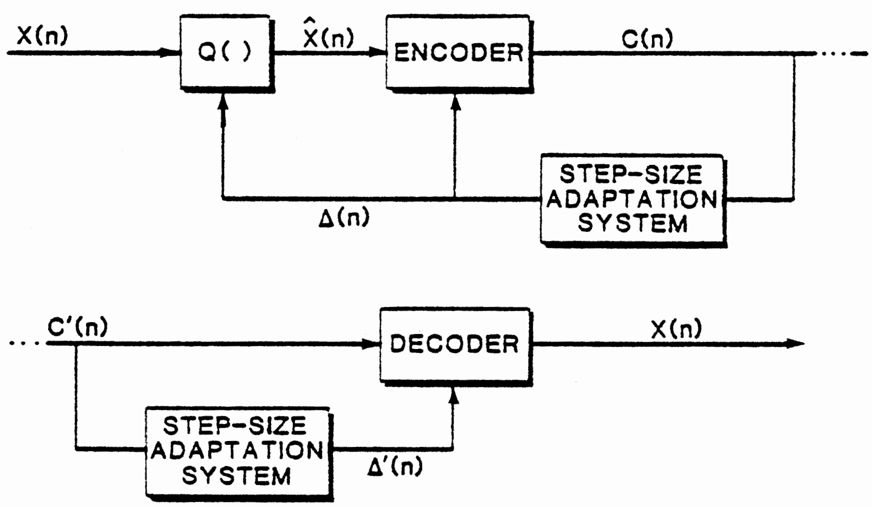
The step-size computation associated with the feed-backward quantizer is given by

$$\Delta(n) = M(|C(n-1)|)\cdot\Delta(n-1) \tag{3.17}$$

where $C(n-1)$ is the previous output code, $\Delta(n-1)$ is the previous step-size, and M is the multiplier array. It can be seen from Equation (3.17) that the current step-size is obtained by multiplying a selected multiplier and the previous step-size. The multiplier is selected from the multiplier array indexed by the absolute value of the previous output code. The multiplier is designed so that the entries in the first half of the array are less than one and the entries in the second half of the array are greater than one. Thus, the step-size will be reduced (increased) if the value of the previous code is less than (greater than) half of the code range. It



(a) FEED-FORWARD ADAPTATION



(b) FEED-BACKWARD ADAPTATION

Figure 20. Adaptive Quantization Procedures (After Rabiner and Schafer [6])

is easy to see that the initial step-size is very critical as the succeeding step-sizes are proportional to the initial step-size. The optimum initial step-size is obtained by the following formula [20].

$$\Delta_{opt} = E[(X(n) - X(n-1)^2]^{\frac{1}{2}} \ln (2F_o) \tag{3.18}$$

$$F_o = F_s/2\ F_n$$

where F_s is the sampling frequency and F_n is the Nyquist sampling rate.

The SNR of this technique is derived in a similar manner as the uniform step-size quantization technique, as the step-size is uniform for each quantization instance. Basically, this technique pursues to meet the third assumption of the uniform quantization so that every bit is used efficiently.

Differential Input Quantization

In the last few sections, various quantization techniques have been examined with respect to their step-size decision process. It has been found that the signal variance influences SNR for uniform quantizers. Non-uniform quantizers were considered to reduce the dependency in signal variance to improve SNR. Another method of improving SNR is by coding the difference signal, which is the difference between the input and the predicted value. This method is called the differential input quantization technique.

When a predictor is designed based on a system model or based on mathematical derivation of an optimal filter, it is referred to as a predictive coding technique. It is differentiated from a simple differential input quantization technique, delta modulation, where the difference between adjacent samples is quantized and coded. Delta modulation is a suboptimal technique; it has a significant advantage over a predictive coding technique in computational simplicity; it uses one delay instead of an optimal filter [21].

This section focuses on general considerations in measuring the SNR and the details of predictive coding techniques will be discussed in Chapter IV. The SNR of the differential input quantization is [22]

$$SNR = \frac{\sigma_x^2}{\sigma_e^2} = \frac{\sigma_x^2}{\sigma_d^2} \cdot \frac{\sigma_d^2}{\sigma_e^2} = G_p \cdot SNR_q \tag{3.19}$$

$$G_p = \frac{\sigma_x^2}{\sigma_d^2}, \quad SNR_q = \frac{\sigma_d^2}{\sigma_e^2}$$

where σ_d^2 is the variance of the difference signal. Equation (3.19) shows that signal-to-noise ratio consists of prediction gain and the signal-to-noise ratio due to quantization. Assuming the prediction gain is greater than one, it can be expected to improve the overall signal-to-noise ratio. In cases of predictive coding, higher order of filter contributes to better prediction. The prediction gain is dependent on the performance of the predictor and it can be maximized by minimizing the prediction error. For applying delta modulation, high correlation of adjacent samples is necessary in order to achieve a good prediction gain. When delta modulation employs more than two quantization levels, it is called a differential pulse code modulation (DPCM). When adaptation quantization is used, it is referred to as an adaptive differential pulse code modulation (ADPCM). Usually, nonuniform quantization techniques are not applied since the variance of difference signal is assumed to be small.

The performance of various digital coding techniques--ADPCM, DPCM, APCM, and LPCM--are illustrated in Table II for 16 traces of vibroseis data. The ADPCM shows the best signal-to-noise ratio.

Optimum Encoding Techniques

In general, there are two types of encoding, source encoding and channel encoding [23]. The main subject of this section is source encoding, defined as the process of converting an information source signal into a binary sequence. An optimum encoder for N symbols corresponds to an average bit rate $(\hat{H}_N)$, which approaches the source entropy (H) as N approaches infinity [23]. This can be expressed as

$$\hat{H}_N = 1/N \sum_{i=1}^{q} n_i p_i \rightarrow 1/N \sum_{i=1}^{q} p_i \log_2 (1/p_i), \tag{3.20}$$

$$H = \lim_{N\rightarrow\infty} \hat{H}_N \text{ (bits/symbol)}, \tag{3.21}$$

where q is the number of messages encoded into the sequence of N symbols, p_i is the probability of the ith message m_i, and n_i is the optimum code word length for the ith code word, c_i.

Any solution of Equation (3.20) is an optimum encoding technique. One example given by Shannon and Fano [14] is discussed below. This algorithm has the property of assigning short (long) code word lengths for high (low) probability messages. Specifically, if q messages m_1, m_2, m_3, . . ., m_q are ordered in decreasing probability, the code length of the ith message is computed from

$$\log_2(1/p_i) < n_i < 1 + \log_2(1/p_i) \tag{3.22}$$

where $p_1 \geq p_2 \geq \ldots \geq p_q$, and n_i is an integer.

After the optimum code word length is computed for the ith message,

TABLE II

SNR(dB) OF 6-BIT DIGITAL CODING METHODS ON VIBROSEIS DATA

TEST	ADPCM	DPCM	APCM	LPCM
1	37.1	32.5	26.7	31.8
2	38.3	34.1	27.6	32.2
3	36.6	33.6	28.6	32.0
4	37.2	31.5	26.1	31.6
5	36.6	30.7	25.0	31.8
6	36.7	30.9	24.9	30.8
7	35.9	31.2	26.2	31.5
8	36.0	30.6	27.5	31.7
9	33.7	31.2	27.8	31.2
10	35.5	33.1	29.6	30.2
11	39.0	28.7	20.5	31.7
12	34.4	30.4	23.2	31.3
13	39.9	38.1	29.1	32.3
14	39.3	36.0	29.9	32.2
15	37.5	35.4	30.6	31.8
16	44.7	43.7	31.0	32.6
AVG	36.8	31.0	25.0	30.8

a unique code word c_i is obtained by truncating the binary expansion of the probability function F_i after a maximum of n_i bits. Let

$$F_i = \sum_{k_i=1}^{i-1} p_k$$

then

$$c_i = (F_i)_{\text{binary } n_i \text{ bits}}.$$

Another example of an optimum encoding technique is the minimum redundancy coding method developed by Huffman [24]. The length of code words is inversely related to the probability of messages as in Shannon's algorithm.

These algorithms require code word tables, and therefore may also require large amounts of memory storage. Second, the message probability computation may not be feasible for some cases. However, these techniques still provide the ideal encoding, and thus can be used as a measure of the performance of other encoding methods. For example, the efficiency of an encoding technique (e) can be obtained by the ratio between the average bit ratio of the given encoding technique, H_N', and $\hat{H}_N$. That is,

$$e = \hat{H}_N / H_N' . \qquad (3.23)$$

Summary

This chapter has evaluated general data compression techniques with respect to their utilities for seismic data compression. The results showed that entropy reducing transforms and interpolation techniques are not adequate for seismic data compression due to the reversibility considerations and the low sampling rate. The prediction techniques which allow for transmitting the prediction error signal instead of the original input signal were considered. They were found to be impractical for large size seismic data since computational complexities involved in obtaining a predictor increase as the square of the number of data. These techniques were suggested for impulsive seismic data for a restricted region. The restricted region is obtained by a data slicing technique where all impulsive waveforms are separated from random waveforms as will be discussed later in the next chapter.

Alternative approaches for seismic data compression were discussed with orthogonal transforms and digital coding methods. For both approaches various techniques were examined and their performances on seismic data compression were evaluated.

The performances including compression ratio and signal-to-noise ratio of the WHT, the DFT, and the DCT were illustrated in Table I. Also, the performances of various digital coding techniques--DPCM, ADPCM, LPCM, and APCM--were shown in Table II.

From these evaluations, it was concluded that a technique which combines an orthogonal transform and a digital coding method may be a proper approach for vibroseis data compression. In particular, the discrete cosine transform was shown to be the best choice for the orthogonal transformation with respect to computational complexity, compression ratio, and signal-to-noise ratio.

In the next chapter, data compression techniques for vibroseis data and impulsive seismic data will be investigated based on these observations of orthogonal transforms, digital coding methods, and prediction techniques.

CHAPTER IV

SEISMIC DATA COMPRESSION

Introduction

In the previous chapter, prediction, orthogonal transforms, and digital coding methods were suggested for seismic data compression. This chapter discusses combinations of these techniques for vibroseis data and impulsive seismic data.

As pointed out earlier, vibroseis data differ from impulsive seismic data in their statistical characteristics. For this reason, the data compression technique is developed separately for each type of seismic data. For vibroseis data compression, a "hybrid technique," which combines an orthogonal transform and a digital coding method is considered. For impulsive seismic data compression, the trace is divided into two sections, an impulsive section and a nonimpulsive section. For the first section, a "predictive coding" technique is investigated; and for the second section, the hybrid technique is considered.

The hybrid technique for seismic data compression can be evaluated in the following manner. First, the signal-to-noise ratio and the compression ratio of the hybrid technique are derived. These derivations are discussed with two aspects, orthogonal transforms and digital coding methods. Second, the selection method for the significant transformed vector coefficients is examined in relation to a threshold value decision scheme. For the retained coefficients, the choice of a digital coding method is discussed based on empirical results of various coding methods. Third, the μ-law quantization is considered as a digital coding method for the retained coefficients with respect to the relation between the μ-value and the compression results. Finally, the implementation of the hybrid technique for a given set of vibroseismic data is illustrated, and the compression results are evaluated.

The predictive coding method for the first segment of the impulsive seismic trace can be analyzed as follows. First, the data segmentation consideration is studied with respect to the waveform characteristics of each segment. Also, the signal-to-noise ratio and the compression ratio of the trace are discussed in relation to the SNR and CPR of each segment. Second, the "linear prediction" algorithm is studied with respect to optimum predictor parameters based on the autocorrelation method and the Lattice method. Finally, the implementation of the predictive coding technique for a given set of impulsive seismic data is illustrated, and the compression results are evaluated.

Vibroseis Data Compression

The signal-to-noise ratio of the hybrid technique can be derived in terms of SNR for the orthogonal transform and the digital coding method. Explicitly,

$$\mathrm{SNR} = \frac{\sigma_x^2}{\sigma_e^2} = \frac{\sigma_x^2}{\sigma_y^2}\,\frac{\sigma_y^2}{\sigma_e^2} \tag{4.1}$$

where σ_x^2 is the variance of the original signal, σ_y^2 is the variance of the orthogonally transformed vector coefficients, and σ_e^2 is the variance of noise. Using Parseval's theorem, it follows that $\sigma_x^2 = \sigma_y^2$ [25].

However, in the hybrid technique the insignificant coefficients are suppressed, and the error due to this suppression needs to be included in Equation (4.1). For simplicity, this error is included with the digital coding error, and expressed in the approximate form.

$$SNR^V \cong \frac{\sigma_x^2}{\sigma_e^2} = \frac{\sigma_y^2}{\sigma_{y'}^2 + \sigma_q^2}$$

$$\cong \frac{1}{\frac{\sigma_{y'}^2}{\sigma_y^2} + \frac{\sigma_q^2}{\sigma_y^2}}$$

$$\cong \frac{SNR_1^V \cdot SNR_2^V}{SNR_1^V + SNR_2^V} \qquad (4.2)$$

where $\sigma_{y'}^2$ is the variance of the suppressed coefficients, and σ_q^2 is the variance of the quantization noise. The term SNR_1^V refers to the signal-to-noise ratio obtained from the orthogonal transform technique, and the terms SNR_2^V refers to the signal-to-noise ratio obtained from a digital coding method.

In order to maintain reversibility, most of the energy of the transformed vector should be preserved, and thus SNR_1^V should be far greater than SNR_2^V. From this relation, the SNR^V can be simply expressed as

$$SNR^V \cong \frac{SNR_1^V \cdot SNR_2^V}{SNR_1^V + SNR_2^V} \cong SNR_2^V \qquad (4.3)$$

where it is assumed that

$$SNR_1^V >> SNR_2^V .$$

The compression ratio can be expressed in general as

$$CPR = \frac{\text{Bit rate of the original signal}}{\text{Bit rate of the compressed signal}} \tag{4.4}$$

Using Equation (4.4) the compression ratio of the hybrid technique is given by

$$CPR^V = \frac{N \cdot b_o}{M \cdot b_1 + N} \tag{4.5}$$

where N is the number of data points in the original signal, b_o is the number of bits used per sample, M is the number of retained coefficients, and b_1 is the number of bits used per coefficient. The last term in the denominator of CPR, N, corresponds to the number of bits necessary for the bookkeeping array. The bookkeeping array preserves the information for selection and suppression of the coefficients.

In general, $M \cdot b_1 >> N$, and Equation (4.5) can be approximated by

$$CPR^V \cong \frac{N}{M} \cdot \frac{b_o}{b_1} = CPR_1^V \cdot CPR_2^V \tag{4.6}$$

where CPR_1^V is the compression achieved by the orthogonal transform and CPR_2^V is the compression achieved by a digital coding method.

In the next section, CPR_1^V and SNR_1^V are examined in relation to the threshold value for the insignificant coefficient decision; also, the characteristics of the retained coefficients are discussed with respect to the digital coding techniques.

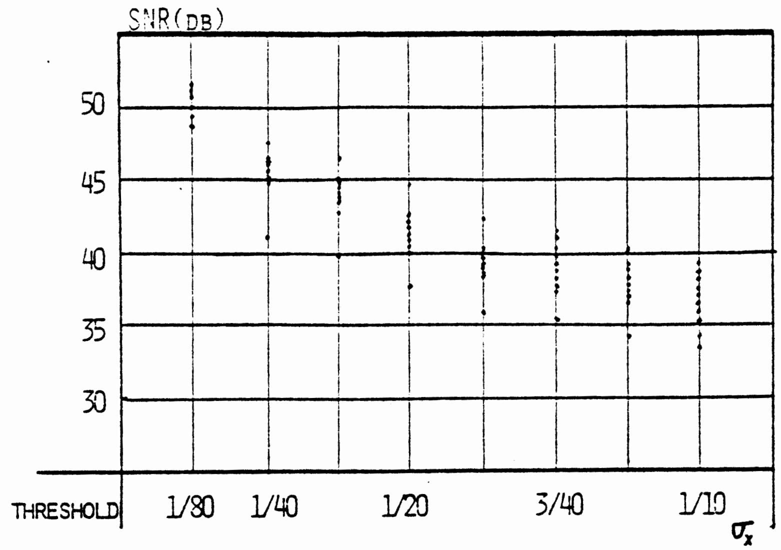
Selection of the Transformed Vector Coefficients

In Chapter II, it was shown that the discrete cosine transform (DCT) is the appropriate transform for the hybrid technique. For the selection of the significant coefficients, a threshold value computed from either the absolute maximum or the standard deviation of the coefficients needs to be determined. From an empirical observation (see Figure 21), it was determined that the threshold value from the standard deviation gives more uniform results for compression and signal-to-noise ratio. Figure 21a and 21b show the distribution characteristics of the signal-to-noise ratio and the compression ratio as functions of the threshold value for 16 traces of a given set of vibroseis data. From Figure 21, it can be seen that the threshold value varies from 1/80 to 1.10 of the standard deviation, and varies from 1/800 to 1/100 of the absolute peak value. Also, the compression ratio is more sensitive to the threshold value than the signal-to-noise ratio.

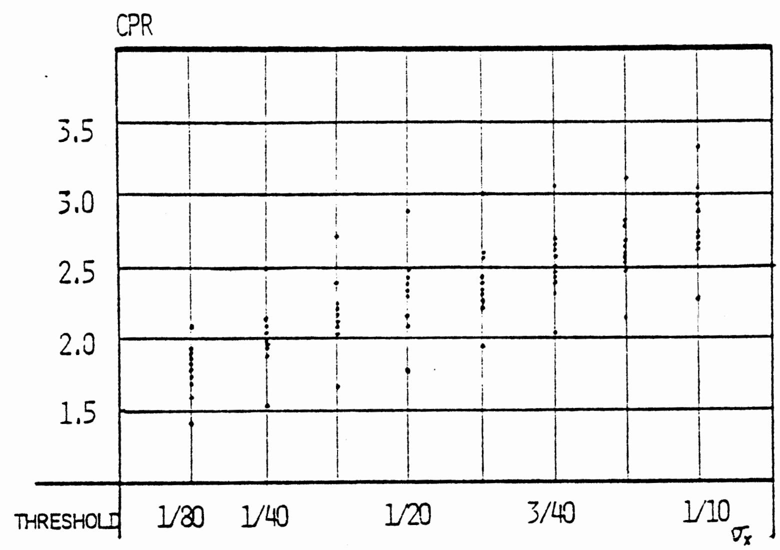
For selection of the significant coefficients, (1/20) σ_x is used as the threshold value for the insignificant coefficients. With this threshold, the CPR ranges from 2.0 to 2.5, and the SNR is approximately 42 dB. These values indicate that by discarding $1/10^4$ of the total energy, at least two to one compression can be achieved from the DCT method. These can be denoted as $SNR_1^V = 10^4$ and $CPR_1^V > 2$.

The selection method has been applied to various lengths of partial vibroseis trace and their compression ratios are illustrated in Figure 22. It can be observed that whole trace shows the best compression result and less than 512 points of partial vibroseis trace shows almost no compression.

In order to obtain SNR_2^V and CPR_2^V, a proper digital coding method needs to be chosen to represent the retained coefficients. The compression results of various digital coding techniques, ADPCM, LPCM, APCM, and μ-law, are compared in Table III. This table shows that the μ-law quantization gives a better compression result than others. This result is due

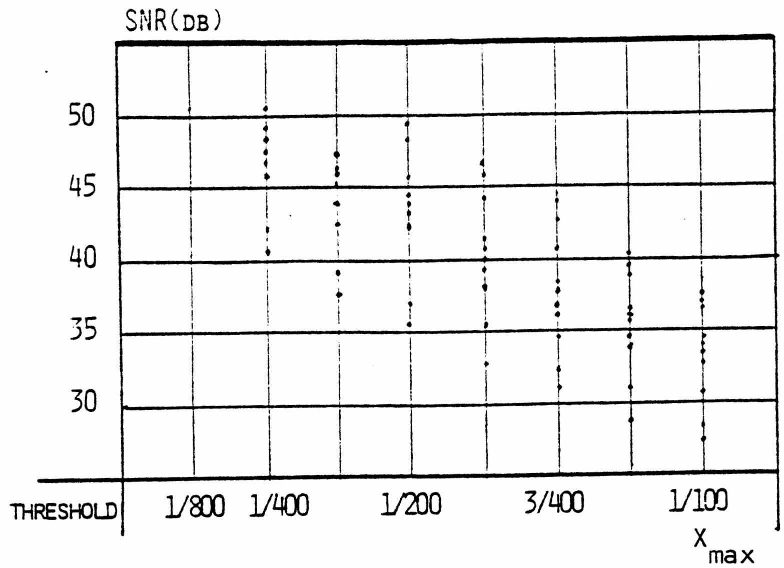


(a) SNR Distribution of Suppressed DCT Coefficients

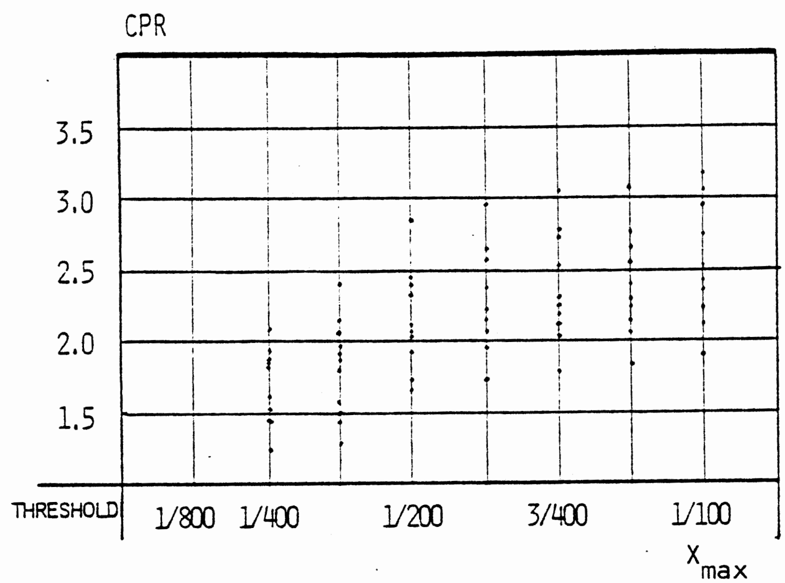


(b) CPR Distribution of Selected DCT Coefficients

Figure 21. Distributions of SNR and CPR as a Function of Threshold



(c) SNR Distribution of Suppressed DCT Coefficients



(d) CPR Distribution of Selected DCT Coefficients

Figure 21. (Continued)

TABLE III

SNR(dB) OF 6-BIT DIGITAL CODING METHODS ON SELECTED DCT COEFFICIENTS

TEST	APCM	ADPCM	LPCM	μ-LAW
1	25.92	18.82	24.26	27.38
2	23.96	13.36	23.96	26.30
3	14.69	13.08	24.24	26.53
4	16.27	18.94	24.83	30.46
5	19.50	12.56	25.65	30.78
6	13.68	11.20	24.07	26.56
7	18.20	22.06	25.66	28.34
8	23.84	19.80	24.92	26.87
9	21.43	20.35	26.11	27.86
10	17.27	14.60	26.54	27.72
11	18.94	16.83	26.93	27.88
12	19.51	19.09	26.38	26.67
13	26.38	28.19	28.80	29.41
14	20.12	23.62	28.27	30.11
15	19.70	18.71	27.97	30.22
16	14.86	10.45	23.86	30.43
AVG	19.64	17.60	25.84	28.34

to the distributional characteristics of the retained coefficients and low correlation between adjacent coefficients.

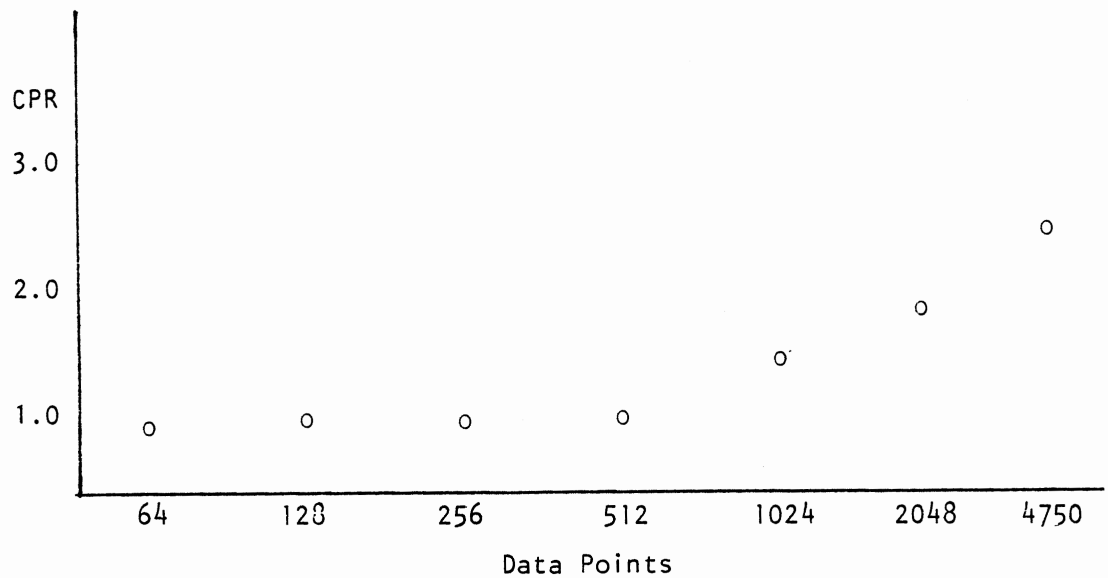


Figure 22. Compression Ratio of Partial Vibroseis Trace

μ-Law Quantization

The μ-law quantization method is applied for quantizing the retained discrete cosine transform coefficients. In Chapter III, it was pointed out that the μ-value controls the dependence of the signal-to-noise ratio on the signal variance. Figure 23 illustrates the signal-to-noise ratio on the signal variance. Figure 23 illustrates the signal-to-noise ratio of μ-law quantization as a function of the signal variance and μ-value [18]. It can be seen that the dependence of the signal-to-noise ratio decreases as the μ-value increases. For example, with $\mu = 500$, the signal-

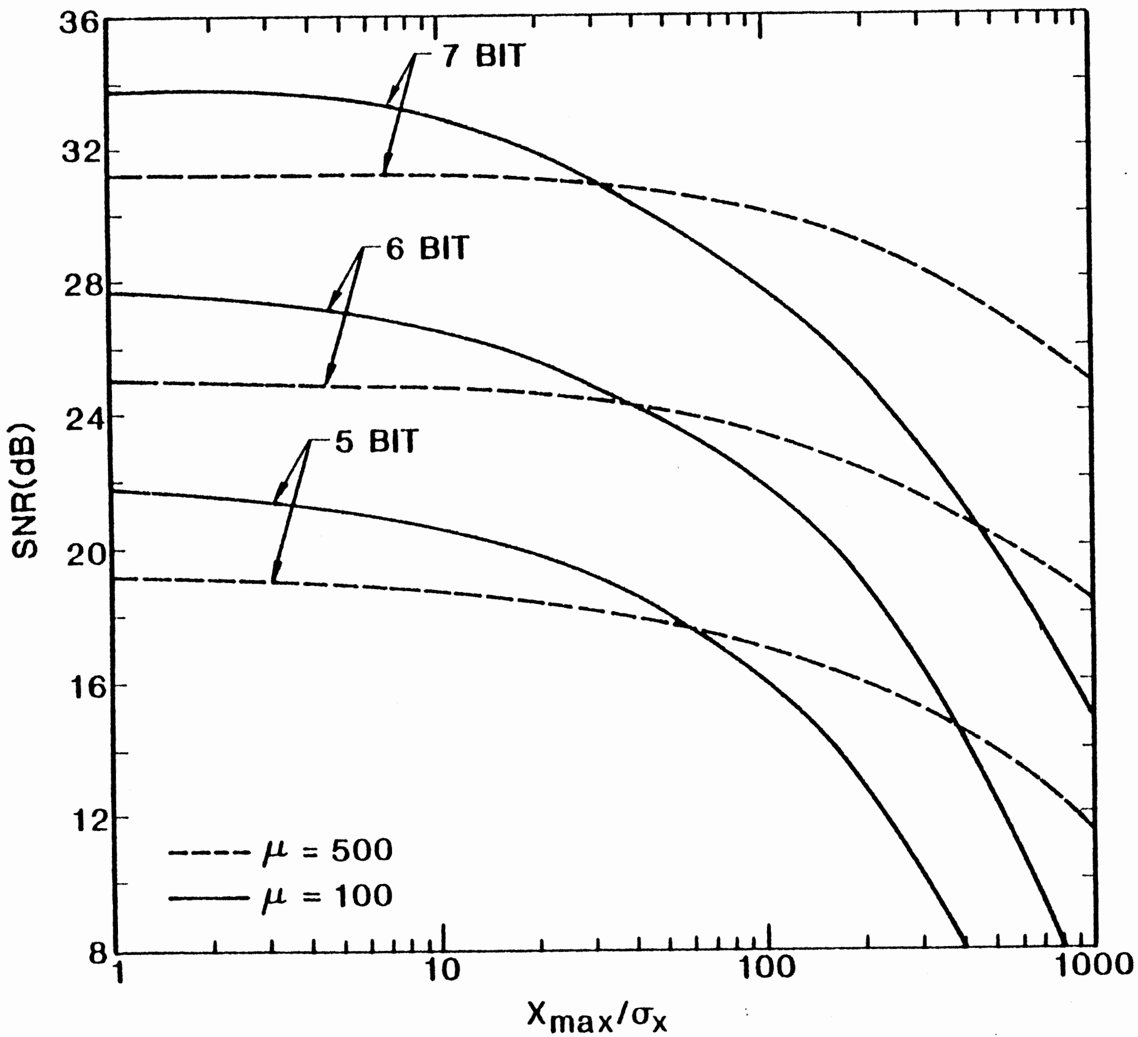


Figure 23. SNR(dB) of μ-law Quantizer as a Function of $|X_{max}|/\sigma_x$
(After Rabiner and Schafer [6])

TABLE IV

μ-VALUES AND $|X_{max}|/\sigma_x$

$\lvert X_{max}\rvert/\sigma_x$	μ-value
0 - 4	0.0
4 - 15	10.0
15 - 20	30.0
20 - 25	50.0
25 - 35	100.0
35 -	

to-noise ratio remains stable over $\sigma_x < X_{max} < 100\ \sigma_x$. For higher values of μ, the expected signal-to-noise ratio is lower. For this reason, a value for μ is adapted for each trace of the seismic data based on the value $(|X_{max}|/\sigma_x)$. It is shown in Table IV and the table is obtained empirically.

For encoding the quantized levels, PCM is used. The number of bits per code word is determined based on the required signal-to-noise ratio referred to as SNR_2^V in the previous section. The results corresponding to 6- and 7-bit encoding with PCM are illustrated in Table V. It was pointed our earlier that SNR^V approaches SNR_2^V when SNR_1^V is much higher than SNR_2^V (see Equation (4.3)). Noting that SNR^V is required to be greater than 30 dB in order to maintain reversibility, SNR_2^V is desired to be at least 30 dB. Table V indicates that a 7-bit PCM is required for encoding the μ-law quantized levels when the μ-value is computed to be greater 10. It can also be seen that a 6-bit PCM can be applied for the traces whose μ-value is ≤ 10.

From Figure 23 and Table V, it can be observed that adaptation of the μ-value prior to applying the μ-law quantization influences the compression significantly. The adaptation of the μ-value requires overhead computation of the value $(|X_{max}|/\sigma_x)$.

Implementation of the "Hybrid Technique"

In the last two sections, the hybrid technique was investigated using the discrete cosine transform followed by a μ-law quantizer with a 7-bit PCM encoder. The encoding and decoding procedures of the hybrid technique are illustrated in Figure 24a, b, c, and d.

In the transmitter, the seismic data are transformed via the DCT, and

TABLE V

RESULTS OF μ-LAW QUANTIZATION

TEST	μ-VALUE	6-BIT SNR(dB)	6-BIT CPR	7-BIT SNR(dB)	7-BIT CPR
1	30.0	28.02	8.50	33.68	6.38
2	100.0	25.85	7.62	31.63	5.71
3	100.0	26.43	8.80	31.55	6.60
4	10.0	30.45	9.13	36.48	6.84
5	10.0	30.78	10.55	36.70	7.91
6	10.0	25.69	8.09	31.60	6.07
7	30.0	27.93	10.02	33,78	7.51
8	30.0	27.61	11.71	34.32	8.78
9	50.0	27.60	9.03	34.14	6.78
10	30.0	27.16	9.73	33.59	7.30
11	100.0	27.47	9.48	33.41	7.11
12	30.0	28.42	8.87	34.64	6.65
13	50.0	27.81	7.96	34.00	5.97
14	30.0	26.69	8.69	33.17	6.52
15	30.0	28.37	8.96	34.52	6.72
16	50.0	27.76	9.18	33.74	6.89
AVG		27.74	9.15	33.81	6.86

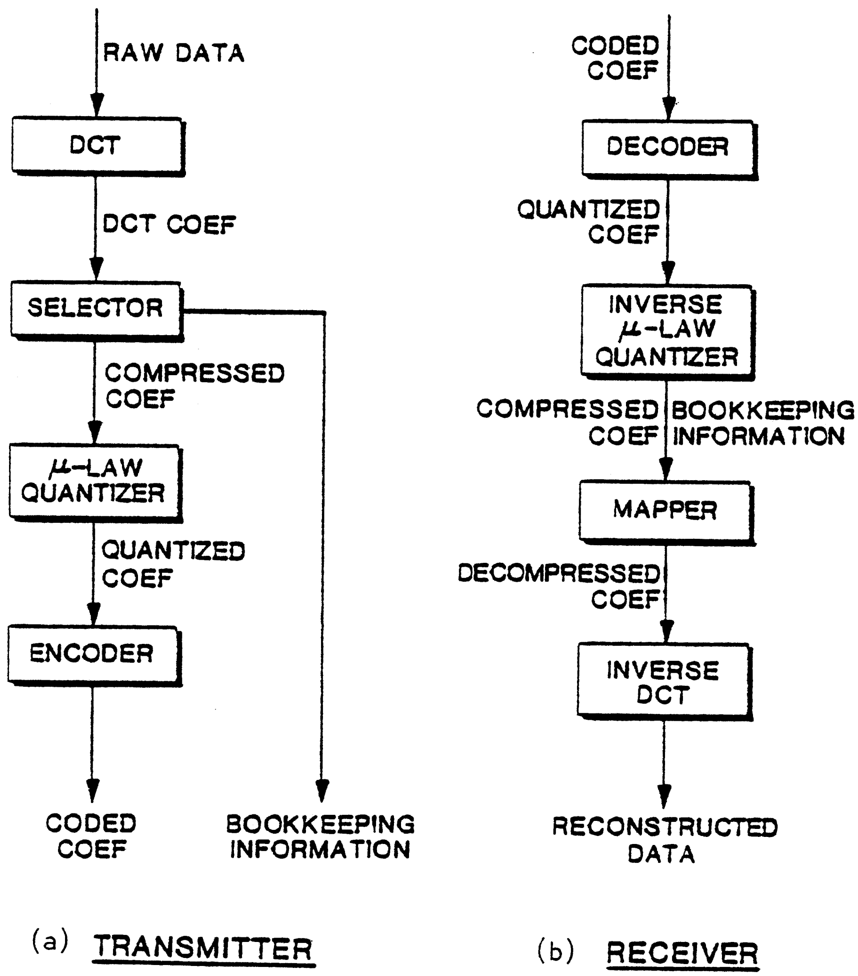
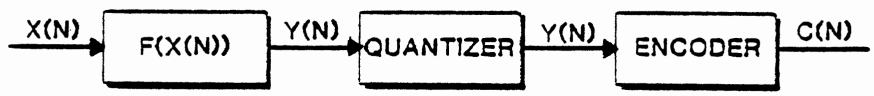


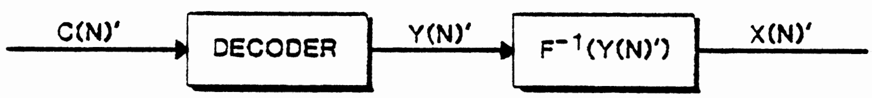
Figure 24. "Hybrid Technique" Procedures



$$Y(N) = F(X(N))$$

$$= \frac{X_{MAX} \cdot LOG\left(1+\mu \frac{X(N)}{X_{MAX}}\right) \cdot SIGN\,(X(N))}{LOG\,(1+\mu)}$$

(c) μ-LAW QUANTIZER



$$X(N)' = F^{-1}(Y(N)')$$

$$= \frac{Y'_{MAX}}{\mu} \left\{ LOG^{-1} \left[\frac{Y(N)' \cdot LOG(1+\mu)}{Y'_{MAX}} \right] - 1 \right\} \cdot SIGN(Y(N)')$$

(d) INVERSE μ-LAW QUANTIZER

Figure 24. (Continued)

the transformed vector coefficients above the threshold value are selected by the selector shown in Figure 24a. The information of selection is transmitted to the receiver through the bookkeeping array. The retained coefficients are quantized with a μ-law quantizer and encoded for transmission. Details are shown in Figure 24c and d.

In the receiver, the coefficients are decoded and then dequantized with an inverse μ-law quantizer. Then, using the bookkeeping information, the mapper reconstructs the transformed coefficients by inserting zeros corresponding to the insignificant coefficients. These coefficients are inversely transformed via the IDCT. The output is the reconstructed seismic data; though it includes a slight distortion, it maintains the reversibility property.

Compression results are evaluated with respect to the signal-to-noise ratio and the compression ratio. The signal-to-noise ratio is computed from

$$SNR^V(dB) = 10 \log \frac{E[(x - x')^2]}{E[x^2]} \qquad (4.7)$$

where x is the raw data and x' is the reconstructed data. The compression ratio is computed from Equation (4.5), simply replacing N with 4750,

$$CPR^V = \frac{4750 \times 20}{7M + 4750} \qquad (4.8)$$

where M is the average number of retained coefficients and 4750 in the denominator indicates the size of the bookkeeping array.

Table VI presents the results of 16 traces of the vibroseis data. It should be pointed out that the SNR is approximately 2 dB lower than SNR_2^V due to the noise introduced by suppressing the insignificant DCT

TABLE VI

RESULTS OF VIBROSEIS DATA COMPRESSION

TEST	SELECT (DCT)	μ-LAW (7-BIT)	OVER-ALL SNR	OVER-ALL CPR
1	43.8	33.7	32.6	4.91
2	42.9	31.6	30.9	4.53
3	43.7	31.7	29.3	5.03
4	43.6	36.5	34.3	5.15
5	44.2	36.7	34.4	5.72
6	43.9	31.6	30.7	4.73
7	44.5	33.8	32.3	5.52
8	43.5	34.3	31.4	6.15
9	45.2	34.1	31.7	5.03
10	43.4	33.6	31.7	5.31
11	42.0	33.4	31.5	5.27
12	44.1	34.6	33.1	5.04
13	43.2	34.0	32.9	4.68
14	42.7	33.2	32.3	4.99
15	43.2	34.5	33.4	5.00
16	41.5	33.7	32.8	5.19
AVG	43.5	33.8	32.2	5.16

coefficients. The bookkeeping array may not be necessary since the transformed vector of each trace shows that most energy is concentrated in two major lobes, and the location of the lobes is common for all traces. These lobes are located at the beginning and ending of the trace. Also, for some traces, 6-bit μ-law quantization can provide over 30 dB of SNR corresponding to a small μ-value. For these cases, i.e., 6 b/sample and no bookkeeping array, the CPR^V can be computed as

$$CPR^V = \frac{4750 \times 20}{6M} \tag{4.9}$$

which gives a significant enhancement in compression ratio. From the statistical observation of the CPR, it can be concluded that compression ratios can be achieved in the range of five-to-one to eight-to-one via the hybrid technique.

Impulsive Seismic Data Compression

The impulsive seismic data have a good deal of similarity from trace to trace, which is different when compared to vibroseis data. It was pointed out in Chapter II that an impulsive trace has two distinct parts. Most of the energy is contained in the beginning of a trace and the rest of the trace is relatively insignificant. Figure 25 illustrates this aspect of an impulsive trace.

In order to examine the energy distribution characteristics, 25 traces of 1000 data points each are divided into five parts with equal duration. These 25 corresponding parts are concatenated to form a segment. For example, the first segment contains 25 first parts from the respective traces. Figure 26a through e illustrates the five segments taken from a 25-trace impulsive data. Considering the similarities, the five

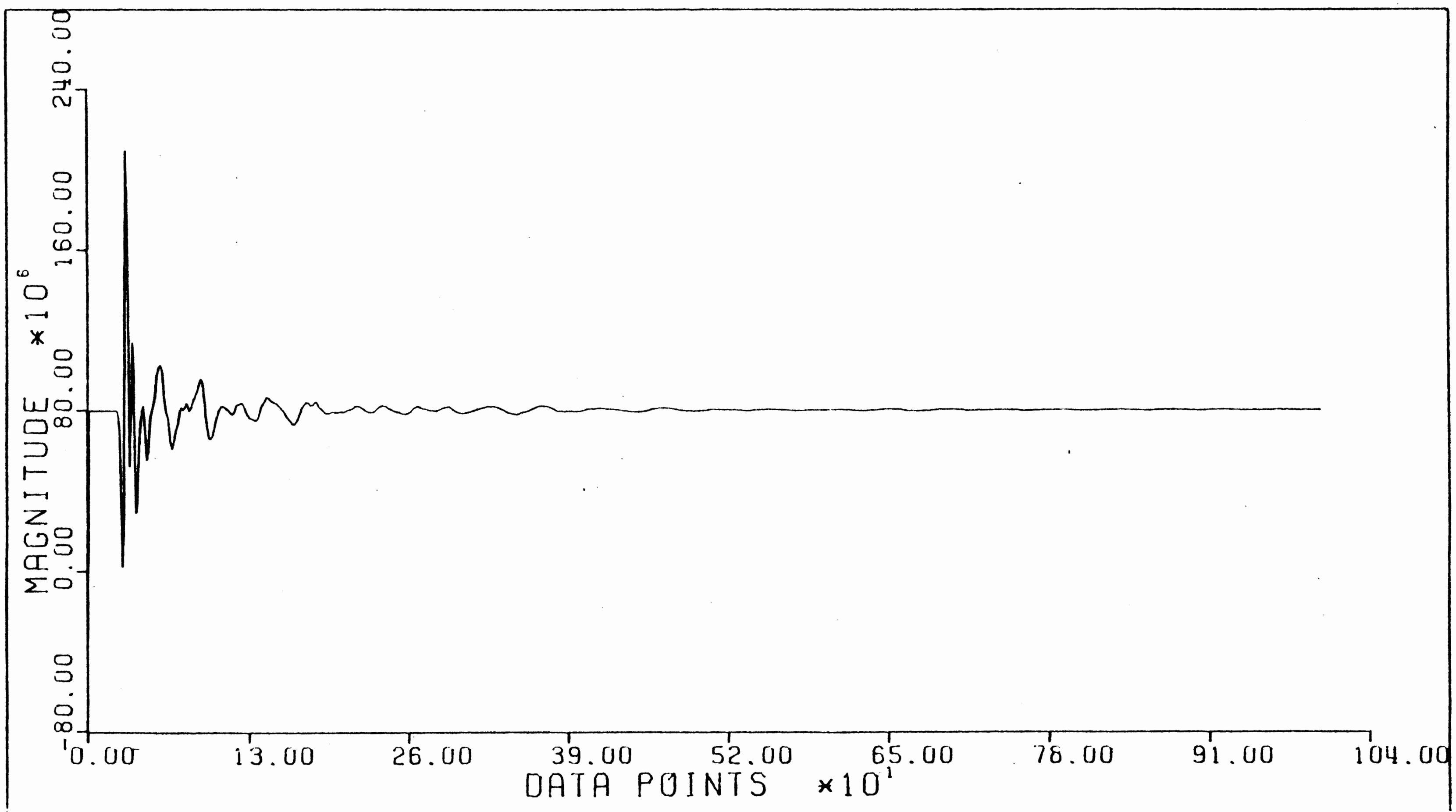
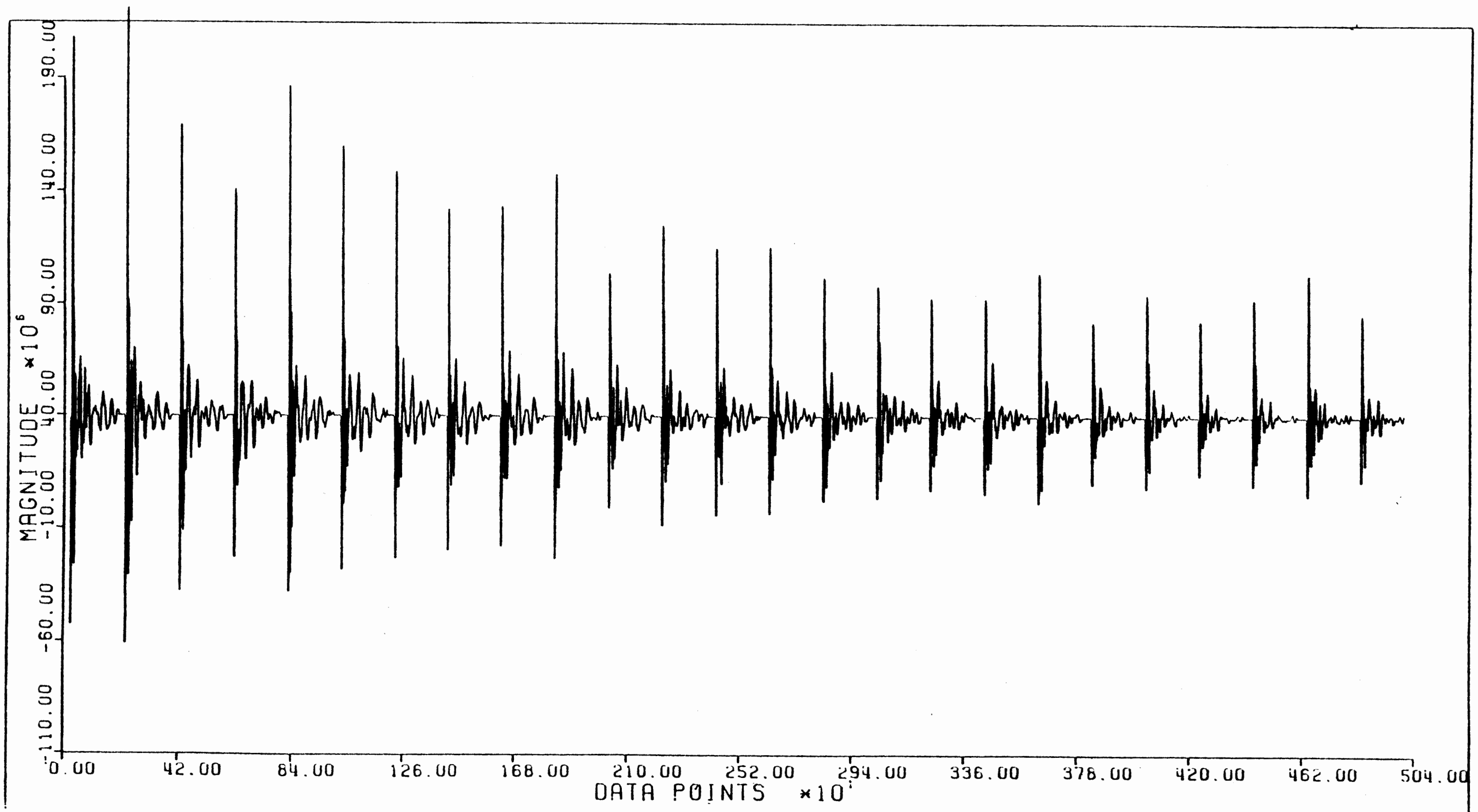
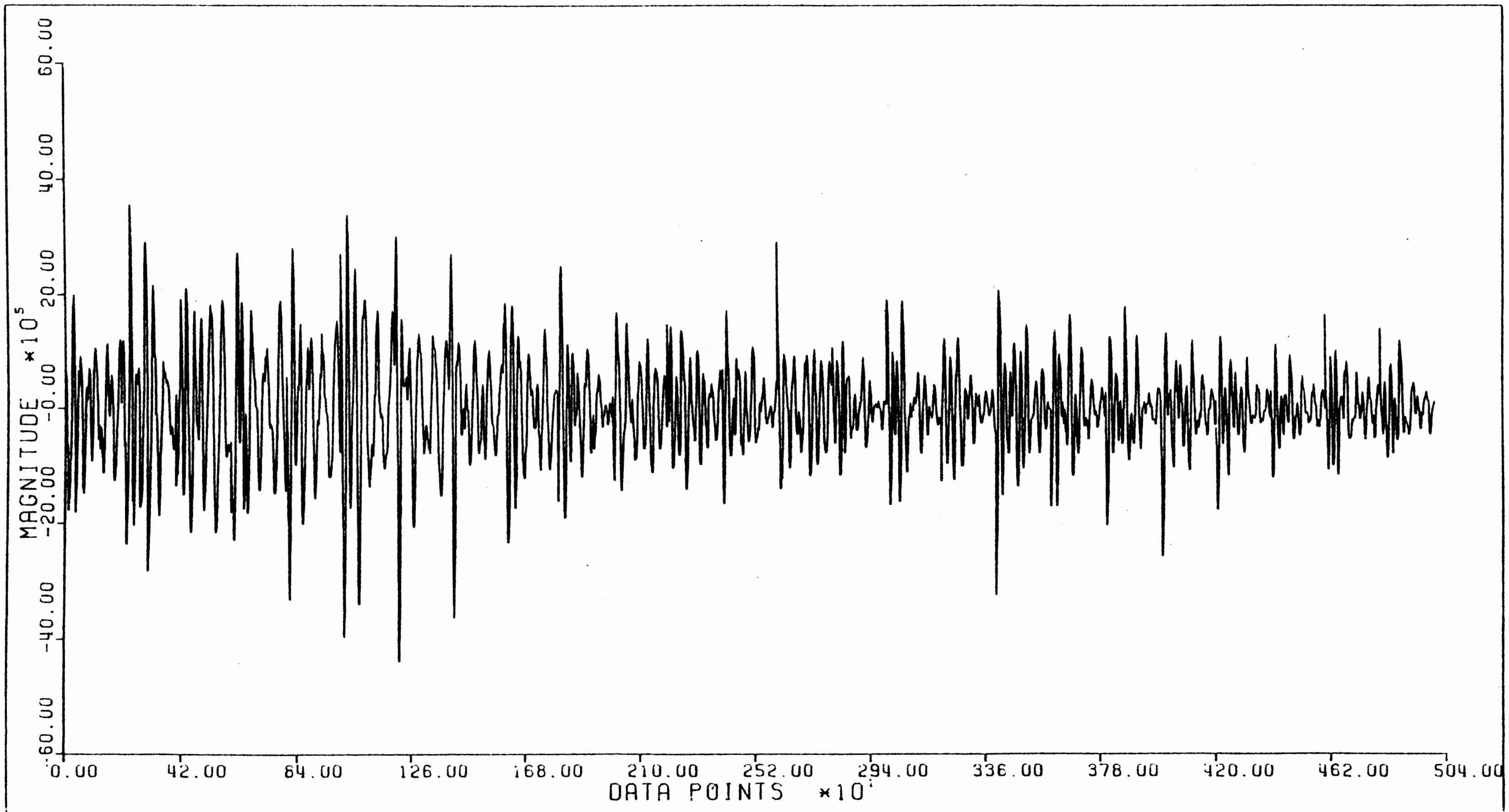


Figure 25. One Trace of Impulsive Seismic Data



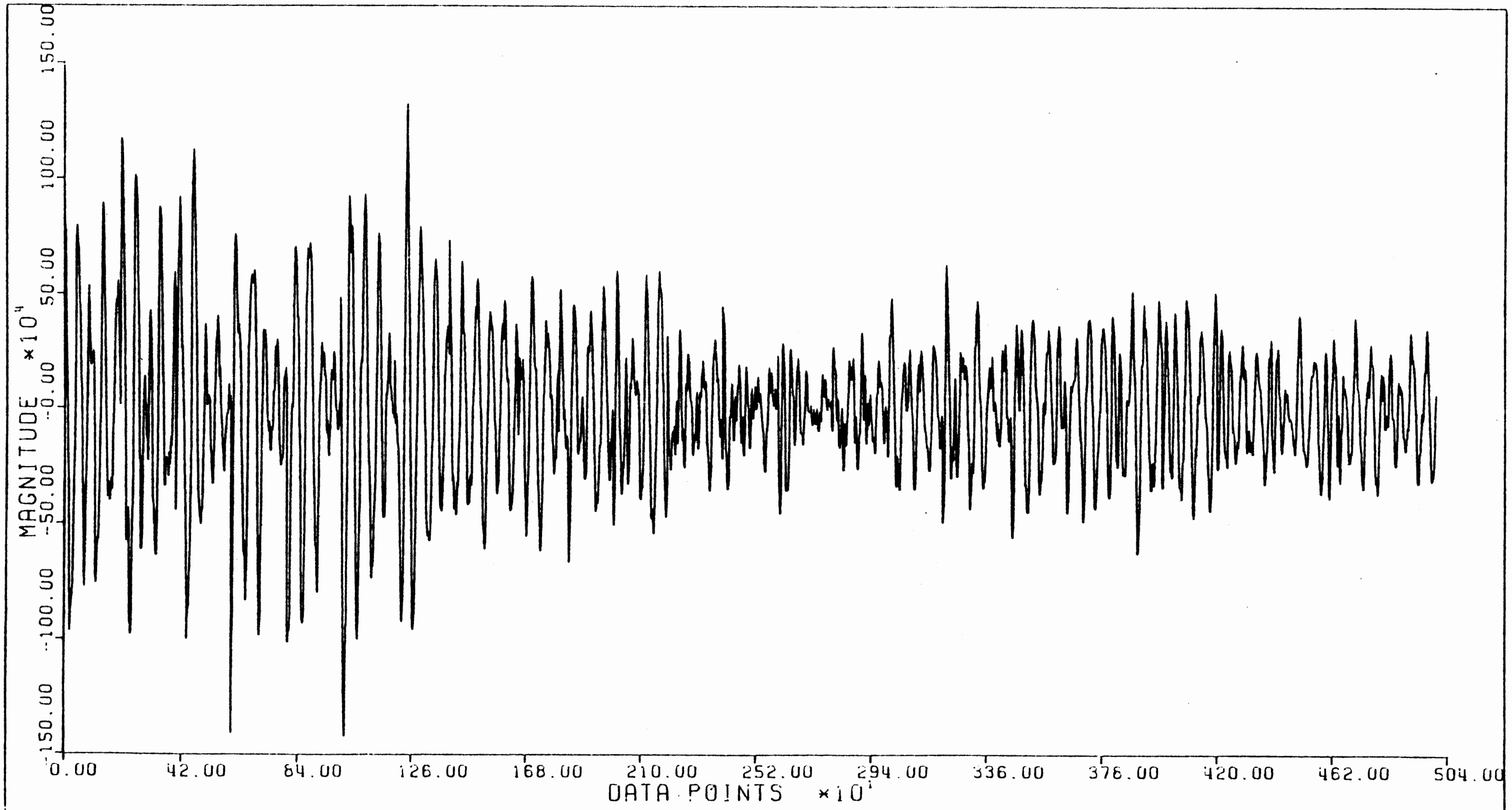
(a) First 200 Points of 25 Impulsive Seismic Data Traces

Figure 26. Illustrations of Five Segments of Impulsive Seismic Data



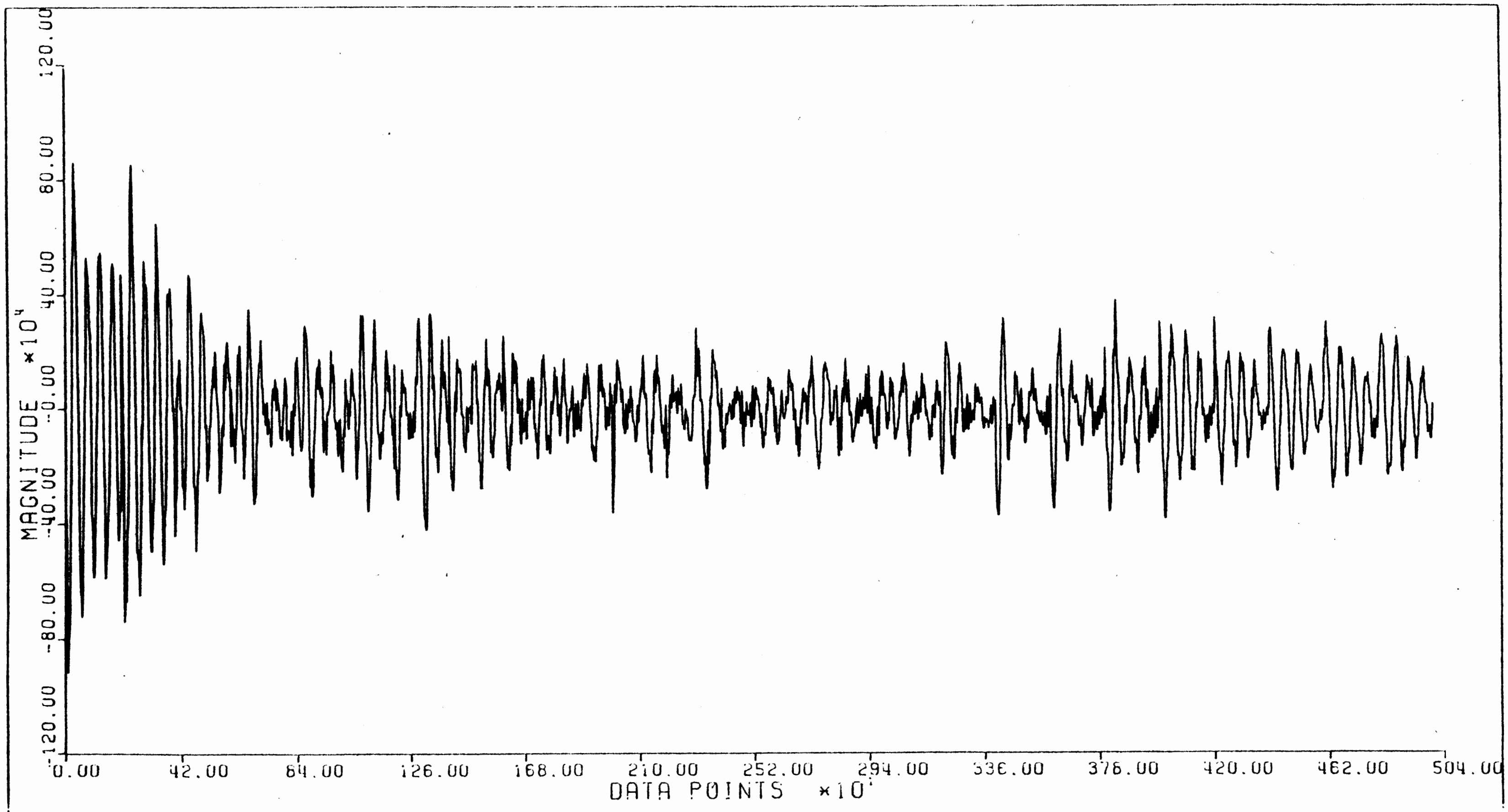
(b) Second 200 points of 25 Impulsive Seismic Data Traces

Figure 26. (Continued)



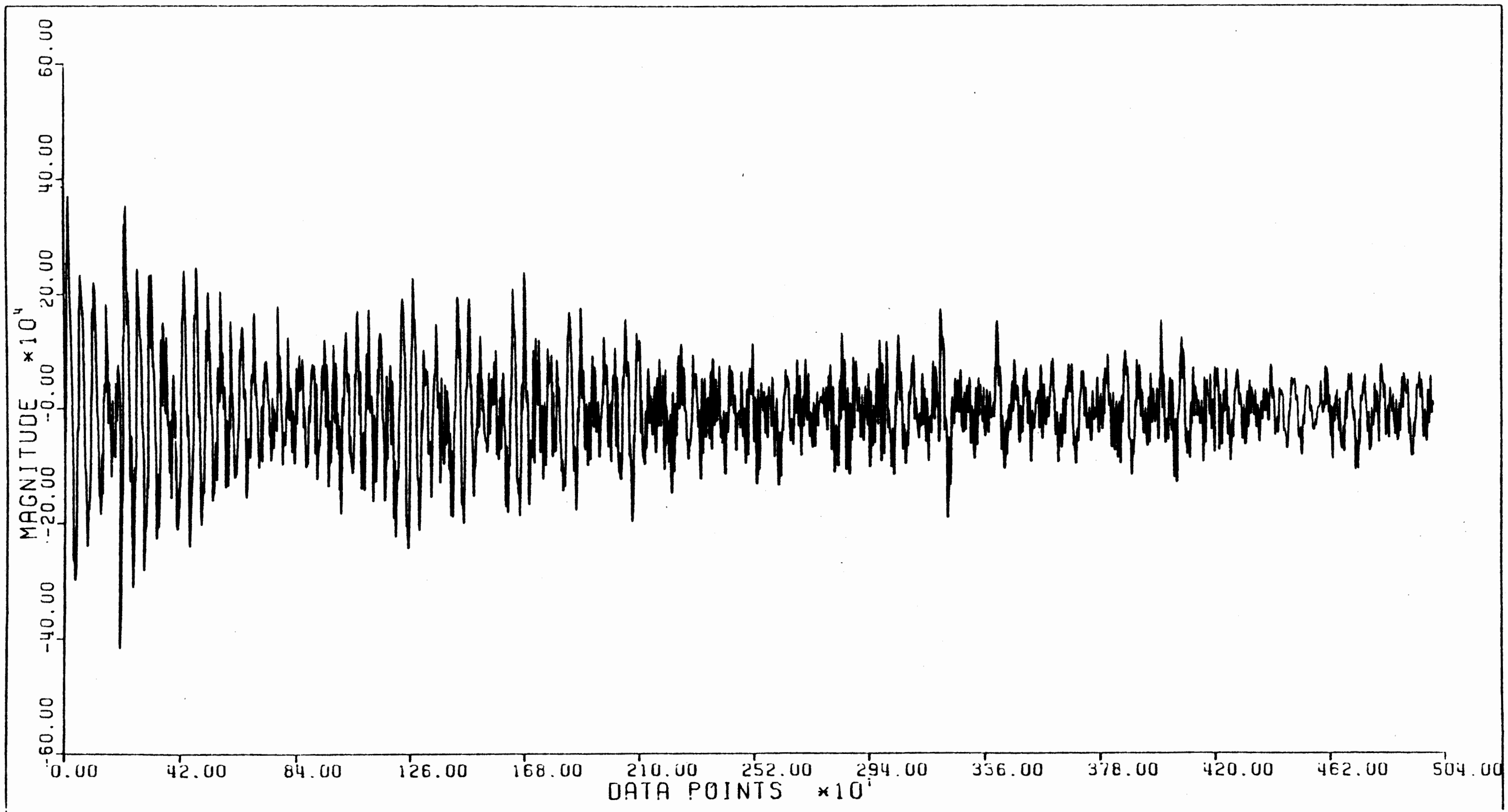
(c) Third 200 points of 25 Impulsive Seismic Data Traces

Figure 26. (Continued)



(d) Fourth 200 Points of 25 Impulsive Seismic Data Traces

Figure 26. (Continued)



(e) Fifth 200 Points of 25 Impulsive Seismic Data Traces

Figure 26. (Continued)

segments are grouped into two sections; since the first part in each trace contains most of the energy, the first segment is identified by impulsive section. The remaining four segments contain insignificant amounts of energy and are referred by nonimpulsive section.

It was found that the impulsive section contains more than 99 percent of the total energy. However, the amount of energy does not necessarily correspond to the amount of information in seismic data analysis. For this reason, signal-to-noise ratio of the both sections, SNR_1^I and SNR_2^I, need to be maintained uniformly for preserving information contained in each section. That is, $SNR_1^I \cong SNR_2^I$.

For simplicity, it will be assumed that the two sections are independent of each other. That is, it will be assumed that $\sigma_x^2 = \sigma_{x_1}^2 + \sigma_{x_2}^2$, where x_1 and x_2 correspond to the two sections. Noting $\sigma_{x_1}^2 >> \sigma_{x_2}^2$, $\sigma_{x_1}^2 >> \sigma_{e_2}^2$, it follows that overall SNR^I can be expressed as

$$SNR^I = \frac{\sigma_x^2}{\sigma_e^2} = \frac{\sigma_{x_1}^2 + \sigma_{x_2}^2}{\sigma_{e_1}^2 + \sigma_{e_2}^2} = \frac{1 + \dfrac{\sigma_{x_2}^2}{\sigma_{x_1}^2}}{\dfrac{\sigma_{e_1}^2}{\sigma_{x_1}^2} + \dfrac{\sigma_{e_2}^2}{\sigma_{x_1}^2}} \cong SNR_1^I \qquad (4.10)$$

where $\sigma_{e_1}^2$ is the noise variance due to the first section compression technique and $\sigma_{e_2}^2$ is the noise variance due to the second section compression technique.

Next, the compression ratio can be expressed as using Equation (4.4),

$$CPR^I = \frac{B}{\dfrac{B_1}{CPR_1^I} + \dfrac{B_2}{CPR_2^I}}$$

$$= \frac{B\ CPR_1 \cdot CPR_2}{B_1 \cdot CPR_2 + B_2 \cdot CPR_1}$$

where $B = B_1 + B_2$. Variables B_1 and B_2 are the bit rates of the first and second sections, and CPR_1^1 and CPR_2^1 are expected compression ratios for the corresponding two sections.

These two sections will be compressed separately. The first section will be compressed using the predictive coding method based on linear prediction analysis, and the second section will be compressed using the hybrid technique discussed earlier. In the next section, predictive coding is discussed with respect to the algorithms for an optimum linear predictor.

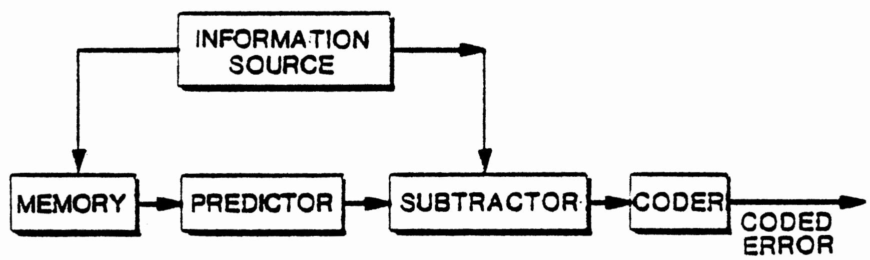
Linear Prediction Analysis

Predictive coding simply corresponds to the differential coding with an optimum predictor, which is based upon Wiener's work [26]. Let P_i be the predicted value of the ith message m_i. Then, the prediction error is given by

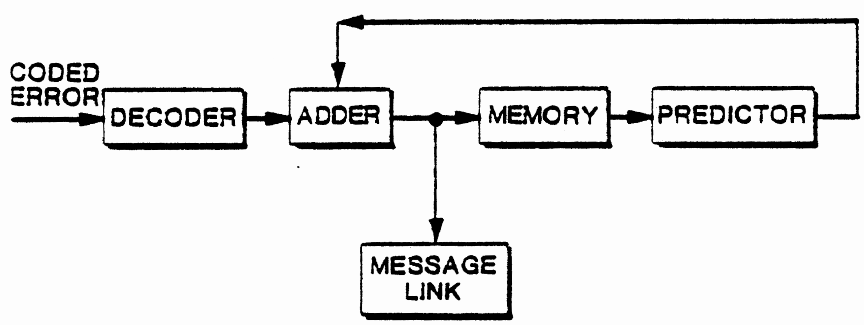
$$e_i = m_i - P_i. \tag{4.12}$$

Since P_i is a deterministic value, it has no information according to Shannon's definition. Thus by transmitting the error term, e_i, no information is lost.

The predictive coding and decoding procedures are illustrated in Figure 27, where an identical predictor appears in the transmitter and the receiver. Since the predictor operates on the past values of the message, storage of the past values is necessary. The size of this storage, or simply the order of the prediction, is an important parameter and is discussed later.



(a) TRANSMITTER



(b) RECEIVER

Figure 27. "Predictive Coding" Procedures
(After Alias [26])

The predicted value P_i is a linear combination of the previous message values. That is,

$$P_i = \sum_{j=1}^{\infty} a_j m_{i-j} \tag{4.13}$$

where the a_j's are some constants to be determined by minimizing the root mean square value of e_i. Wiener has shown that this predictor is determined not by the message ensemble, but by the autocorrelation function of the ensemble [26]. In general, there will be many ensembles with the same autocorrelation function, and all of these will have the same linear predictor.

For obvious reasons, Equation (4.13) cannot be implemented with infinite sum, and P_i is given below with finite sum

$$P_i = \sum_{j=1}^{P} a_j m_{i-j} \tag{4.14}$$

where P corresponds to the order of the filter.

For this case, there are various formulations, such as the covariance method [27], the autocorrelation method [28], the lattice method [29], the inverse filter formulation [28], the spectral estimation formulation [30], the maximum-likelihood formulation [31], and the inner product formulation [28]. The most simple method is the autocorrelation method, which uses Durbin's recursive solution [28].

Consider the autocorrelation equations [28]

$$\sum_{k=1}^{P} \alpha_k R(i-k) = R(i) \qquad 1 \leq i \leq p \tag{4.15}$$

$$R(i) = \sum_{m=0}^{N-i-1} X(m)\ X(m+i) \tag{4.16}$$

where R(i) is the ith autocorrelation lag, and N is the number of data points. The solution of Equation (4.15), by Durbin's method, is given by

$$E^{(o)} = R(o) \tag{4.17}$$

$$k_i = (R(i) - \sum_{j=1}^{i-1} \alpha_j^{(i-1)} R(i-j))/E(i-j) \tag{4.18}$$

$$\alpha_j^{(i)} = k_i \tag{4.19}$$

$$\alpha_j^{(i)} = \alpha_j^{(i-1)} - k_i\ \alpha_{i-j}^{(i-1)} \tag{4.20}$$

$$E^{(i)} = (1 - k_i^2)\ E^{(i-1)} \tag{4.21}$$

where E is the variance of the prediction error, $\alpha_j^{(i)}$ is the jth parameter of the ith order predictor, and i is contained in the closed interval [1, P] while j is contained in the closed interval [1, i-1]. It should be noted that

$$\alpha_j = \alpha_j^{(p)}$$

which implies that α_j of the pth order predictor is equal to α_j of an ith order predictor where $i \leq p$.

The most popular method of implementation of a linear predictor is by the Lattice method, which uses k_i in Equation (4.19). The variable k_i is often referred to as partial correlation coefficients or PARCOR coefficients [29], and k_i's can be computed recursively. It is guaranteed to yield a stable filter without requiring the use of a window [6].

The Lattice method computes the prediction error as follows [32]. The prediction error sequence, $e^{(i)}(n)$, can be expressed as

$$e^{(i)}(m) = e^{(i-1)}(m) - k_i\, b^{(i-1)}(m-1). \tag{4.22}$$

Recursively, the ith stage backward prediction error is computed from

$$b^{(i)}(m) = b^{(i-1)}(m-1) - k_i\, e^{(i-1)}(m) \tag{4.23}$$

where

$$e^{(o)}(m) = b^{(o)}(n) = s(m).$$

This procedure is illustrated in Figure 28.

Implementation of "Predictive Coding"

It was discussed earlier that impulsive seismic data are divided into two sections due to the energy distribution characteristics. The predictive coding technique is used for the impulsive section in order to achieve better signal-to-noise ratio by taking advantage of the prediction gain discussed in Chapter III (see Equation (3.8)). For the second section, referred to as non-impulsive section, the hybrid technique with a 6-bit μ-law quantizer is used for the DCT coefficients. The details of the hybrid technique were discussed earlier.

In the following implementation, considerations of predictive coding are discussed. The predictor coefficients are derived from the linear prediction analysis using Durbin's autocorrelation method. The residual signal is computed from the Lattice method [29]. It should be noted that the prediction parameters and the PARCOR coefficients are computed only

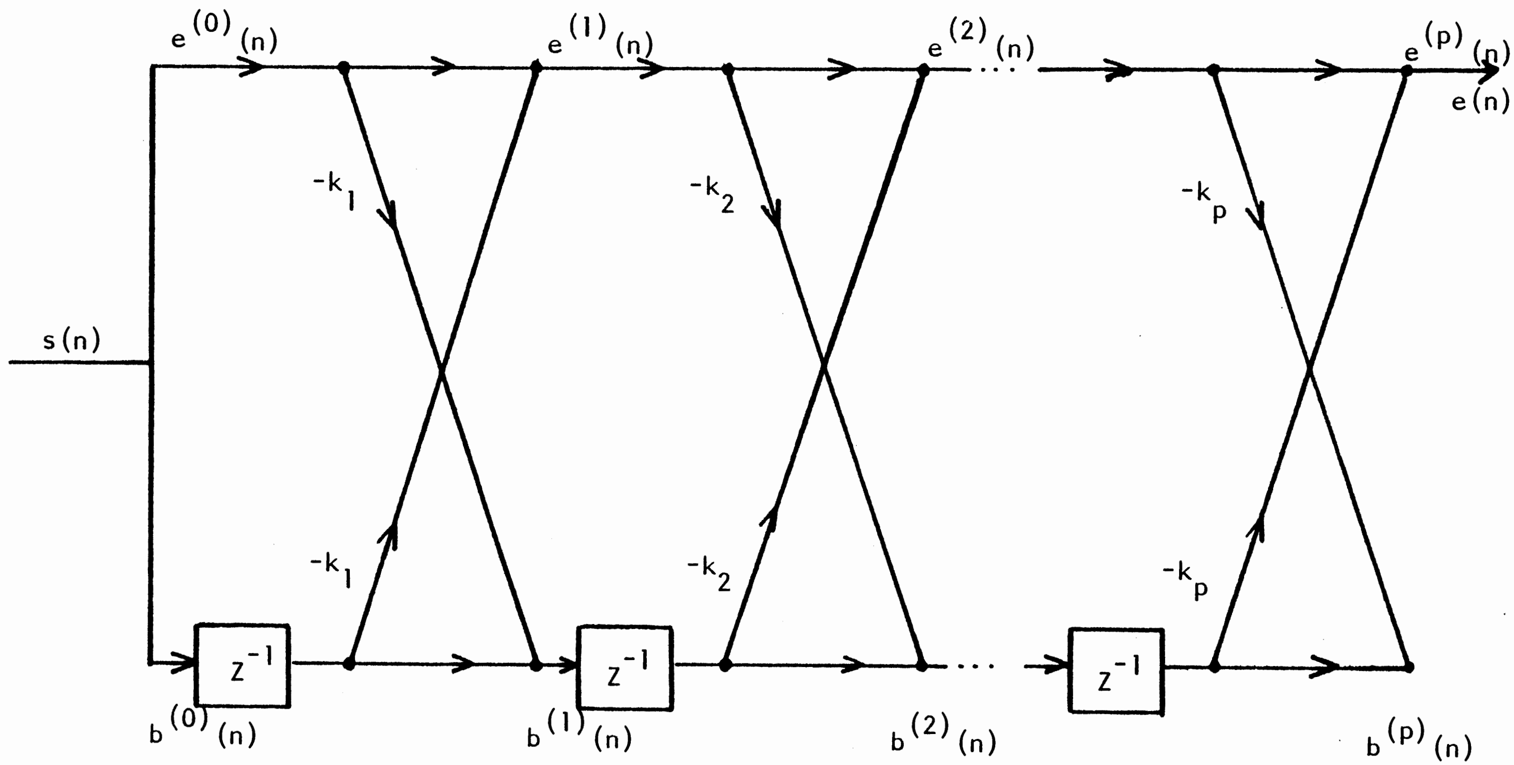


Figure 28. Block Diagram of Implementation of the lattice Method
(After Rabiner and Schafer [6])

once and shared by all traces. Also, the PARCOR coefficients are transmitted to the receiver for synthesizing the original seismic data.

Table VII gives ten parameters corresponding to a tenth-order linear predictor for eight impulsive seismic traces. It can be seen that the first five parameters for each trace are approximately same. It was found from empirical result that a fifth-order predictor is sufficient. Using the Lattice method residual signal, or simply prediction error, is computed where the PARCOR coefficients are obtained from the fifth-order linear predictor. For the residual signal coding, a 6-bit μ-law quantizer is used. These two coded sections are edited into one array for transmission. Table VIII illustrates the quantization signal-to-noise ratios of prediction method comparing with LPCM and 6-bit μ-law coding. It is shown that μ-law coding method approaches the result of prediction method by 1 dB.

At the receiver, the coded residual signal and the coded transformed coefficients are separately decoded. The decoded residual signal is synthesized and the impulsive section is reconstructed. For reconstructing the nonimpulsive section, the hybrid technique is used. Then, both reconstructed sections are concatenated for obtaining the full trace of the impulsive seismic data. These procedures are illustrated in Figure 29. The impulsive sections and their residual signals are shown in Figure 30, where the prediction gain can be easily noted.

The compression results are evaluated with respect to the signal-to-noise ratio and the compression ratio. The SNR of two sections are computed from

$$SNR_1^I = E[(X_1 - X_1^I)^2]/E[(X_1^2)]$$

TABLE VII

PREDICTION PARAMETERS

trace	1	2	3	4	5	6	7	8	9	10
1	-0.594	0.781	-0.697	0.764	-0.583	0.629	-0.267	0.061	0.199	-0.050
2	-0.572	0.768	-0.714	0.731	-0.551	0.540	-0.193	0.166	0.165	-0.077
3	-0.680	0.770	-0.728	0.738	-0.555	0.619	-0.268	0.210	0.043	-0.127
4	-0.719	0.726	-0.741	0.730	-0.560	0.698	-0.202	0.182	0.116	-0.029
5	-0.627	0.836	-0.736	0.752	-0.637	0.653	-0.342	0.179	0.028	-0.090
6	-0.656	0.769	-0.755	0.686	-0.600	0.624	-0.344	0.453	-0.216	-0.191
7	-0.673	0.773	-0.742	0.674	-0.493	0.367	-0.101	-0.101	0.024	0.058
8	-0.755	0.751	-0.712	0.763	-0.567	0.574	-0.329	0.291	-0.146	0.118

TABLE VIII

RESULTS OF IMPULSIVE SEISMIC DATA
COMPRESSION/DECOMPRESSION

	IMPULSIVE SECTION			NON-IMPULSIVE SECTION	OVER-ALL CPR
TRACE	LPCM	μ-LAW	PREDICTION	HYBRID	
1	27.16	28.56	30.09	34.62	6.48
2	27.40	28.62	28.57	30.76	5.47
3	27.17	29.43	30.44	30.17	5.99
4	27.08	29.02	30.30	31.04	6.13
5	27.43	29.58	30.44	32.53	6.83
6	25.49	28.32	29.92	32.21	6.82
7	27.95	30.01	30.37	32.37	6.63
8	28.11	29.83	30.40	31.83	5.61
AVG	27.22	29.18	30.06	31.94	6.25

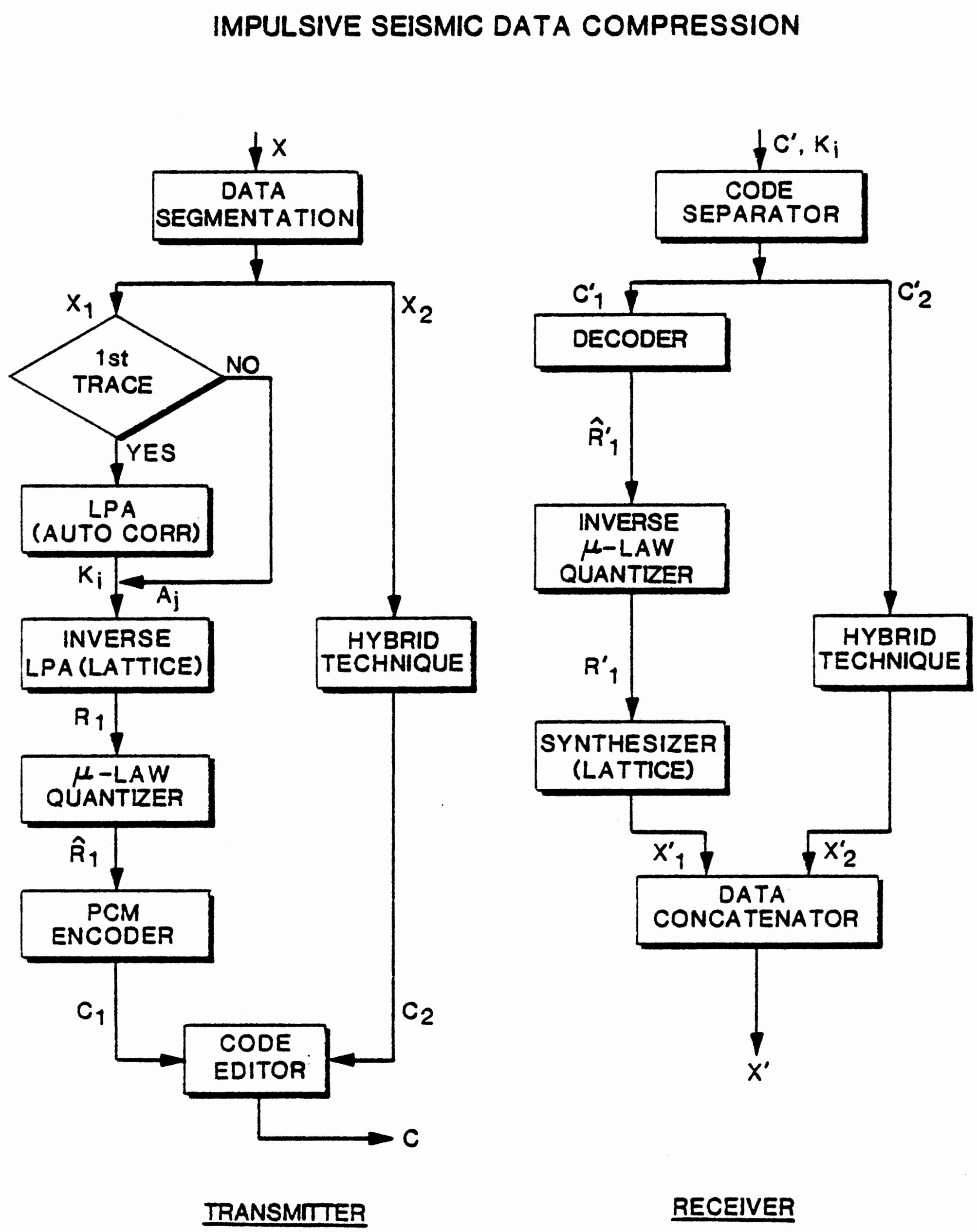
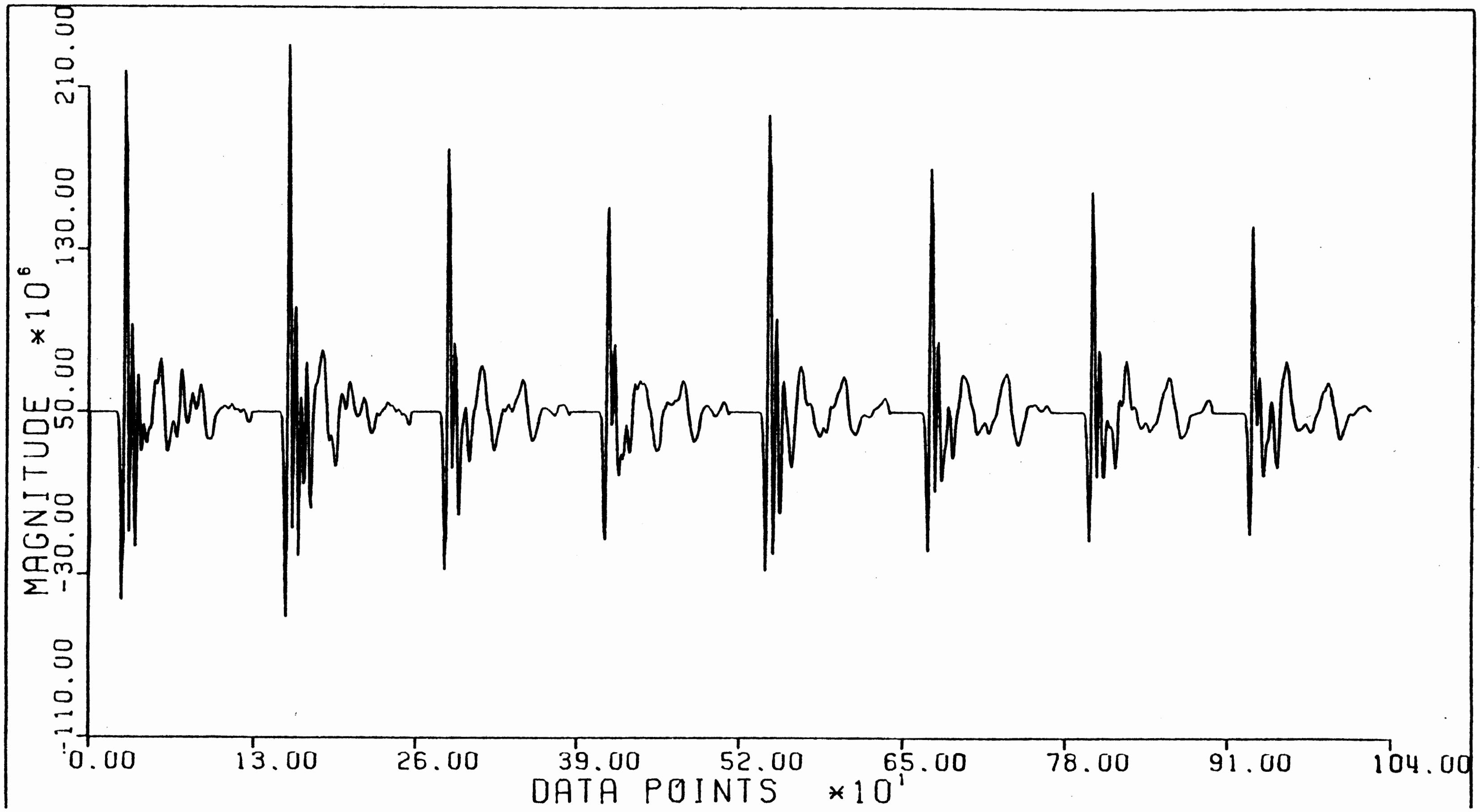
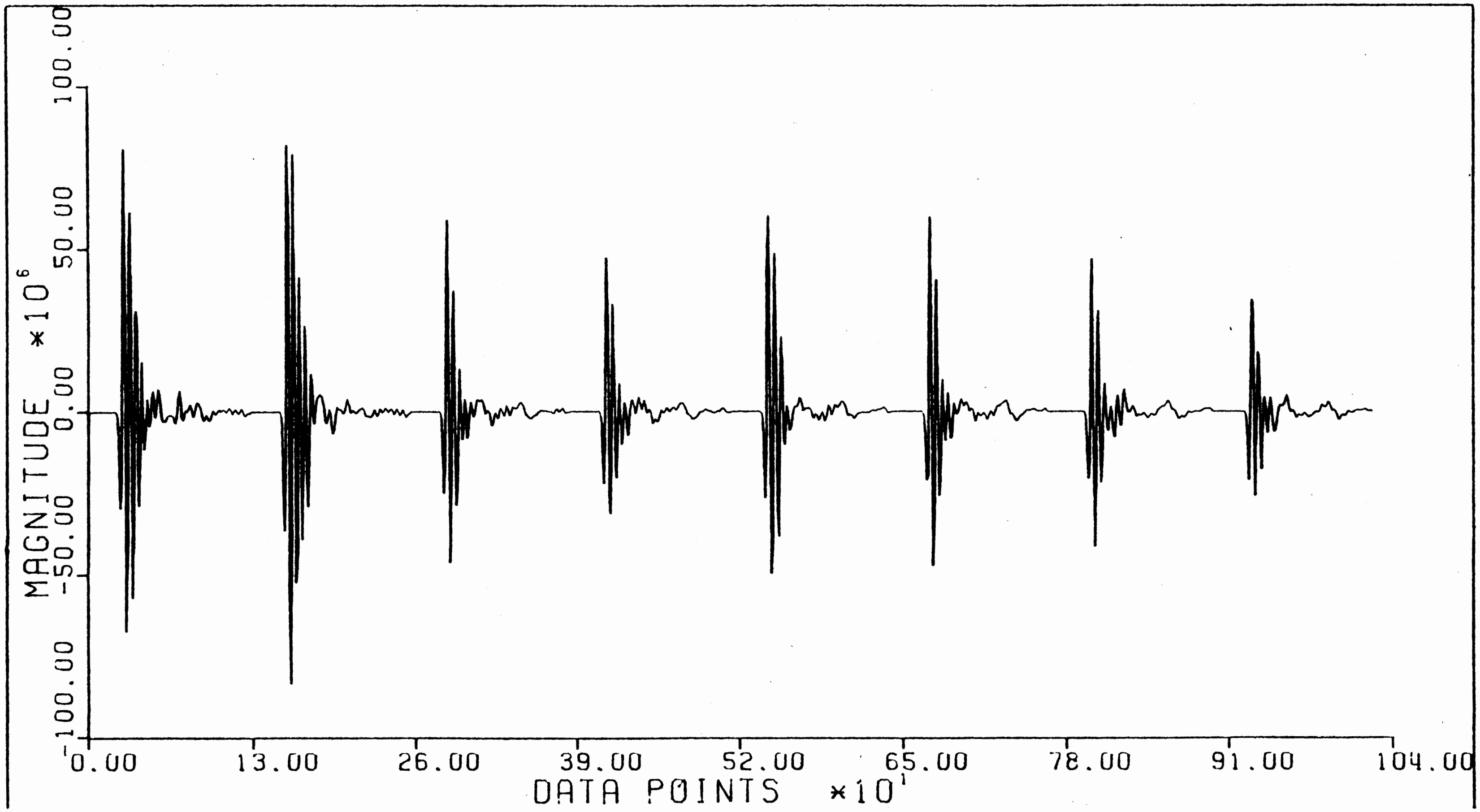


Figure 29. Impulsive Seismic Data Compressive/Decompressive Procedures Using "Predictive Coding" and "Hybrid Technique"



(a) Impulsive Section of eight impulsive seismic data traces

Figure 30. Illustration of Prediction residual signal of Impulsive Section



(b) Prediction Residual Signal of Eight Impulsive Sections

Figure 30. (Continued)

$$SNR_2' = E[(X_2 - X_2')^2]/E[(X_2^2)]$$

where X_1 is the original impulsive section, X_2 is the original non-impulsive section, and X_1' and X_2' are their reconstructed data.

The compression ratio is computed from

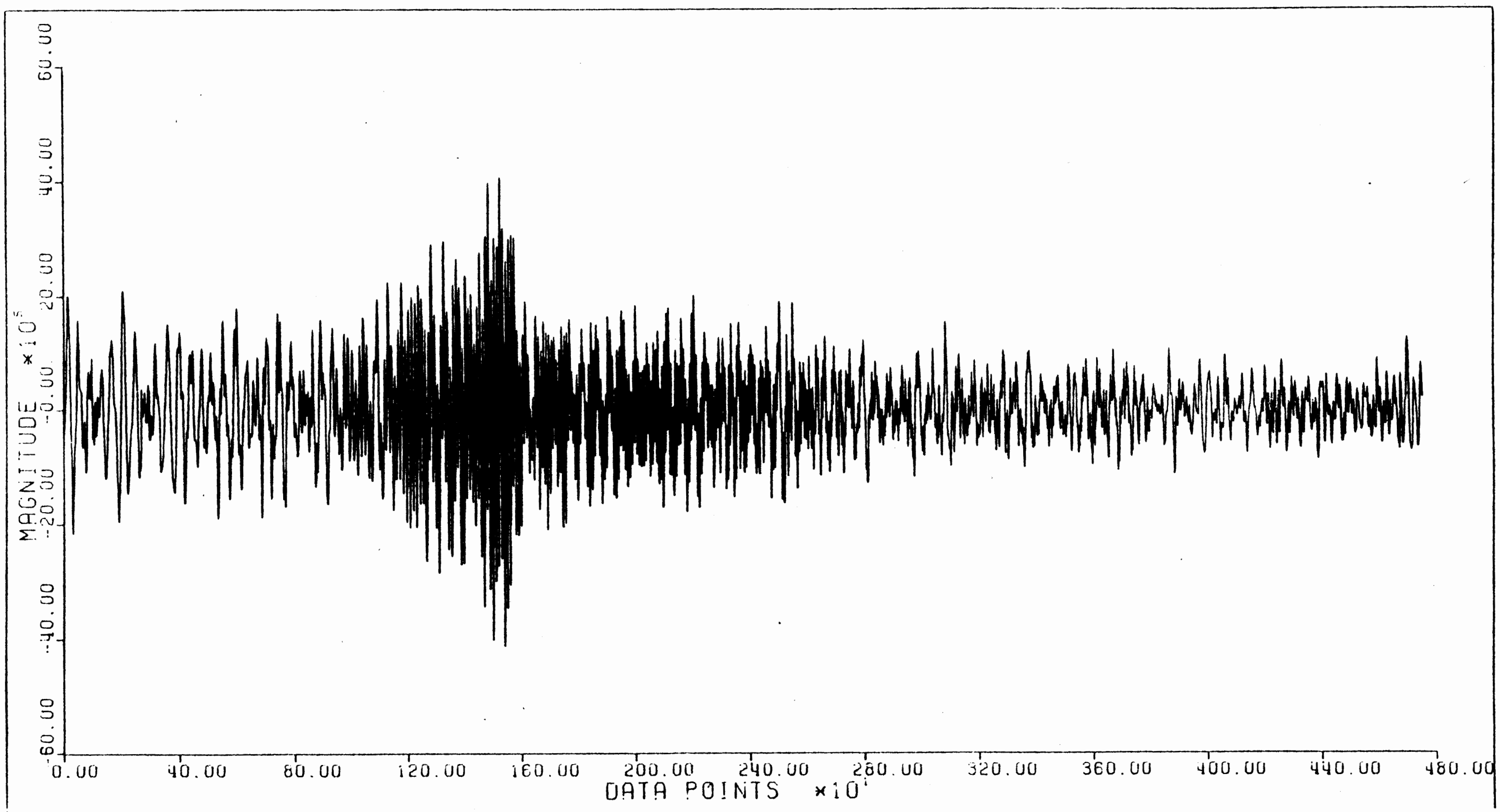
$$CPR = (N_1 \times 6 + M \times 6 + N_2)/(1000 \times 20)$$

where N_1 is the number of data in the impulsive section, N_2 is the number of data in the non-impulsive section, and M is the number of the retained coefficients of the non-impulsive section. N_2 is included as a bookkeeping information array. SNR_1', SNR_2', SNR', and CPR are illustrated in Table VIII, and the average compression ratio is approximately 6.25 to 1.00 for the impulsive seismic data at hand.

Examples

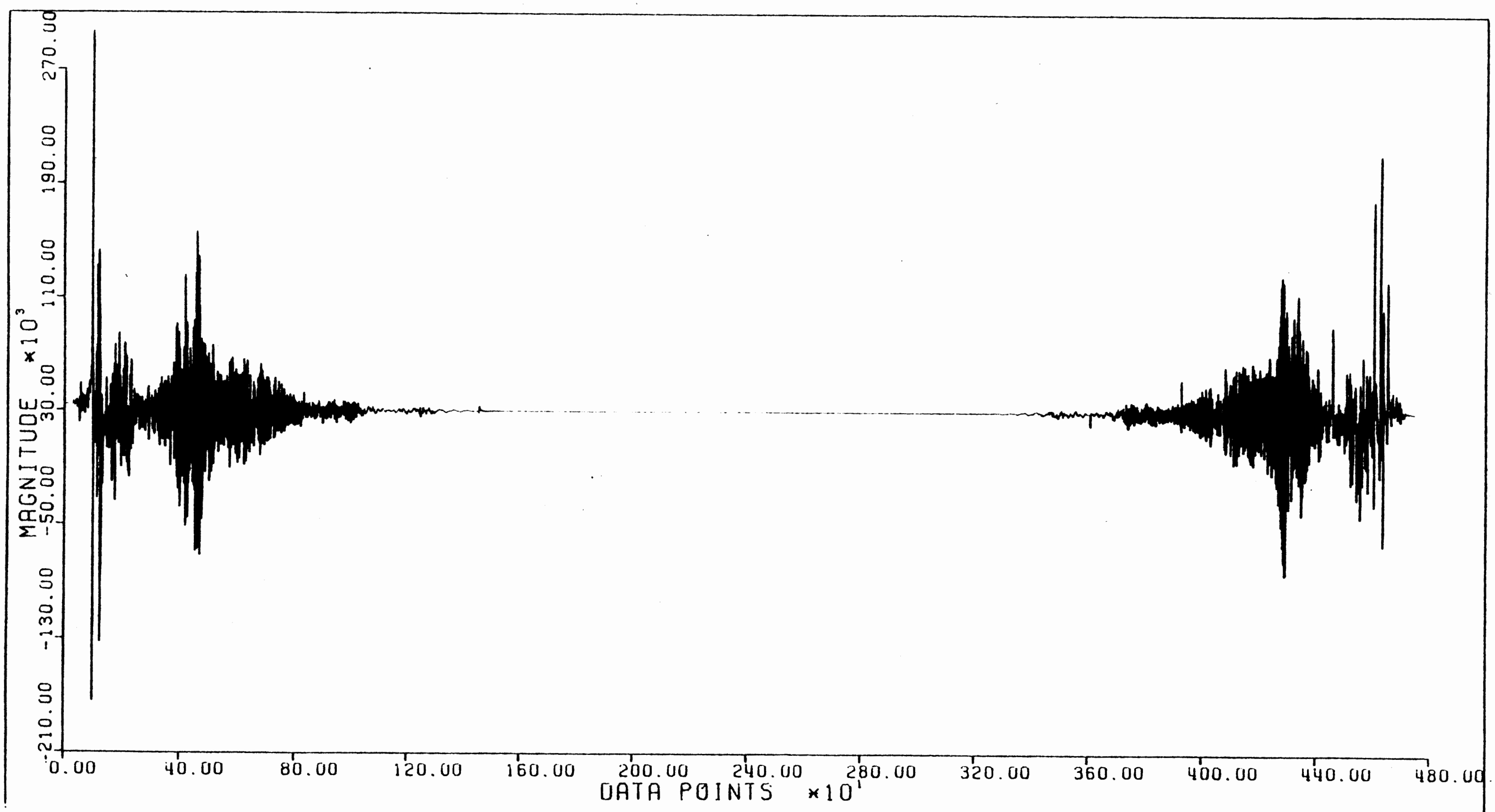
Compression techniques for vibroseis data and impulsive seismic data have been developed and their performances were evaluated earlier. In order to visualize these compression procedures on seismic data, Figures 31 and 32 illustrate outputs of each functional block of the hybrid technique and predictive coding shown in Figures 24a, 24b and 27. Figure 31a is the plot of one vibroseis trace with 4750 data points, Figure 31b is the DCT coefficients of the vibroseis trace, Figure 31c is the selected DCT coefficients reduced to 2216 points, and Figure 31d is the μ-law quantized and a 7-bit PCM coded result of the selected DCT coefficients. Exact inverse procedures are performed (see Figure 24b) at the receiver and Figure 31e illustrates the reconstructed vibroseis trace.

The impulsive seismic data case is illustrated in Figure 32. Figure 32a is the plot of one impulsive seismic trace with 1000 data points.



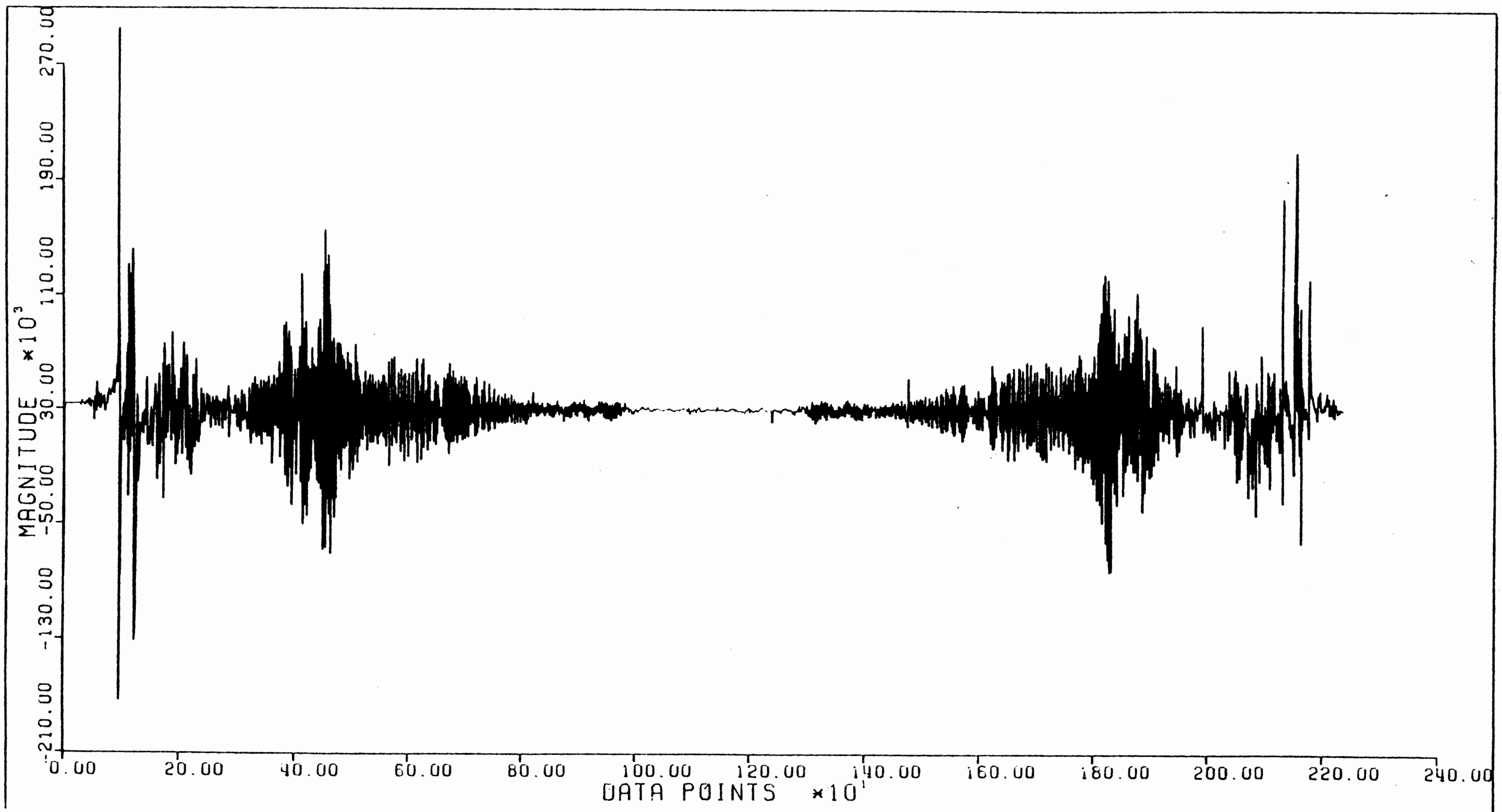
(a) One Trace of Vibroseis Data

Figure 31. Illustration of Vibroseis Data Compression/Decompression



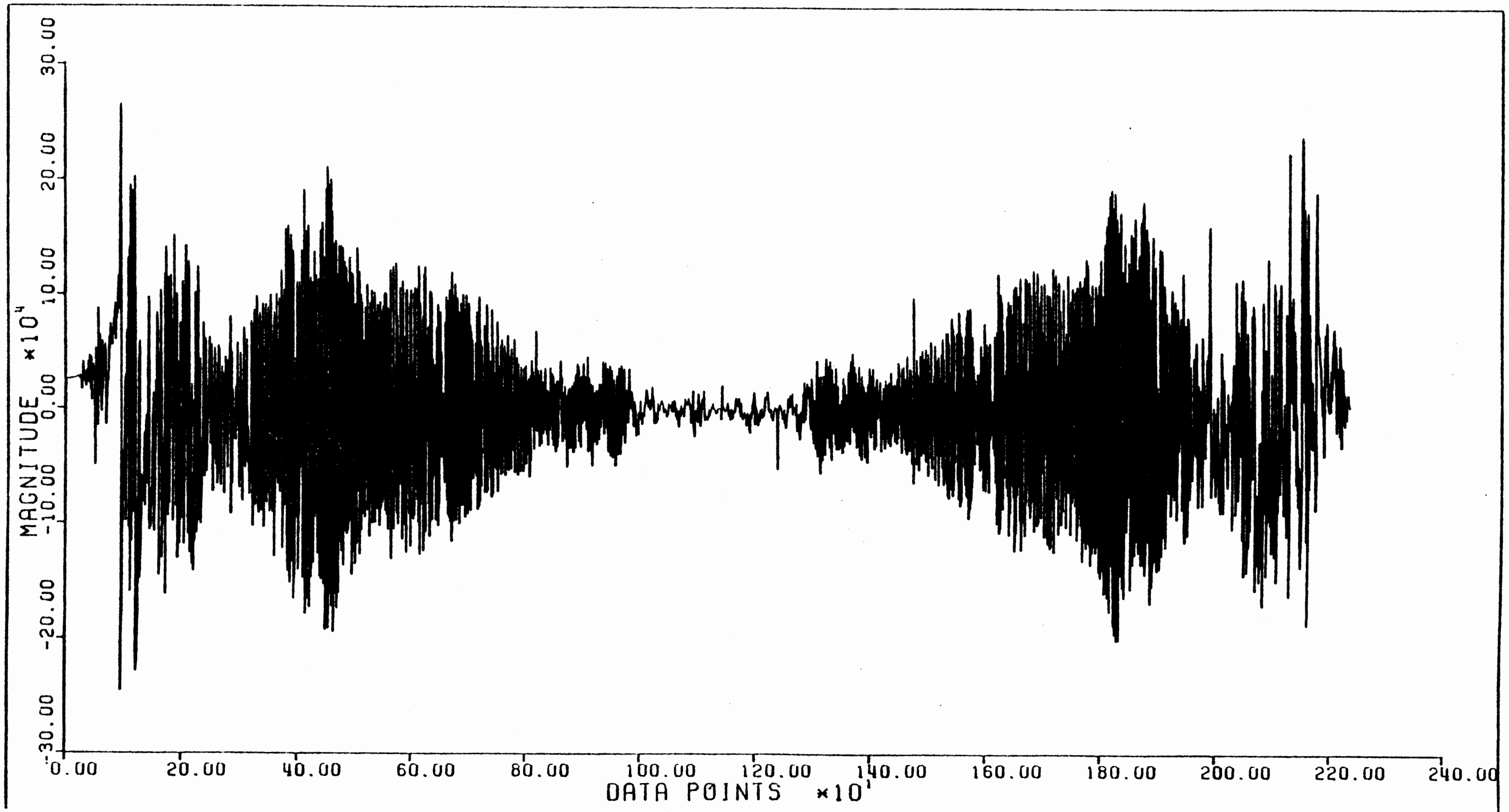
(b) Discrete Cosine Transformed Vector Coefficients

Figure 31. (Continued)



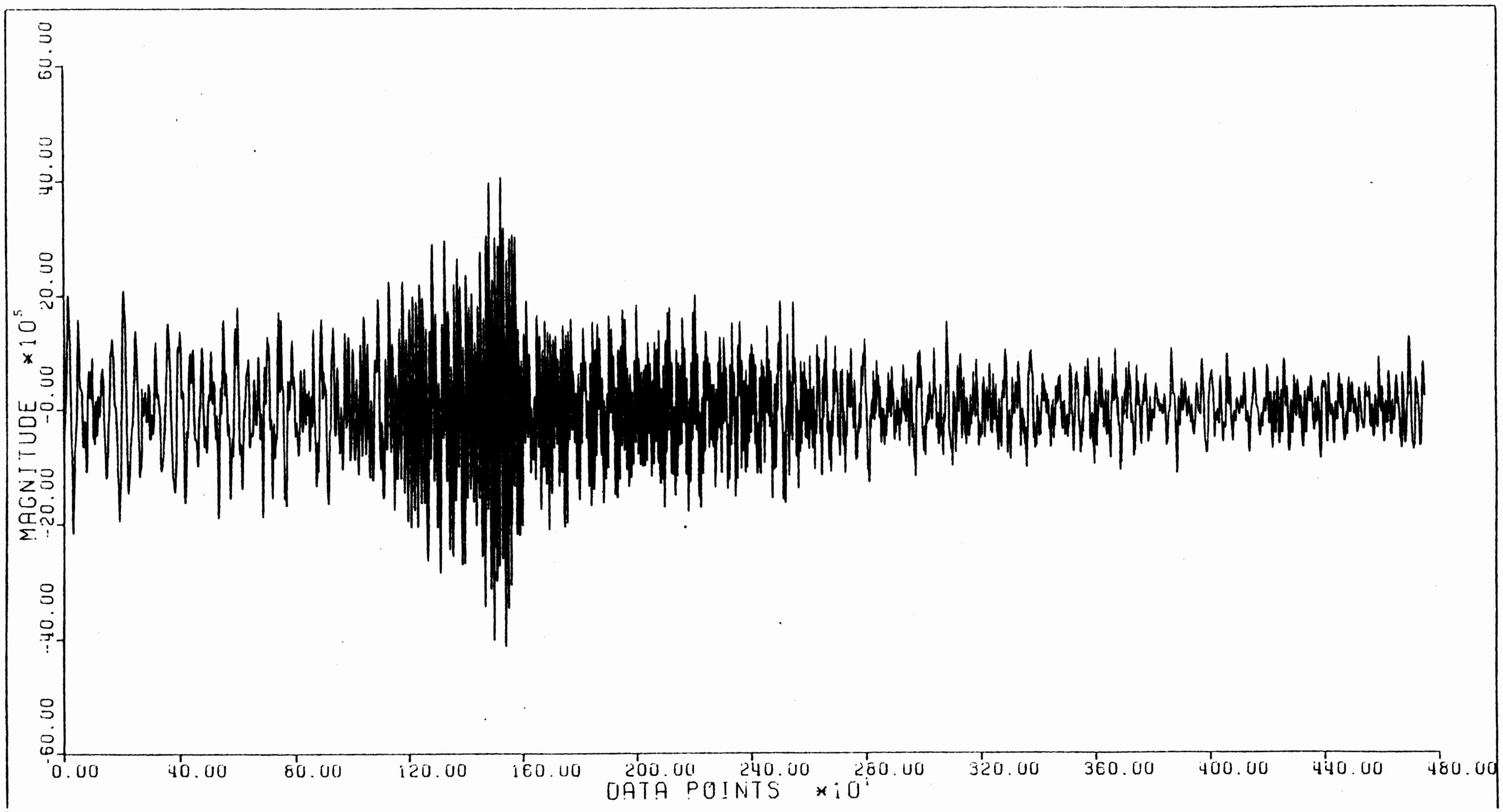
(c) Selected Discrete Cosine Vector Transformed Coefficients

Figure 31. (Continued)



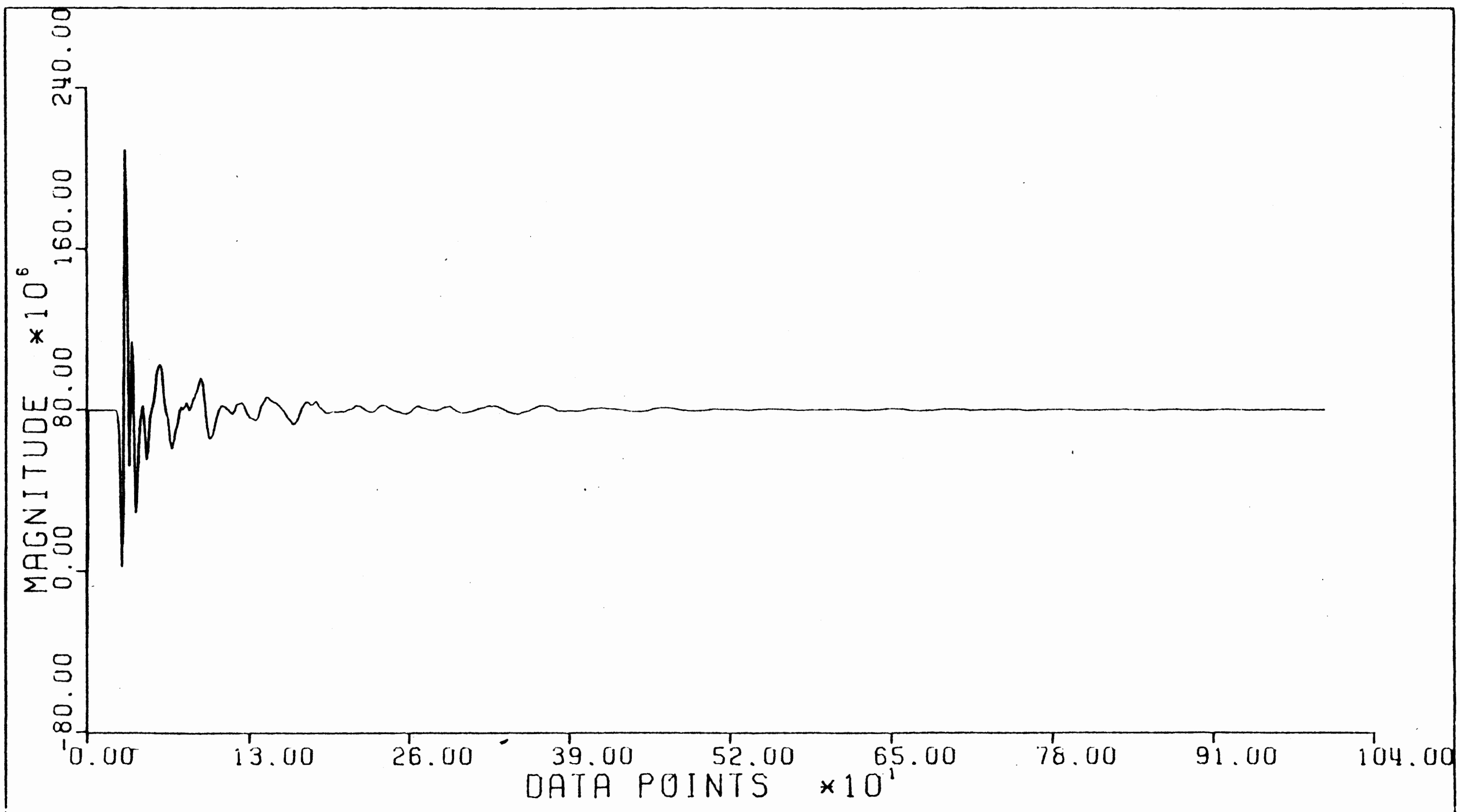
(d) μ-law Quantized Output of the Selected DCT Coefficients

Figure 31. (Continued)



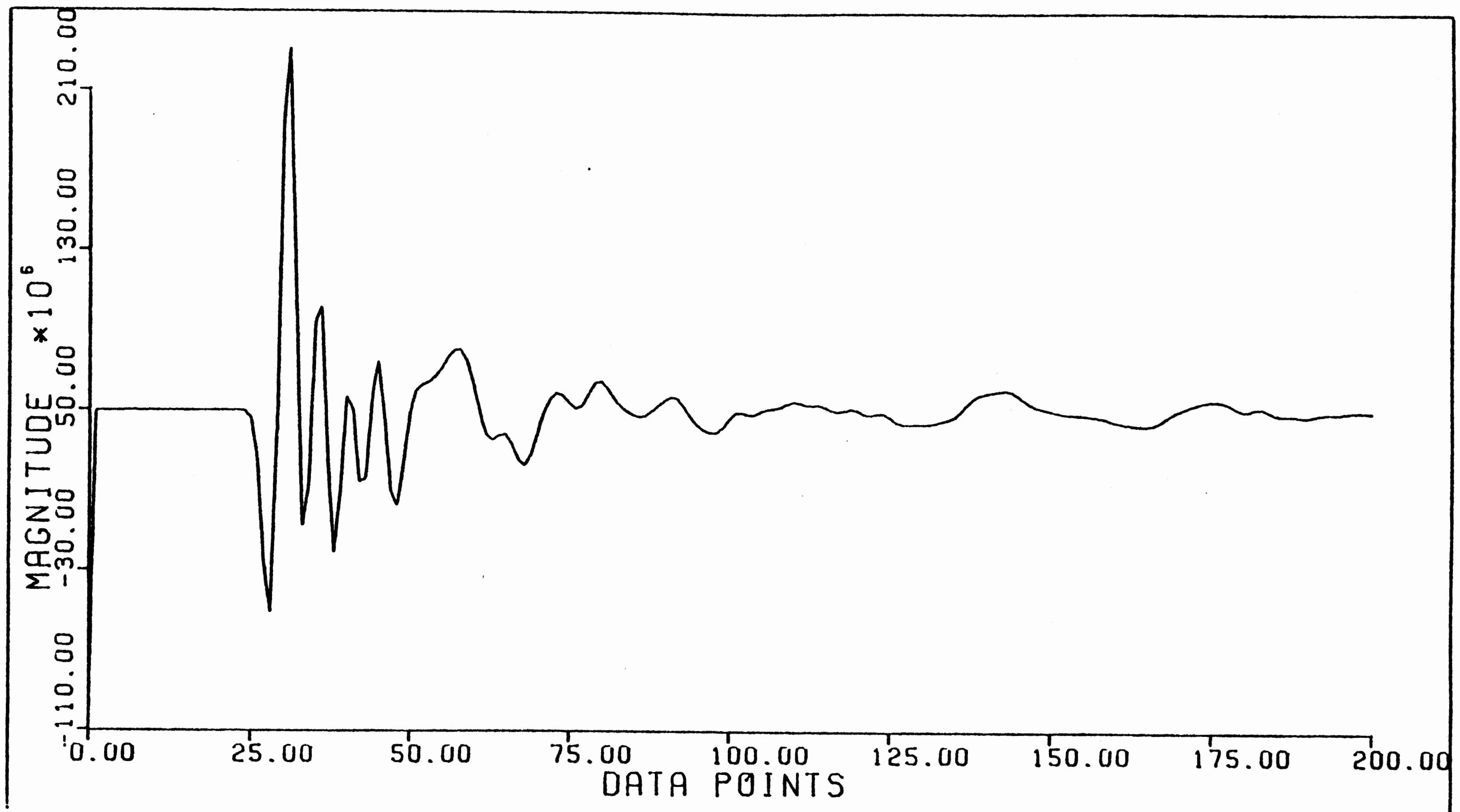
(e) Reconstructed Vibroseis Data Trace

Figure 31. (Continued)



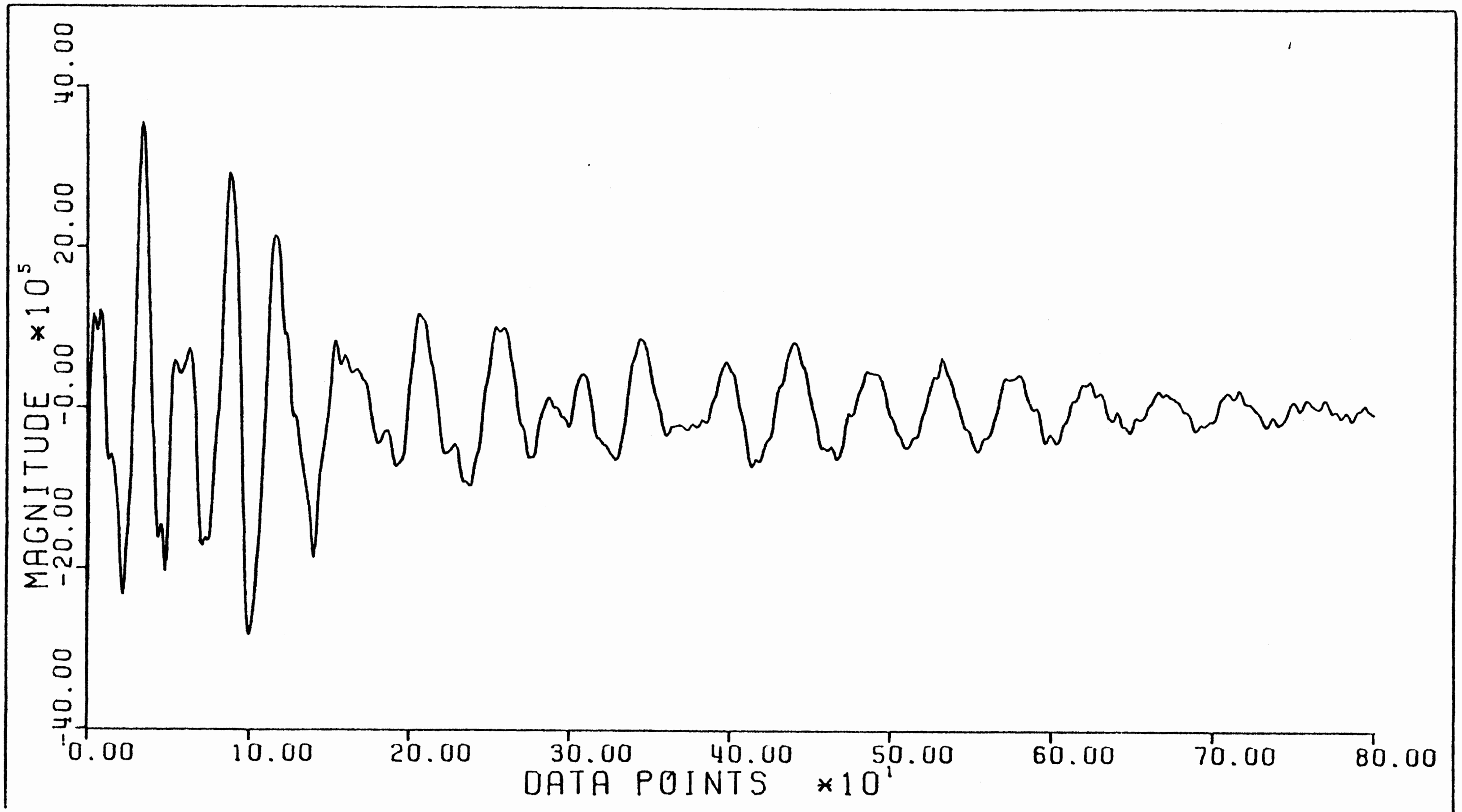
(a) One Trace of Impulsive Seismic Data

Figure 32. Illustrations of Impulsive Seismic Data Compression/Decompression



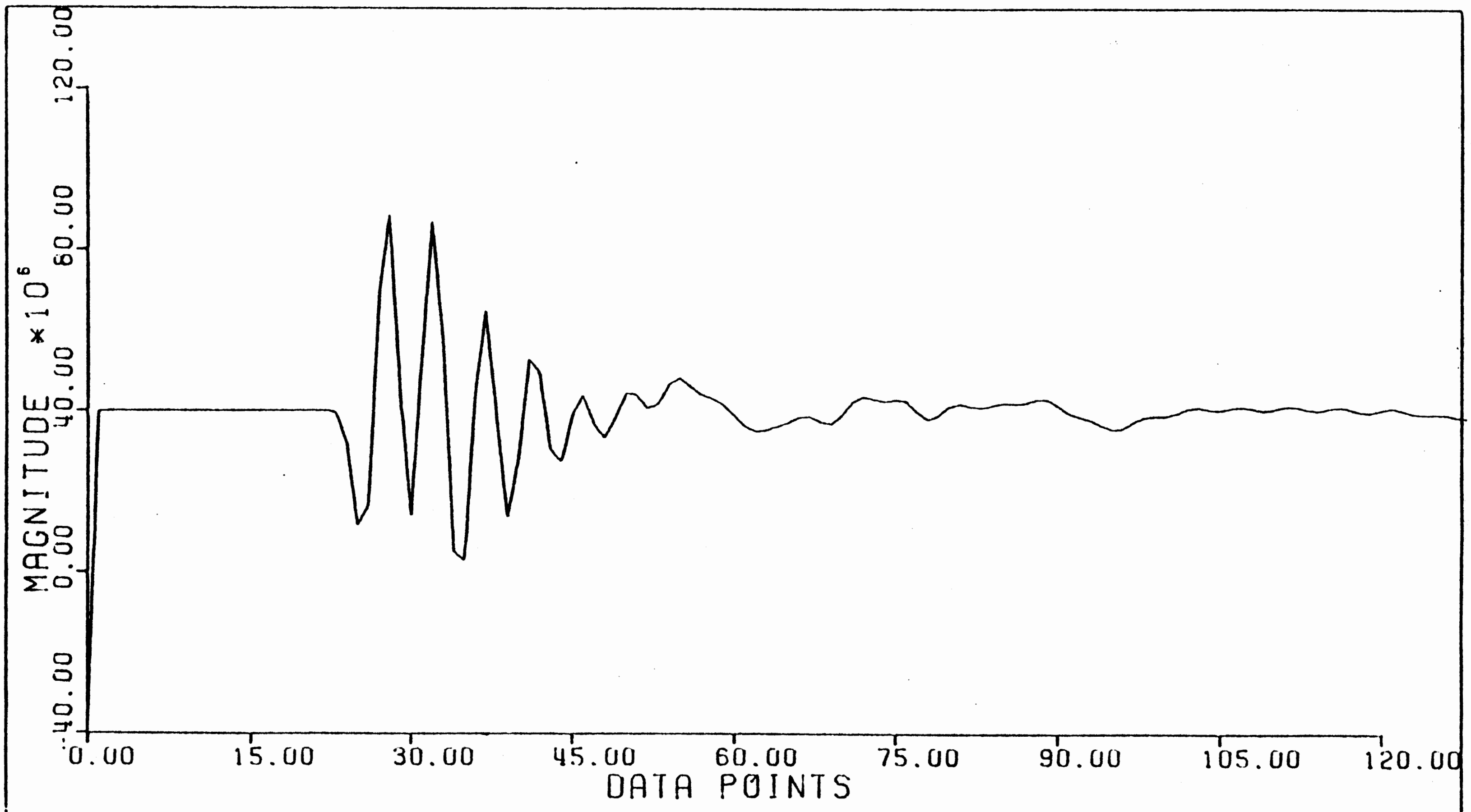
(b) Impulsive Section of Impulsive Seismic Data

Figure 32. (Continued)



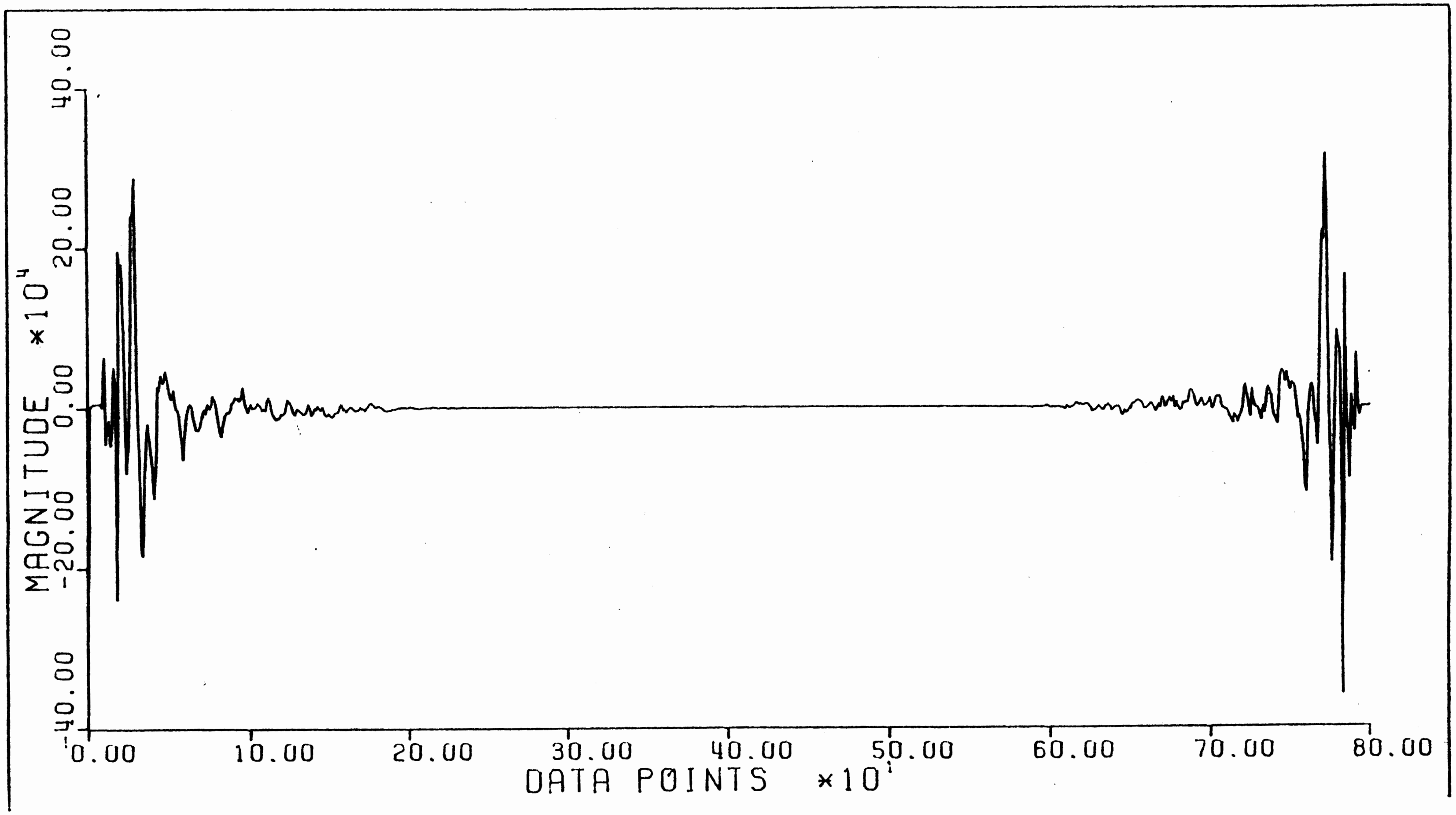
(c) Nonimpulsive Section of Impulsive Seismic Data

Figure 32. (Continued)



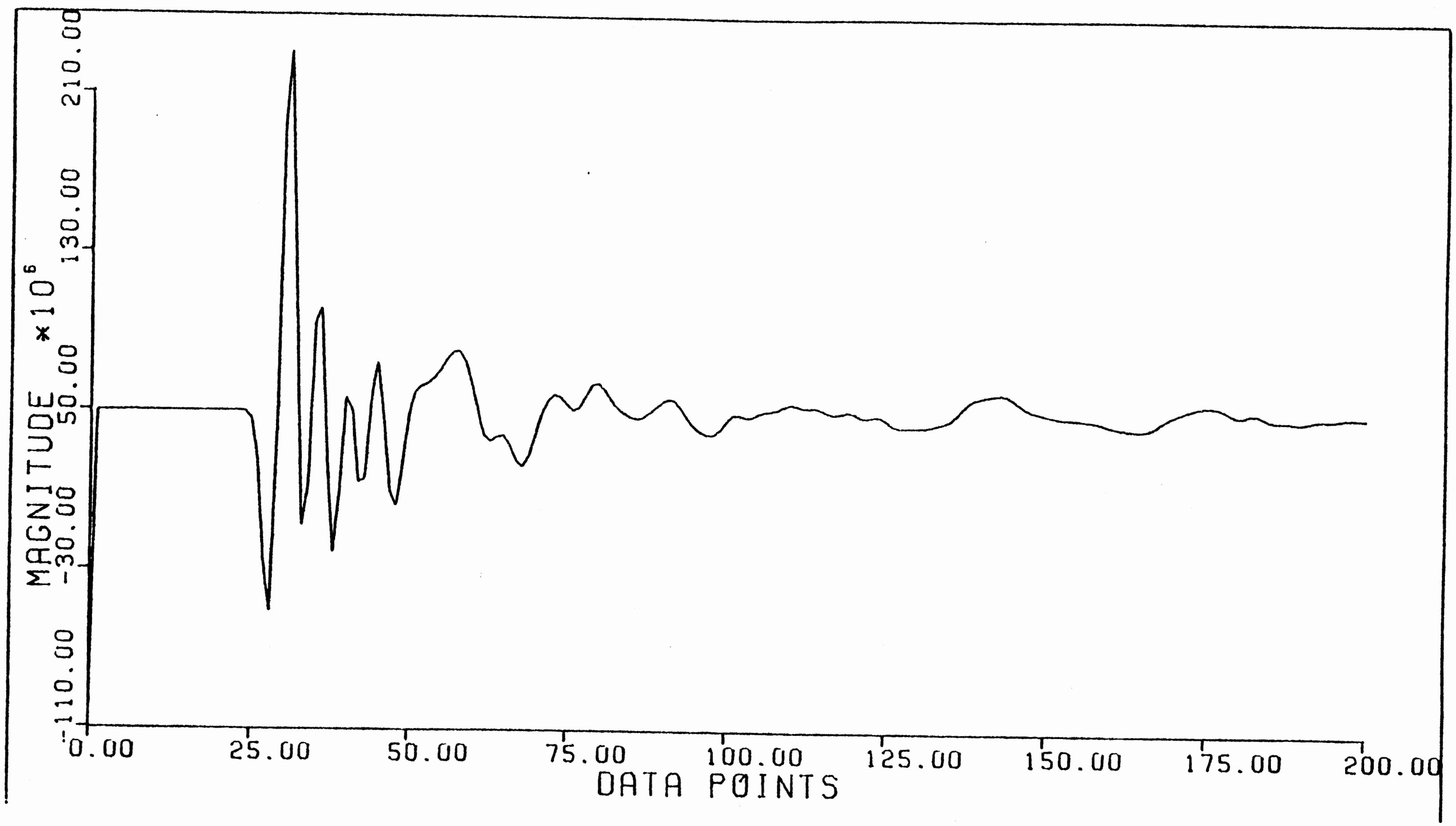
(d) Prediction Residual Signal of Impulsive Section

Figure 32. (Continued)



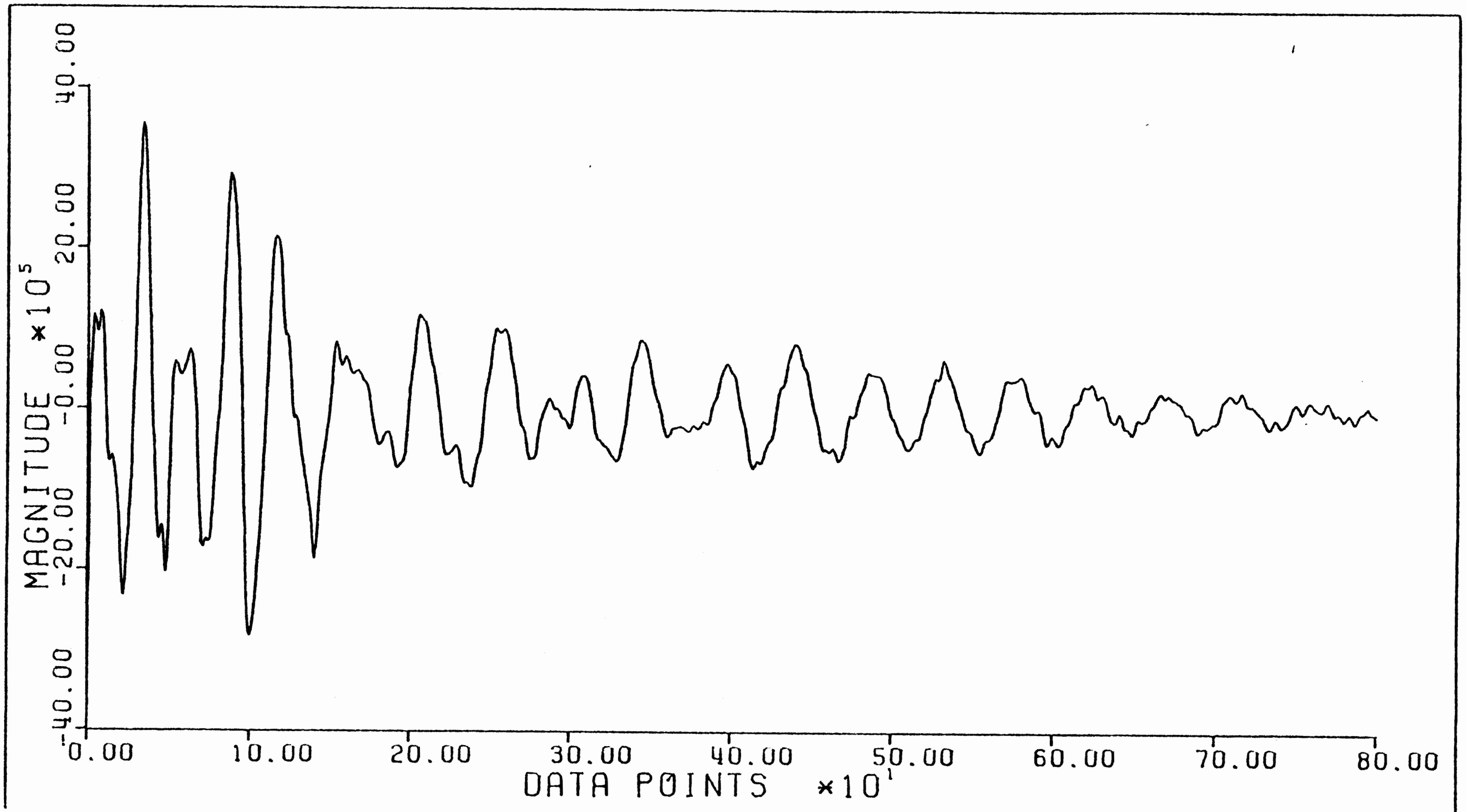
(e) Discrete Cosine Transformed Vector Coefficients of Non-impulsive Section

Figure 32. (Continued)



(f) Reconstructed Impulsive Section of Impulsive Seismic Data

Figure 32. (Continued)



(g) Reconstructed Nonimpulsive Section of Impulsive Seismic Data

Figure 32. (Continued)

This trace is segmented into two sections, impulsive and nonimpulsive, as illustrated in Figures 32b and 32c. Figure 32d shows the residual signal of the impulsive section, and 32e is the DCT coefficients of non-impulsive section. Selection of the significant DCT coefficients and coding of the selected coefficients are performed in a similar manner as the vibroseis data case. The reconstructed data of the both sections at the receiver are shown in Figures 32f and 32g,respectively.

From Figures 31 and 32, it can be seen that the reconstructed waveforms have no noticeable distortion. Furthermore, the objective data given in terms of SNR's in Table VI and VIII indicate that 30 dB SNR requirement is, in general, satisfied for the data in hand.

In the next chapter, simulation program steps will be evaluated with respect to their execution time and core size requirement for real-time implementation considerations.

CHAPTER V

SEISMIC DATA TRANSMISSION VIA SATELLITE

Introduction

Most satellite systems provide a variety of bandwidths so that the interface equipment for the terrestrial links can also be used for satellite circuits. In Chapter II, the basic idea of seismic data transmission via satellite was proposed due to the bandwidth constraints of channels, storage limits, and transmission costs, data compression has been considered. Specific compression methods have been developed for vibroseis data and impulsive seismic data in Chapter IV.

This chapter considers some important aspects of the compressed seismic data transmission over a satellite channel. Figure 33 illustrates a digital communication system [23]. This includes several functional blocks, such as source encoder/decoder, channel encoder/decoder, modulator/demodulator, and the communication channel. Satellite systems provide a variety of services so that the user can interface with this system properly. This chapter discusses only the portion of the overall system that needs to be interfaced.

First, the source encoder and decoder, the seismic data compressor and decompressor in this thesis, are examined with respect to their execution time and core size requirement. These are evaluated from the simulation program of the hybrid technique and predictiving coding discussed in

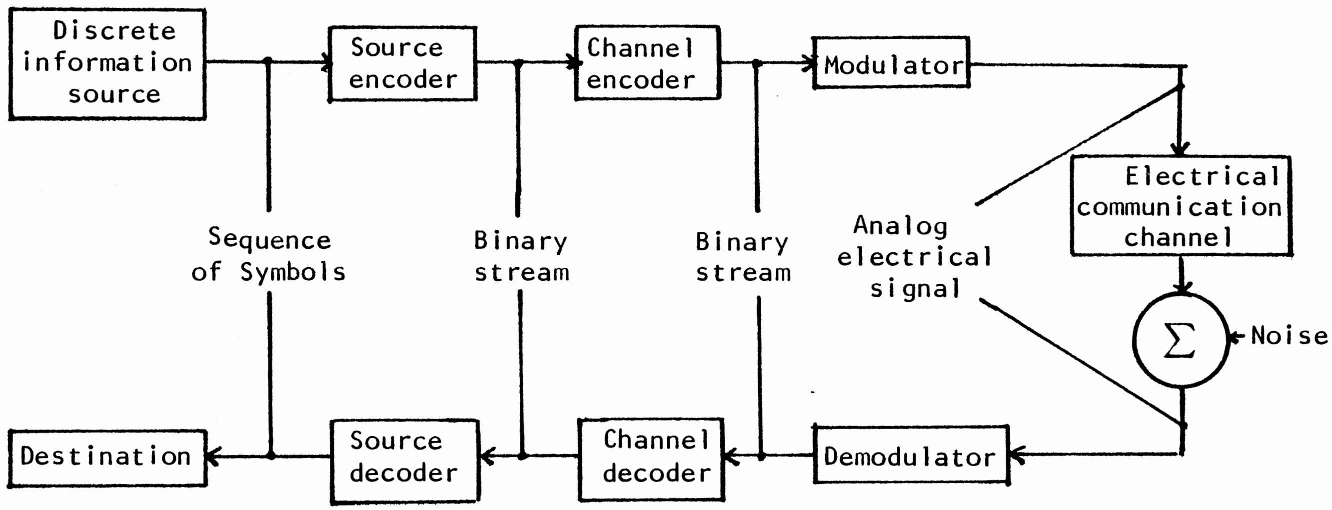


Figure 33. Digital Communication System
(After Shanmougam [23])

Chapter IV. Also, some important factors of real-time system design considerations are discussed.

Second, access methods such as frequency division multiple access and time division multiple access of the satellite channel are explored. Finally, network protocols for satellite channels are examined with two types of link control procedures, half-duplex and full-duplex, and their transmission efficiencies are evaluated.

Time and Space Configuration

In Chapter IV, the hybrid technique and predictive coding have been developed for compressing vibroseis data and impulsive seismic data. These techniques have been simulated in FORTRAN language with the IBM 370. All FORTRAN subroutines that are used in this thesis are included in Appendix C. The hybrid technique involves seven subroutines: FDCT (fast discrete cosine transform), SELECT (significant DCT coefficients selector), CONMEU (μ-law quantization), ENCODE (PCM coder), DECODE (mapping and decoding), INVMEU (inverse μ-law quantization), and FIDCT (fast inverse DCT). The first four subroutines are used for compression at the transmitter, and the remaining three subroutines are used for compression at the receiver for vibroseis data and/or nonimpulsive section of impulsive seismic data. The predictive coding involves three subroutines: AUTO (autocorrelation method for LPA), INVERS (lattice method for inverse LPA), and SYNTHZ (synthesizer), in addition to four coding and decoding subroutines: CONMEU, ENCODE, DECODE, and INVMEU. AUTO is used only for the first trace in order to obtain prediction parameters. INVERS, CONMEU, and ENCODE are used for compression at the transmitter, and DECODE, INVMEU, and SYNTHZ are used for decompression of the impulsive section of the impulsive seismic data. In the following, these subroutines are evaluated with their execution time and core size requirements.

First, all the routines mentioned above are compiled with the FORTRAN H compiler and cross-referenced with IBM 370 assembler language (see Appendix C). Since execution time of each instruction may vary among computer systems, the execution time is expressed as a combination of instruction types rather than absolute numbers for the IBM 370 case.

Second, the instructions are divided into six different types, such as load/store, multiply/divide, add/subtract, branch, compare, and external subroutine calls. These divisions are based on characteristics of instructions, and it should be pointed out that the differences of execution time within one type of instruction, such as load, load address, and load resistor, are ignored for simplicity. The execution time of the above six types are denoted as t_l, t_m, t_a, t_b, t_c, and t_x, respectively.

Third, instructions inside "DO" loops are evaluated rather than entire program steps, since the execution time is mostly occupied by "DO" loops. This assumption will not introduce a great deal of error in time estimation if the number of iterations of a "DO" loop is high.

For illustrative purposes, these procedures are implemented for a subroutine CONMEU. The source listing and cross-referenced assembler listing of CONMEU are shown in Table IX. It can be seen that there are five-load, three-store, three-multiply, two-divide, one-add, and three-branch instructions inside "DO" loop 10. The "DO" loop is iterated as many times as the value of the variable NUM. The variable NUM indicates the number of selected DCT coefficients in this case. Thus, the execution time can be estimated as

TABLE IX

COMPILED LISTING OF SUBROUTINE "CONMEU"

```
                                   / STRUCTURED SOURCE LISTING /
(002  ISN 0002          SUBROUTINE CONMEU(RDATA,NUM,EPSLON,XMAX,RMEU)                              00000910
                        C        MEU-LAW CONVERTER                                                 00000920
                        C                                                                          00000930
                        C        RDATA   :    INPUT ARRAY DCT COEFFICIENTS OF SEISMIC DATA TRACE   00000940
                        C        RMEU    :    MEU-VALUE                                            00000950
                        C        XMAX    :    ABSOLUTE MAXIMUM VALUE OF RDATA ARRAY                00000960
                        C        NUM     :    NO. OF DATA POINTS PER SWEEPS                        00000970
                        C        EPSLON  :    THRESHOLD VALUE OF INSIGNIFICANT DCT COEFFICIENTS    00000980
                        C                                                                          00000990
      ISN 0003          DIMENSION RDATA(1)                                                         00001000
                        C        APPLY MEU-LAW                                                     00001010
      ISN 0004          RMEU1=RMEU+1.0                                                             00001020
      ISN 0005          DEN=ALOG(RMEU1)                                                            00001030
      ISN 0006          EPSLON=EPSLON/XMAX                                                         00001040
      ISN 0007          EPSLON=1.0+RMEU*EPSLON                                                     00001050
      ISN 0008          EPSLON=XMAX*ALOG(EPSLON)                                                   00001060
      ISN 0009          EPSLON=(EPSLON/DEN)                                                        00001070
      ISN 0010          DO 10 I=1,NUM                                                              00001080
(001  ISN 0011          |RDATA(I)=0.0                                                              00001090
      ISN 0012          SIGN=1.0                                                                   00001100
      ISN 0013          ABSR=ABS(RDATA(I))                                                         00001110
      ISN 0014          IF (RDATA(I).LT.0.0) SIGN=-1.0                                             00001120
      ISN 0016          ABSR=ABSR/XMAX                                                             00001130
      ISN 0017          ABSR=1.0+RMEU*ABSR                                                         00001140
      ISN 0018          ABSR=XMAX*ALOG(ABSR)                                                       00001150
      ISN 0019          ABSR=(ABSR/DEN)*SIGN                                                       00001160
      ISN 0020          RDATA(I)=ABSR                                                              00001170
      ISN 0021       10 CONTINUE                                                                   00001180
 001)                   C
      ISN 0022       20 RETURN                                                                     00001190
 002)                   C
      ISN 0023          END                                                                        00001200
```

TABLE IX (Continued)

```
*LEVEL 2.3.0 (JUNE 78)                      OS/360  FORTRAN H EXTENDED                    DATE 81.153/21.05.18

                  000000  47 F0 F 00C        CONMEU    BC     15,12(0,15)
                  000004  07                           DC     XL1'07'
                  000005  C3D6D5D4C5E440               DC     CL7'CONMEU '
                  00000C  90 EC D 00C                  STM    14,12,12(13)
                  000010  18 4D                        LR     4,13
                  000012  98 CD F 020                  LM     12,13,32(15)
                  000016  50 40 D 004                  ST     4,4(0,13)
                  00001A  50 D0 4 008                  ST     13,8(0,4)
                  00001E  07 FC                        BCR    15,12

CONSTANTS
                  000080  00000000                     DC     XL4'00000000'
                  000084  00000001                     DC     XL4'00000001'
                  000088  41100000                     DC     XL4'41100000'
                  00008C  00000000                     DC     XL4'00000000'
                  000090  00000000                     DC     XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                  0000C8  00000000                     DC     XL4'00000000'                          ALOG
                  0000CC  00000000                     DC     XL4'00000000'                         RDATA
                  0000EC  58 80 D 0A4         100001   L       8, 164( 0,13)
                  0000F0  58 A0 D 0B4                  L      10, 180( 0,13)                            4
                  0000F4  58 70 D 074                  L       7, 116( 0,13)                          NUM
                  0000F8  78 00 D 060                  LE      0,  96( 0,13)                     41100000
                  0000FC  7A 00 D 07C                  AE      0, 124( 0,13)                         RMEU
                  000100  70 00 D 088                  STE     0, 136( 0,13)                        RMEU1
                  000104  58 F0 D 0A0                  L      15, 160( 0,13)                         ALOG
                  000108  41 10 D 04C                  LA      1,  76( 0,13)
                  00010C  05 EF                        BALR   14,15
                  00010E  47 00 0 005                  BC      0,   5( 0, 0)
                  000112  70 00 D 0BC                  STE     0, 188( 0,13)                         .100
                  000116  70 00 D 070                  STE     0, 112( 0,13)                          DEN
                  00011A  78 20 D 090                  LE      2, 144( 0,13)                       EPSLON
                  00011E  7D 20 D 084                  DE      2, 132( 0,13)                         XMAX
                  000122  70 20 D 090                  STE     2, 144( 0,13)                       EPSLON
                  000126  7C 20 D 07C                  ME      2, 124( 0,13)                         RMEU
                  00012A  7A 20 D 060                  AE      2,  96( 0,13)                     41100000
                  00012E  70 20 D 090                  STE     2, 144( 0,13)                       EPSLON
                  000132  58 F0 D 0A0                  L      15, 160( 0,13)                         ALOG
                  000136  41 10 D 050                  LA      1,  80( 0,13)
```

TABLE IX (Continued)

00013A	05 EF		BALR	14,15	
00013C	47 00 0 0C8		BC	0, 8(0, 0)	
000140	78 20 D 0E4		LE	2, 132(0,13)	XMAX
000144	3C 20		MER	2, 0	
000146	70 20 D 090		STE	2, 144(0,13)	EPSLON
00014A	7D 20 D 0BC		DE	2, 188(0,13)	.100
00014E	70 20 D 090		STE	2, 144(0,13)	EPSLON
000152	78 00 D 060		LE	0, 96(0,13)	41100000
000156	33 00		LCER	0, 0	
000158	70 00 D 0B0		STE	0, 176(0,13)	.C02
00015C	18 B7		LR	11, 7	
00015E	89 B0 0 002		SLL	11, 2	
000162	18 9A		LR	9,10	
000164	78 00 D 058	100002	LE	0, 88(0,13)	0
000168	70 09 B 000		STE	0, 0(9, 8)	FDATA
00016C	78 00 D 060		LE	0, 96(0,13)	41100000
000170	70 00 D 080		STE	0, 128(0,13)	SIGN
000174	78 29 B 000		LE	2, 0(9, 8)	FDATA
000178	30 02		LPER	0, 2	
00017A	70 00 D 078		STE	0, 120(0,13)	ABSF
00017E	32 22		LTER	2, 2	
000180	47 A0 D 164		BC	10, 356(0,13)	100004
000184	78 00 D 0B0	100003	LE	0, 176(0,13)	.C02
000188	70 00 D 080		STE	0, 128(0,13)	SIGN
00018C	78 20 D 078	100004	LE	2, 120(0,13)	ABSF
000190	7D 20 D 084		DE	2, 132(0,13)	XMAX
000194	7C 20 D 07C		ME	2, 124(0,13)	RMEL
000198	7A 20 D 060		AE	2, 96(0,13)	41100000
00019C	70 20 D 078		STE	2, 120(0,13)	ABSF
0001A0	58 F0 D 0A0		L	15, 160(0,13)	ALOG
0001A4	41 10 D 054		LA	1, 84(0,13)	
0001A8	05 EF		BALR	14,15	
0001AA	47 00 0 012		BC	0, 18(0, 0)	
0001AE	78 20 D 084		LE	2, 132(0,13)	XMAX
0001B2	3C 20		MER	2, 0	
0001B4	7D 20 D 070		DE	2, 112(0,13)	DEN
0001B8	7C 20 D 080		ME	2, 128(0,13)	SIGN
0001BC	70 29 B 000		STE	2, 0(9, 8)	FDATA
0001C0	87 9A D 13C	10	BXLE	9,10, 316(13)	100002
0001C4	1B FF	20	SR	15,15	
0001C6	58 E0 D 000		L	14, 0(0,13)	
0001CA	07 FE		BCR	15,14	

TABLE IX (Continued)

```
ADDRESS OF EPILOGUE
              0001CC  58 A0 D 004          L     10,   4( 0,13)
              0001D0  58 E0 A 00C          L     14,  12( 0,10)
              0001D4  58 B0 A 018          L     11,  24( 0,10)
              0001D8  58 10 B C08          L      1,   8( 0,11)
              0001DC  78 20 D 090          LE     2, 144( 0,13)            EPSLON
              0001E0  70 20 1 000          STE    2,   0( 0, 1)
              0001E4  18 DA                LR    13,10
              0001E6  92 FF A 00C          MVI     12(10),255
              0001EA  98 2C A 01C          LM     2,12,  28(10)
              0001EE  07 FE                BCR   15,14
ADDRESS OF PROLOGUE
              0001F0  98 7A 1 C04          LM     7,10,   4( 1)
              0001F4  58 20 7 000          L      2,   0( 0, 7)
              0001F8  50 20 D C74          ST     2, 116( 0,13)            NUM
              0001FC  78 2C 8 000          LE     2,   0( 0, 8)
              000200  70 20 D 090          STE    2, 144( 0,13)            EPSLON
              000204  7E 20 9 000          LE     2,   0( 0, 9)
              000208  70 20 D 084          STE    2, 132( 0,13)            XMAX
              00020C  78 20 A 000          LE     2,   0( 0,10)
              000210  7C 20 D C7C          STE    2, 124( 0,13)            DMEL
              000214  58 20 1 000          L      2,   0( 0, 1)
              000218  41 30 2 000          LA     3,   0( 0, 2)
              00021C  41 50 0 C04          LA     5,   4
              000220  1E 25                SR     2, 5
              000222  50 20 D CA4          ST     2, 164( 0,13)
              000226  50 30 D 0A8          ST     3, 168( 0,13)            BLATA
              00022A  47 F0 D 0C4          BC    15, 196( 0,13)
```

$$E_t(\text{CONMEU}) = \text{NUM} \cdot (8t_l + 5t_m + t_a + 3t_b). \tag{5.1}$$

In a similar manner, execution time for the remaining routines can be evaluated. The number of occurrences of each type of instruction set inside the "DO" loops for the remaining subroutines are given in Table X. The subroutines FDCT and FIDCT call FFT subroutines of IMSL (International Mathematical Subroutine Library), FFTRC, and FFTCC. Since the FFT function can be performed by a dedicated processor and there are numerous software packages of FFT, the execution time of these particular FFT routines are not evaluated here. For FDCT, the execution time can be expressed as

$$E_t\ (\text{FDCT}) = \text{NUM} \cdot (37t_l + 2t_m + 5t_a + 7t_b) + t_x\ , \tag{5.2}$$

where the time t_x is solely dependent on a chosen FFT algorithm processor, and NUM is the number of data points to be transformed.

From these analyses, total execution time of the hybrid technique at the transmitter, that is, a compression only, can be computed from

$$TE_t^H\ (\text{Tr}) = E_t(\text{FDCT}) + E_t(\text{SELECT}) + E_t(\text{CONMEU}) + E_t(\text{ENCODE}). \tag{5.3}$$

Similarly, at the receiver, corresponding to the decompression, the execution time is given by

$$TE_t^H\ (\text{Re}) = E_t(\text{DECODE}) + E_t(\text{INVMEU}) + E_t(\text{FIDCT}) \tag{5.4}$$

Also, the execution time for the predictive coding at the transmitter is given by

$$TE_t^P\ (\text{Tr}) = E_t(\text{AUTO}) + E_t(\text{INVERS}) + E_t(\text{CONMEU}) + E_t(\text{ENCODE}). \tag{5.5}$$

TABLE X

FREQUENCY LIST OF 6-TYPE INSTRUCTIONS
INSIDE "DO" LOOP

SUBROUTINE	LOAD/ STORE	MULT/ DIV.	ADD/ SUB.	BRANCH	COMP.	EXT. CALL
FDCT	37	2	5	7		FFTRC
SELECT	18	1	8	6	2	
CONMEU	15	5	1	3		
ENCODE	20	2	7	5	1	
DECODE	8	1	1	2	1	
INVMEU	22	3	2	6		
FIDCT	26	1	3	6		FFTCC
AUTO	114	6	36	12	6	
INVERS	89	10	10	11		
SYNTHZ	94	10	20	11		

At the receiver, the execution time for reconstructing the impulsive section from the coded residual signal is given by

$$TE_t^P\ (Re) = E_t(DECODE) + E_t(INVMEU) + E_t(SYNTHZ). \qquad (5.6)$$

It should be pointed out that CONMEU, ENCODE, DECODE, and INVMEU, which are used in both the predictive coding and the hybrid technique, are functions of the iteration value. Also, note that predictive coding is applied only for the impulsive section of an impulsive seismic trace. The subroutine AUTO will be used only for the first trace of impulsive seismic data, and therefore Equation (5.5) can be rewritten as

$$TE_t^P\ (Tr) = E_t(INVERS) + E_t(CONMEU) + E_t(ENCODE). \qquad (5.7)$$

Finally, the core size requirement can be obtained by examining the address range of the assembler listing of each routine. For example, the address range of CONMEU, in terms of base 16, is from 0_{16} to $22E_{16}$, or, in terms of base 10, from 0_{10} to 558_{10}. The unit of memory is, in general, a byte (8-bit) and the address range shows that the subroutine CONMEU needs 558 bytes of memory size. Table XI illustrates the core size requirement and the number of program statements for all routines involved in the hybrid technique and predictive coding.

For estimating the required memory size of the computer system for implementing these techniques, the following need to be considered. If all routines are loaded simultaneously in the memory, the memory size needs to be a sum of all required core sizes of subroutines and a main routine which handles subroutines, that is,

$$C = \sum_{i=a}^{x} C_i + C(Main), \qquad (5.8)$$

TABLE XI

MEMORY SIZE REQUIREMENT

SUBROUTINE	CORE SIZE (BYTES)	PROGRAM STATEMENT
FDCT	59582	16
SELECT	914	56
CONMEU	558	22
ENCODE	558	22
DECODE	418	11
INVMEU	560	23
FIDCT	59460	13
AUTO	1026	44
INVERS	662	19
SYNTHZ	694	19

where C_i is the core size for the subroutine i. However, in the proposed method, one routine is used at one time and the remaining routines are stored in the secondary storage. With this assumption, the memory size can be computed from

$$C = \text{MAX}\ (C_a,\ C_b,\ \ldots,\ C_x) + C(\text{MAIN}). \qquad (5.9)$$

For example, the required core size of the hybrid technique for compressing the vibroseis data trace (4750 data points) is given by

$$C^H(\text{Tr}) = \text{MAX}\ (914,\ 558,\ 59582,\ 558) + 38260$$

$$= 97842\ (\text{bytes}). \qquad (5.10)$$

The large core size requirement for the FDCT and FIDCT can be explained by the working area that FFT routines use. This working area can be significantly reduced by using chirp z-transform (CZT) algorithm [9]. The size of the MAIN routine is a function of the data points and it includes all global variable storages, such as input array, code array, and bookkeeping array. It can be concluded that the total core size requirement may be down to 64k-byte for implementing the compression technique for vibroseis trace if CZT is used for FDCT and FIDCT.

Real-Time Design Considerations

The definition of real time is obviously application dependent and can vary anywhere from milliseconds to hours [32]. For the proposed seismic data transmission via satellite, general relationships among processing time, transmission time, and depth of queue are investigated to some extent. The term "queue" indicates in general the place where a job waits to be serviced by the system. There may be several queues in one system, such as input queue waiting for CPU or output queue waiting for printer or display terminal. In this section, the queue is mainly used for the data to be transmitted, as shown in Figure 34.

The processing time is a flexible factor and very much dependent on the structure of the system, such as multiprocessor structure, dedicated processor, or hardware multiplier system, and so forth. The response time, in general, dictates the type of processing. The processing time of the hybrid technique using a multiprocessor system can be obtained from Equation (5.3), and is expressed as

$$T_p = TE_t^H(Tr)/N \ , \tag{5.11}$$

where N is the number of processors in the system.

The depth of queue can be computed from [33]

$$Q_d = \text{Input rate} - \text{Output rate} \quad \text{(bits/second)} \tag{5.12}$$

where the input rate is the incoming data rate (bits/second) into the queue and is given by

$$\begin{aligned}\text{Input rate} &= \text{Original seismic data rate/CPR} \cdot T_p \\ &= \text{Compressed seismic data rate}/T_p \ ,\end{aligned} \tag{5.13}$$

and the output rate is the data rate which is taken out of the queue. It is given by

$$\text{Output rate} = \text{MIN (Input rate [Speed of circuit} \cdot \text{e]}) , \tag{5.14}$$

where e is the transmission efficiency and is defined by [34]

$$e = \frac{\text{Data transmission time}}{\text{Total transmission time}} \ . \tag{5.15}$$

The speed of circuit indicates the bandwidth of the channel. Satellite circuits include network protocols which control satellite channels. It

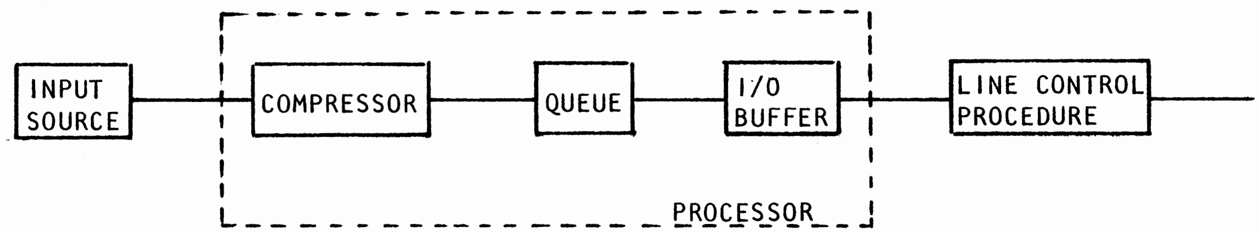


Figure 34. Data Compression and Transmission System

is clear that the speed of the circuit multiplied by the transmission efficiency should be less than the input rate in order that the channel bandwidth is used efficiently. From Equations (5.13), (5.15), and (5.15) the depth of queue in Equation (5.12) can be rewritten as

$$Q_d = \frac{\text{Compressed seismic data rate}}{T_p} - (\text{Channel bandwidth} \cdot e). \tag{5.16}$$

The transmission time (T_t) of the compressed seismic data is computed from

$$T_t = \frac{\text{Compressed seismic data}}{(\text{Channel bandwidth} \cdot e)} . \tag{5.17}$$

The response time of the system can be obtained from

$$R = \text{MAX}\ (T_p, T_t), \tag{5.18}$$

provided there is enough space in the queue so that processing time can be independent from the transmission time. It indicates that the processing time may be as long as the transmission time without degrading the response time.

The above considerations have not taken into account the effects of transmission delay and/or the overhead control bits to be transmitted. In the next section, detail of the satellite links and constraints of block size in relation to the bandwidth will be discussed. Also, the transmission efficiency will be examined with two types of line control procedures.

Satellite Communication

Satellite links have the following general properties [34]. There is approximately 270 msec of propagation delay and transmission cost is independent of distance within the range of a satellite. A signal sent to a satellite is transmitted to all receivers within the range of the satellite antenna, simply referred to as broadcast property. Also, a satellite provides large bandwidths and uses digital transmission. The broadcast property of satellites may cause a serious security problem. However, it can be economic for transmitting data to geographically dispersed places.

Access methods of satellite links are different from terrestrial links due to their propagation delay and large bandwidth. Some of the basic terms associated with satellite communications are defined in Appendix D.

Network Protocols

Network protocols are sets of rules that govern the flow of data in a network. This involves automatic error detection and correction as well as recovery procedures [35]. In general, protocols are divided into three levels. The lowest-level protocol is the hardware level, such as hardware interfaces, where "handshaking" sequences can be achieved. The high-level protocol, referred to as a link control procedure, is a set of rules that ensures a block of data gets from one end of a data link to the other without errors. The highest-level protocol is another set of rules related to message flow. This level interacts with the line control procedure for complete message reception. This protocol is often referred to as a network handler.

A system which detects an error in data and has those data automatically retransmitted is called ARQ (automatic repeat request). ARQ systems are of two types: stop and wait ARQ with half-duplex line and continuous ARQ with full-duplex line. These two types of line control procedures are discussed in this section in relation to their message exchange sequence and transmission efficiencies. Also, the optimum frame size (I/O buffer size) for continuous ARQ is examined with respect to the speed of the circuit and error rate.

Half-Duplex Transmission. This is the most common line control procedure in use today, and stop and wait ARQ uses this transmission. In stop and wait ARQ, the source waits for an acknowledgment from the receiver before transmitting the next block of data. If the source receives ACK (no error acknowledgment), it continues transmitting the next block; but if NAK (error acknowledgment) is received, the source retransmits the last block of data. Figure 35 illustrates this procedure.

The total transmission time of this type of line control procedure can be computed, as illustrated in Table XII. In this table, 4800 bps (600 bytes/sec) channel is used to transmit 240 bytes of data and it gives a transmission efficiency of 400/934 = 43 percent. Improvement on transmission efficiency of such a system can be achieved by increasing the size of message blocks. However, this may create other problems, as long messages are more error-prone than short messages.

Full-Duplex Transmission. Another method of improving the throughput is to use full-duplex circuit and to transmit messages without acknowledgments. This method is examined with continuous ARQ, shown in Figure 36. In continuous ARQ, while the blocks are being transmitted the stream of acknowledgments is examined by the transmitting terminal. When the transmitting terminal receives a negative acknowledgment or fails to receive a

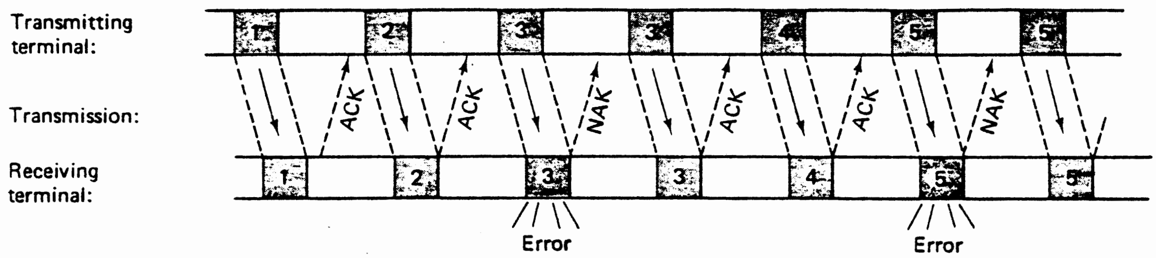
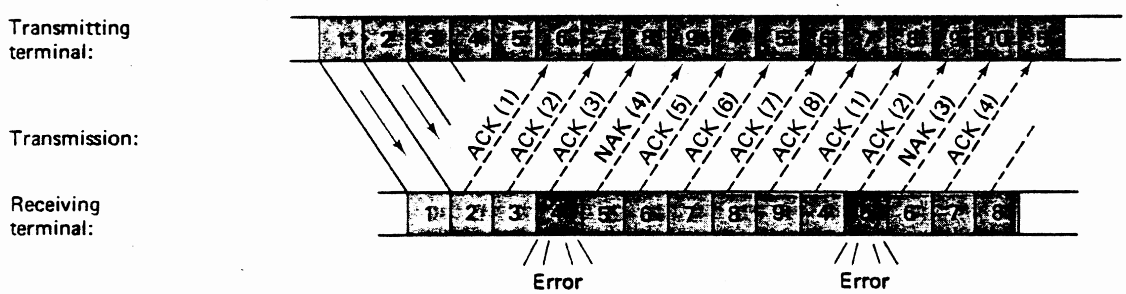
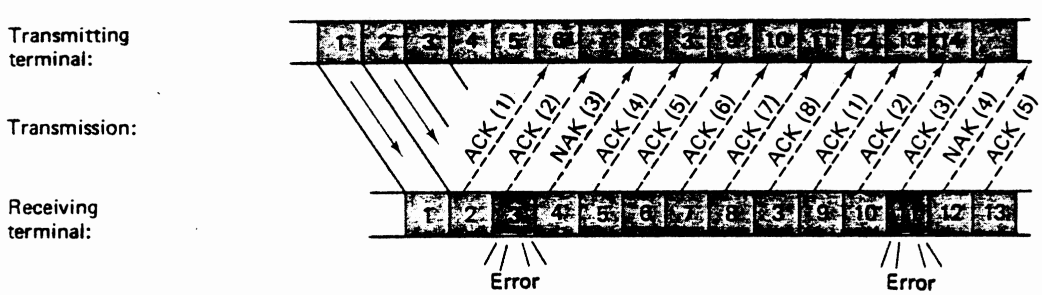


Figure 35. Stop and Wait ARQ (After Martin [35])



(a) Full Duplex with Pull-back



(b) Full Duplex with Selective Repeat

Figure 36. Continuous ARQ (After Martin [35])

TABLE XII

TRANSMISSION TIME LIST

Message transmission time	240/600 = 400
Propagation delay	250
Modem delay	10
Receiver reaction time	2
Transmission time for acknowledgement	10
Propagation delay	250
Modem delay	10
Computer reaction time	2
	Total : 934 msec

After Housley [34].

positive acknowledgment, it must determine which block was incorrect. The blocks are therefore numbered.

Considering the transmission time delay of the satellite, the acknowledgment may be received more than several blocks after it was transmitted. For this reason, usually a 7-bit counter is used for the satellite channels while a 3-bit counter is used for the terrestrial links. With a 7-bit counter, 128 blocks can be numbered before it reinitializes the counter.

The transmission efficiency of the continuous ARQ is computed from

$$e = N_d/(N_d + N_h), \tag{5.19}$$

where N_d is the number of data bits in a frame, and N_h is the number of overhead bits. The transmission efficiencies of various speeds are shown in Figure 37 as a function of a frame size.

The minimum frame size of an efficient transmission is shown in Figure 38 as a function of the speed of the circuit and the block counter. Figure 39 illustrates the optimum frame sizes for various error rates and circuit speed. For example, compressed seismic data transmission time with a channel bandwidth of 9600 bps can be computed from Figure 37. It can be seen that frame size should be greater than 5000 bits in order to approach 100 percent efficiency. From this constraint, the compressed seismic data need to be segmented into frames with a size of 5000 bits. Then transmission time can be estimated by

$$T_t = \frac{N \cdot 5000 \text{ bits}}{9600 \text{ bps}} \tag{5.20}$$

where

$$N = \frac{\text{Compressed seismic data}}{5000} .$$

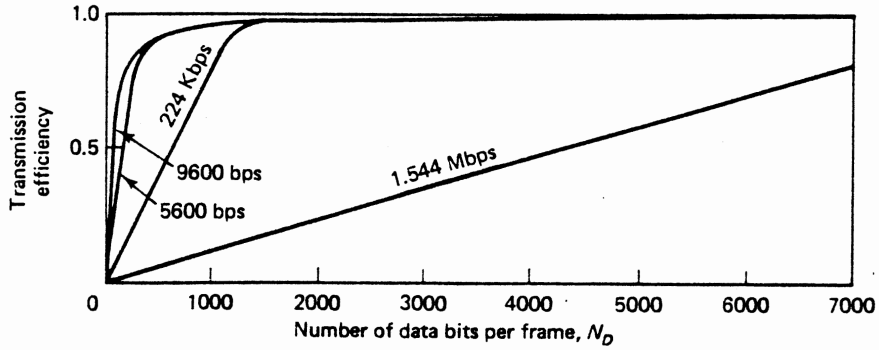


Figure 37. Transmission Efficiency of Satellite Circuits with Common Data Link Controls (M=127) (After Martin [35])

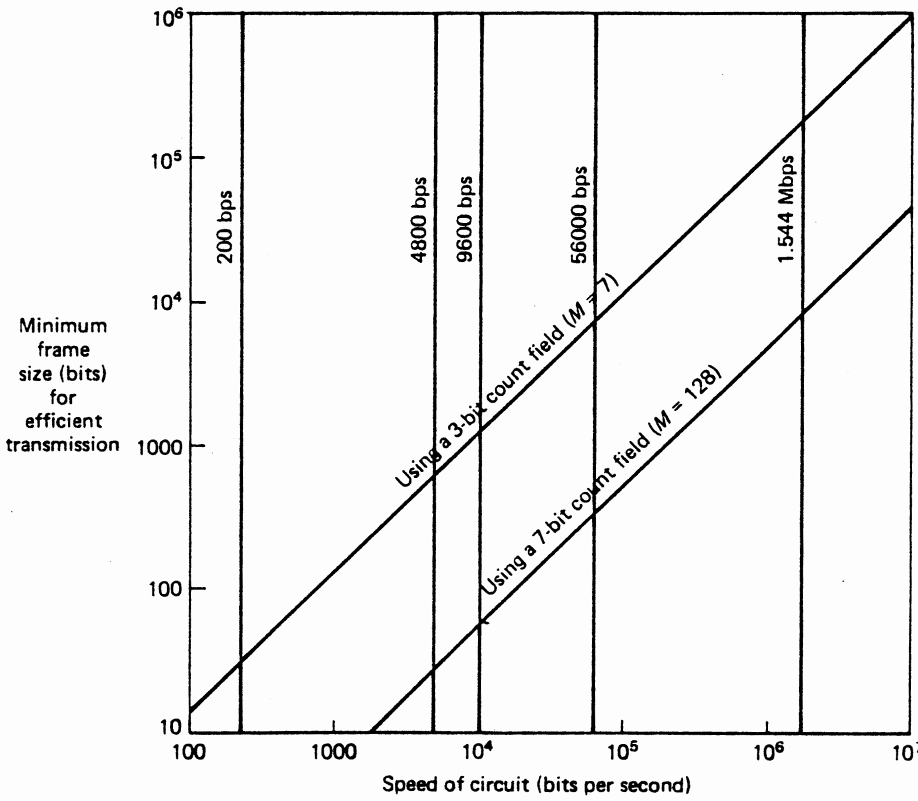


Figure 38. The Minimum Frame Size for Efficient Transmission via Satellite at Different Speeds (After Martin [35])

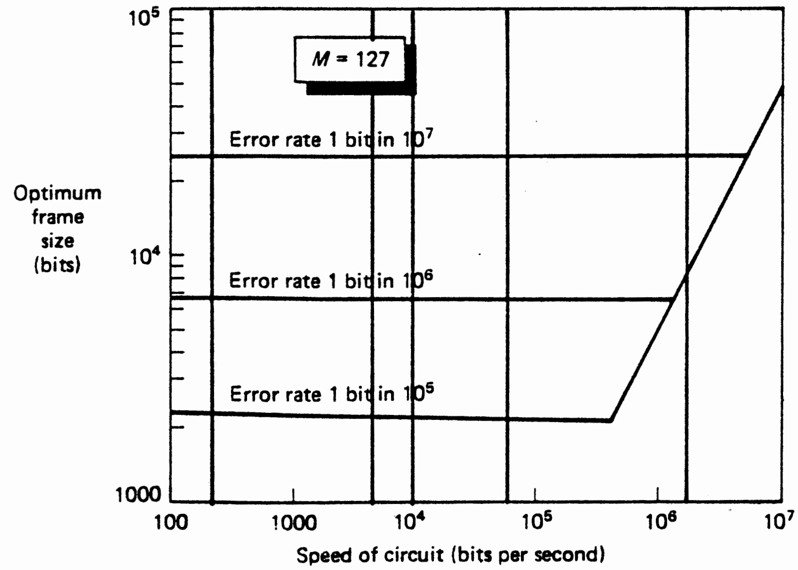


Figure 39. The Optimum Frame Size for Full Duplex Line Control (After Martin [35])

Also, the error rate can be found in Figure 39 such that the chosen frame size can maintain approximately 10^{-6} error rate.

Summary

This chapter has considered general aspects of implementing seismic data compression techniques with respect to execution time, memory size, depth of queue, and transmission time. The execution time and memory size requirements were evaluated in the assembler listing of all subroutines used in the compression techniques. It was shown that time and space requirements are functions of data points, and response time dictates the system structure depth of queue and speed of transmission circuit.

Transmission time is determined by transmission efficiency and speed of circuit when the data rate is fixed. Transmission efficiency was examined with two types of line control procedures: stop and wait ARQ and continuous ARQ. From these examinations, the following aspects were found: stop and wait ARQ cannot achieve high transmission efficiency since it has to wait for the ACK signal response and the response is delayed by the propagation delay of the satellite circuit. High transmission efficiency (above 95%) can be achieved by continuous ARQ, provided that the size of frame is chosen properly. The optimum frame size can be obtained according to the speed of circuit and a block counter. A 7-bit block counter is necessary for a satellite link due to a long propagation delay.

In general, the transmission time of continuous ARQ line control procedure can be obtained from

$$T_t = \frac{N \cdot F}{B \cdot e}, \tag{5.21}$$

where N is the number of frames, F is the frame size, B is the speed of the circuit (or channel bandwidth), and e is the transmission efficiency.

CHAPTER VI

CONCLUSIONS

New avenues into seismic data compression techniques have been developed. Compression techniques have been considered based on orthogonal transforms, digital coding methods, and prediction methods. A hybrid technique, which is a combination of DCT and a μ-law quantization has been developed for vibroseis data and nonimpulsive section of impulsive seismic data. Prediction coding has been developed for the impulsive section of impulsive seismic data, where a predictor is designed by the linear prediction analysis.

A range between five-to-one and eight-to-one compression has been achieved with at least a 30 dB signal-to-noise ratio. This result is obtained empirically, and it is dependent upon sampling rate and signal distribution.

This study differs from previous work [8] in the following aspects. First, earlier work focused on vibroseis data sampled at 500 Hz. This study investigates vibroseis data sampled at 250 Hz and impulsive seismic data sampled at 1000 Hz. Second, in the earlier work, the reconstructed signal at the receiver was measured objectively. In this study, the error in the compression-decompression process is maintained within a 30 dB SNR for every trace. This is defined as reversible in this study. Third, the seismic signal was treated as a two-dimensional image in earlier work. In this study, the seismic signal is treated as a one-dimensional vector.

Finally, earlier work was based on sequency limiting of the Walsh domain. Compression techniques of this study are based on redundancy and entropy reduction. Compression ratios of these two studies need not be compared, since compression is a function of the signal-to-noise ratio.

In this thesis, all sensors are weighted equally and a 30 dB SNR is maintained for each trace. A two-dimensional analysis was not performed due to energy differences among traces. An energy normalization method may be required to pursue two-dimensional data compression for further research.

All compression techniques are simulated in FORTRAN with the IBM 370. For implementing these techniques in mini- or microcomputers, execution time and core size requirements of all subroutines are evaluated with a cross-referenced list in assembler language. The evaluation is based on types and frequency of occurrences of instructions inside "DO" loops, where the iteration of "DO" loops is determined by the number of seismic data points. In order to minimize the core size requirement, a "load and swap" method is recommended, which allows for loading only the executing subroutine into the core memory. Also, general relationships among processing time, depth of queue, transmission time, and response time are discussed. Further research is required for completing a real-time system with respect to system structure and response time.

Data compression techniques have been investigated due to constraints in channel bandwidth, channel capacity, limited storage, and/or transmission cost. However, compression techniques do require computer systems, and thus compression cost needs to be analyzed in order to evaluate the trade-offs between compression cost and transmission cost. Further research in the areas, two-dimensional seismic data compression, real-time system design, cost analysis, and evaluation of computational optimality of algorithm versus optimality of hardware design should be fruitful. Optimality in terms of computation along with hardware implementation should be considered in parallel.

BIBLIOGRAPHY

[1] Davisson, L. D., and R. M. Gray. Data Compression. Stroudsburg, Penn.: Dowden, Hutchinson & Ross, Inc., 1976.

[2] Blasbalg, H., and R. Van Blerkom. "Message Compression." IRE Trans., Space Electron. Telemetry, Vol. 8 (Sept., 1962), pp. 228-238.

[3] Markel, J. D., and A. H. Gray, Jr. Linear Prediction of Speech. New York: Springer-Verlag, 1976.

[4] Davisson, L. D. "Data Compression Using Straight Line Interpolation." IEEE Trans., Inform. Theory, Vol. IT-14, No. 3 (1968), pp. 390-394.

[5] Ahmed, N., and K. R. Rao. Orthogonal Transforms for Digital Signal Processing. New York: Springer-Verlag, 1975.

[6] Rabiner, L. R., and R. W. Schafer. Digital Processing of Speech Signals. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1978.

[7] Robinson, E. A., and S. Treitel. Geophysical Signal Analysis. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1980.

[8] Wood, L. C. "Seismic Data Compression Methods." Geophysics, Vol. 39, No. 4 (Aug., 1974), pp. 499-525.

[9] Oppenheim, A. V., and R. W. Schafer. Digital Signal Processing. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1965.

[10] Paez, M. D., and T. H. Glisson. "Minimum Mean Square Error Quantization in Speech." IEEE Trans., Comm., Vol. COM-20 (April, 1972), pp. 225-230.

[11] Pratt, W. K. "Generalized Wiener Filtering Computation Techniques." IEEE Trans., Computers, Vol. C-21 (1972), pp. 630-641.

[12] Manz, J. W. "A Sequency-Ordered Fast Walsh Transform." IEEE Trans., Audio and Electroacoustics, Vol. AU-20 (1972), pp. 204-205.

[13] Chen, W., C. H. Smith, and S. C. Fralik. "A Fast Computational Algorithm for the Discrete Cosine Transform." IEEE Trans., Comm., Vol. COM-25 (Sept., 1977), pp. 1004-1008.

[14] Shannon, C. E. "Mathematical Theory of Communication." Bell System Tech. Journal, Vol. 27 (1948), pp. 379-423, 623-656.

[15] Wood, R. C. "On Optimum Quantization." IEEE Trans., Inform. Theory, Vol. IT-15, No. 2 (1969), pp. 248-252.

[16] Jayant, N. S. "Digital Coding of Speech Wave Forms: PCM, DPCM, and DM Quantizers." Proc., IEEE, Vol. 62 (May, 1974), pp. 611-632.

[17] Widrow, B. "A Study of Rough Amplitude Quantization by Means of Nyquist Sampling Theory." IRE Trans., Circuit Theory, Vol. CT-3, No. 4 (1956), pp. 266-276.

[18] Smith, B. "Instantaneous Compounding of Quantized Signals." Bell System Tech. Journal, Vol. 36, No. 3 (May, 1957), pp. 653-709.

[19] Jayant, N. S. "Adaptive Quantization With a One Word Memory." Bell System Tech. Journal, Vol. 52, No. 7 (Sept., 1973), pp. 1119-1144.

[20] Abate, J. E. "Linear and Adaptive Delta Modulation." Proc., IEEE, Vol. 55 (March, 1967), pp. 298-308.

[21] McDonald, R. A. "Signal to Noise and Idle Channel Performance of DPCM Systems." Bell System Tech. Journal, Vol. 45, No. 7 (Sept., 1966), pp. 1123-1151.

[22] Schouten, J. S., F. E. DeJager, and J. A. Greafkes. "Delta Modulation, a New Modulation System for Telecommunications." Philips Tech. Rept. (March, 1952), pp. 237-245.

[23] Shannugam, K. S. Digital and Analog Communication Systems. New York: John Wiley and Sons, 1979.

[24] Huffman, D. A. "A Method for the Construction of Minimum Redundancy Codes." Proc., IRE, Vol. 40, No. 9 (1952), pp. 1098-1101.

[25] Dym, H., H. P. McKean. Fourier Series and Integrals. New York: Academic Press, Inc., 1972.

[26] Elias, P. "Predictive Coding I." IRE Trans., Inform. Theory, Vol. IT-1, No. 1 (1955), pp. 16-23.

[27] Atal, B. S., and S. L. Hanauer. "Speech Analysis and Synthesis by Linear Prediction of the Speech Wave." Journal, Acoust. Soc. Am., Vol. 50 (1971), pp. 637-655.

[28] Markel, J. D., and A. H. Gray. Linear Prediction of Speech. New York: Springer-Verlag, 1976.

[29] Makhoul, J. M. "Stable and Efficient Lattice Methods for Linear Prediction." IEEE Trans., Acoustics, Speech, and Signal Proc., Vol. ASSP-25, No. 5 (Oct., 1977), pp. 423-428.

[30] Burg, J. "A New Analysis Technique for Time Series Data." Proc., NATO Advanced Study Institute on Signal Proc. Enscheda, Netherlands, 1968.

[31] Coker, C. H. "A Model of Articulatory Dynamics and Control." Proc., IEEE, Vol. 54, No. 4 (April, 1976), pp. 452-459.

[32] Martin, J. Design of Real-Time Computer System. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1967.

[33] Kleinrock, L. Queueing Systems. New York: John Wiley & Sons, Inc., 1976.

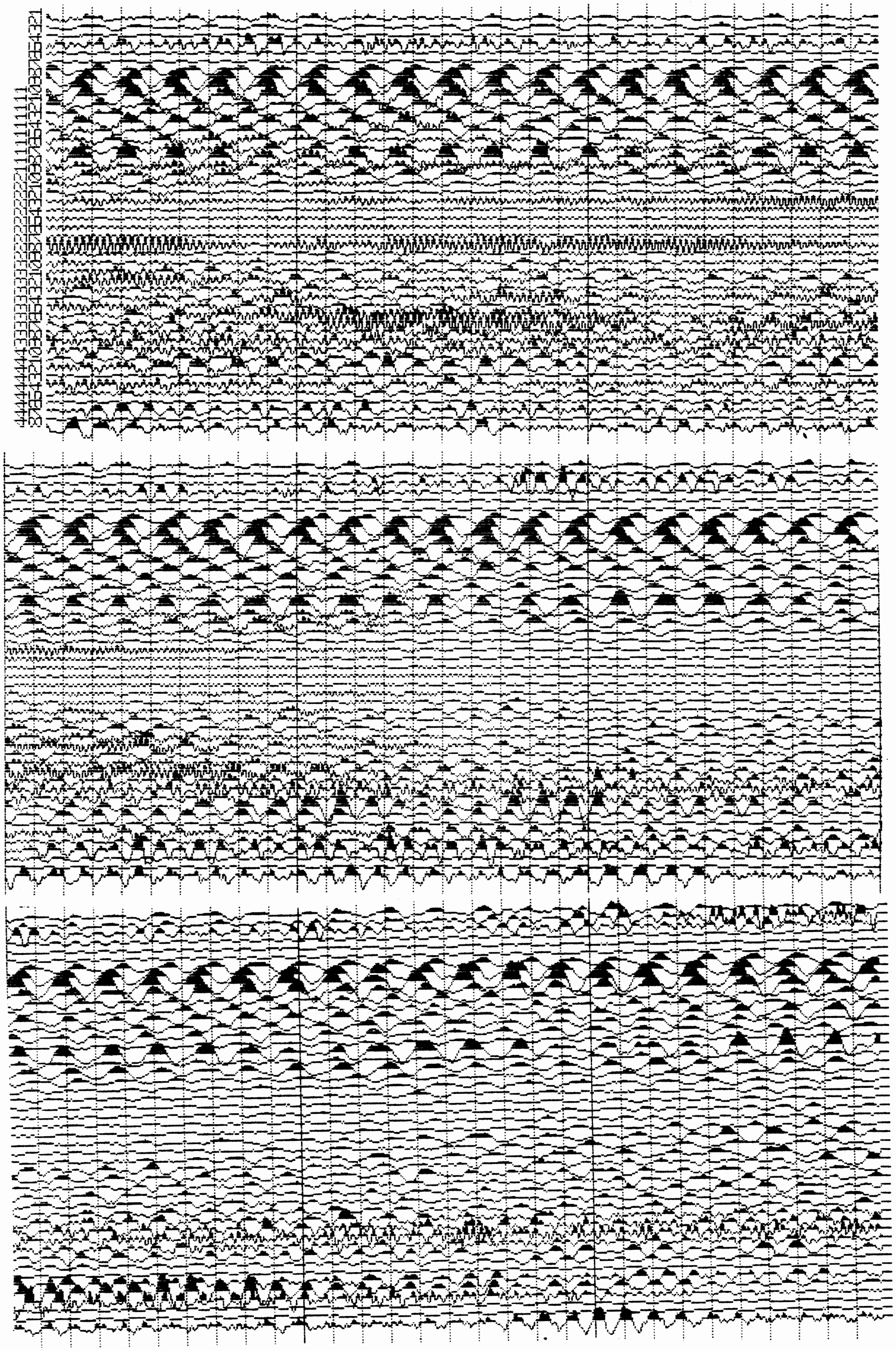
[34] Housley, T. Data Communication and Teleprocessing Systems. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1979.

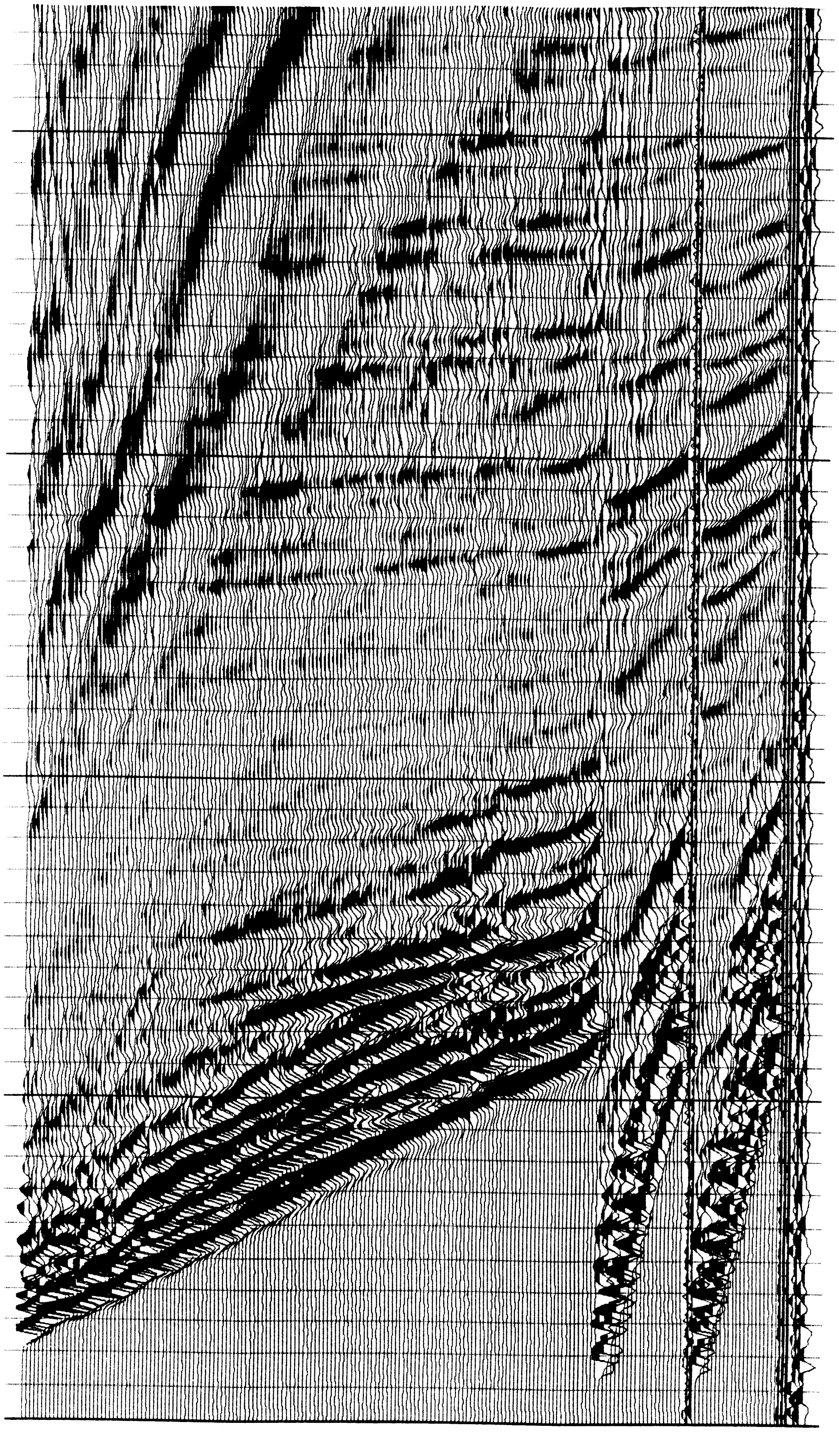
[35] Martin, J. Communications Satellite Systems. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1978.

[36] Spilker, J. J., Jr. Digital Communications by Satellite. Englewood Cliffs, N.J.: Prentice-Hall Inc., 1977.

APPENDIX A

SEISMIC DATA PLOTS





APPENDIX B

CROSS CORRELATION TABLES

CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:

	TEST1	TEST2	TEST3	TEST4	TEST5	TEST6	TEST7	TEST8
TEST1	1.00000	0.01290	0.00928	0.00915	-0.01023	-0.01073	-0.00146	-0.00865
	0.0000	0.3740	0.5228	0.5284	0.4810	0.4599	0.9198	0.5514
TEST2	0.01290	1.00000	0.22363	0.13457	-0.32770	-0.13741	0.07056	-0.18383
	0.3740	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST3	0.00928	0.22363	1.00000	-0.04224	0.35505	0.07982	-0.24093	-0.01549
	0.5228	0.0001	0.0000	0.0036	0.0001	0.0001	0.0001	0.2857
TEST4	0.00915	0.13457	-0.04224	1.00000	-0.09241	0.21682	-0.09634	0.29413
	0.5284	0.0001	0.0036	0.0000	0.0001	0.0001	0.0001	0.0001
TEST5	-0.01023	-0.32770	0.35505	-0.09241	1.00000	0.34325	0.01698	0.16591
	0.4810	0.0001	0.0001	0.0001	0.0000	0.0001	0.2419	0.0001
TEST6	-0.01073	-0.13741	0.07882	0.21682	0.34325	1.00000	-0.13009	0.15432
	0.4599	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001
TEST7	-0.00146	0.07056	-0.24093	-0.09634	0.01698	-0.13009	1.00000	-0.33200
	0.9198	0.0001	0.0001	0.0001	0.2419	0.0001	0.0000	0.0001
TEST8	-0.00865	-0.18383	-0.01549	0.29413	0.16591	0.15432	-0.33200	1.00000
	0.5514	0.0001	0.2857	0.0001	0.0001	0.0001	0.0001	0.0000
TEST9	-0.00233	0.13273	-0.05842	-0.30177	-0.08934	0.04416	0.30696	-0.54240
	0.8722	0.0001	0.0001	0.0001	0.0001	0.0023	0.0001	0.0001
TEST10	0.00752	-0.09432	0.01484	0.02165	0.19623	-0.26016	0.02629	0.35329
	0.6045	0.0001	0.3065	0.1357	0.0001	0.0001	0.0700	0.0001
TEST11	-0.00130	0.03054	-0.04344	0.05689	-0.18822	0.15242	-0.02753	-0.03028
	0.9286	0.0353	0.0027	0.0001	0.0001	0.0001	0.0578	0.0369
TEST12	0.01212	-0.11036	0.01950	-0.21376	0.17588	-0.25899	0.35239	-0.45109
	0.4038	0.0001	0.1790	0.0001	0.0001	0.0001	0.0001	0.0001
TEST13	-0.01048	-0.09080	0.03564	0.20481	0.05570	0.25937	-0.28625	0.23167
	0.4703	0.0001	0.0140	0.0001	0.0001	0.0001	0.0001	0.0001
TEST14	-0.01768	-0.03133	-0.04155	-0.03029	-0.05867	0.00296	0.04704	0.23509
	0.2232	0.0308	0.0042	0.0369	0.0001	0.8383	0.0012	0.0001
TEST15	-0.00201	-0.05645	-0.11508	-0.01857	0.11404	0.05608	-0.04545	0.09516
	0.8900	0.0001	0.0001	0.2006	0.0001	0.0001	0.0017	0.0001
TEST16	-0.01391	-0.03284	-0.03896	-0.00450	-0.00886	0.01141	-0.00460	-0.00180
	0.3377	0.0236	0.0072	0.7565	0.5417	0.4319	0.7513	0.9013

RHO=0 / N = 4750

TEST9	TEST10	TEST11	TEST12	TEST13	TEST14	TEST15	TEST16
-0.00233	0.00752	-0.00130	0.01212	-0.01048	-0.01768	-0.00201	-0.01391
0.8722	0.6045	0.9286	0.4039	0.4703	0.2232	0.8900	0.3377
0.13273	-0.09432	0.03054	-0.11096	-0.09080	-0.03133	-0.05645	-0.03284
0.0001	0.0001	0.0353	0.0001	0.0001	0.0308	0.0001	0.0236
-0.05842	0.01484	-0.04344	0.01950	0.03564	-0.04155	-0.11508	-0.03896
0.0001	0.3065	0.0027	0.1790	0.0140	0.0042	0.0001	0.0072
-0.30177	0.02165	0.05689	-0.21376	0.20481	-0.03029	-0.01857	-0.00450
0.0001	0.1357	0.0001	0.0001	0.0001	0.0369	0.2006	0.7565
-0.08934	0.19623	-0.18622	0.17588	0.05570	-0.05867	0.11404	-0.00886
0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.5417
0.04416	-0.26016	0.15242	-0.25899	0.25937	0.00296	0.05608	0.01141
0.0023	0.0001	0.0001	0.0001	0.0001	0.8383	0.0001	0.4319
0.30696	0.02629	-0.02753	0.35239	-0.28625	0.04704	-0.04545	-0.00460
0.0001	0.0700	0.0578	0.0001	0.0001	0.0012	0.0017	0.7513
-0.54240	0.35325	-0.03028	-0.45109	0.23167	0.23508	0.09516	-0.00180
0.0001	0.0001	0.0369	0.0001	0.0001	0.0001	0.0001	0.9013
1.00000	-0.59711	0.35055	0.16366	-0.02231	-0.17160	-0.27690	0.00476
0.0000	0.0001	0.0001	0.0001	0.1241	0.0001	0.0001	0.7432
-0.59711	1.00000	-0.54762	0.16913	-0.12580	0.12381	0.28819	-0.01216
0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.4022
0.35055	-0.54762	1.00000	-0.17766	0.30768	-0.21733	-0.38187	0.01512
0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.2974
0.16366	0.16913	-0.17766	1.00000	-0.46665	-0.19628	0.29209	0.00695
0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.6322
-0.02231	-0.12580	0.30768	-0.46665	1.00000	-0.17891	-0.19543	0.00926
0.1241	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.5236
-0.17160	0.12381	-0.21733	-0.19628	-0.17891	1.00000	-0.08172	0.00998
0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.4918
-0.27690	0.28819	-0.38187	0.29209	-0.19543	-0.08172	1.00000	-0.01446
0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.3192
0.00476	-0.01216	0.01512	0.00695	0.00926	0.00998	-0.01446	1.00000
0.7432	0.4022	0.2974	0.6322	0.5236	0.4918	0.3192	0.0000

CORRELATION COEFFICIENTS / PROB > |R| UNDER HO:R

	TEST1	TEST2	TEST3	TEST4	TEST5	TEST6	TEST7	TEST8
TEST1	1.00000	-0.98097	-0.98202	-0.98114	0.97968	0.98829	-0.97720	-0.98227
	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST2	-0.98097	1.00000	0.99998	1.00000	-0.99995	-0.99871	0.99982	0.99996
	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST3	-0.98202	0.99998	1.00000	0.99959	-0.99991	-0.99892	0.99970	1.00000
	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001
TEST4	-0.98114	1.00000	0.99995	1.00000	-0.99994	-0.99874	0.99981	0.99997
	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001
TEST5	0.97968	-0.99995	-0.99991	-0.99954	1.00000	0.99834	-0.99990	-0.99989
	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001
TEST6	0.98829	-0.99871	-0.99892	-0.99874	0.99834	1.00000	-0.99775	-0.99891
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001
TEST7	-0.97720	0.99982	0.99970	0.99981	-0.99990	-0.99775	1.00000	0.99966
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001
TEST8	-0.98227	0.99996	1.00000	0.99957	-0.99989	-0.99891	0.99966	1.00000
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
TEST9	-0.98278	0.99994	0.99999	0.99955	-0.99984	-0.99901	0.99958	1.00000
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST10	0.97892	-0.99988	-0.99978	-0.99987	0.99984	0.99827	-0.99989	-0.99972
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST11	0.99688	-0.99151	-0.99227	-0.99162	0.99081	0.99540	-0.98899	-0.99251
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST12	0.98084	-1.00000	-0.99997	-1.00000	0.99994	0.99870	-0.99984	-0.99955
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST13	0.98230	-0.99997	-0.99999	-0.99998	0.99987	0.99903	-0.99967	-0.99998
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST14	-0.97894	0.99993	0.99984	0.99952	-0.99991	-0.99827	0.99995	0.99979
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST15	-0.97909	0.99993	0.99985	0.99952	-0.99992	-0.99823	0.99993	0.99981
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TEST16	0.97872	-0.99993	-0.99986	-0.99952	0.99995	0.99811	-0.99995	-0.99983
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

HO=0 / N = 4790

TEST9	TEST10	TEST11	TEST12	TEST13	TEST14	TEST15	TEST16
-0.98278 0.0001	0.97892 0.0001	0.99688 0.0001	0.98084 0.0001	0.98230 0.0001	-0.97894 0.0001	-0.97909 0.0001	0.97872 0.0001
0.99994 0.0001	-0.99988 0.0001	-0.99151 0.0001	-1.00000 0.0001	-0.99997 0.0001	0.99993 0.0001	0.99993 0.0001	-0.99993 0.0001
0.99999 0.0001	-0.99978 0.0001	-0.99227 0.0001	-0.99997 0.0001	-0.99999 0.0001	0.99984 0.0001	0.99985 0.0001	-0.99986 0.0001
0.99995 0.0001	-0.99987 0.0001	-0.99162 0.0001	-1.00000 0.0001	-0.99998 0.0001	0.99992 0.0001	0.99992 0.0001	-0.99992 0.0001
-0.99984 0.0001	0.99984 0.0001	0.99081 0.0001	0.99994 0.0001	0.99987 0.0001	-0.99991 0.0001	-0.99992 0.0001	0.99995 0.0001
-0.99901 0.0001	0.99827 0.0001	0.99540 0.0001	0.99870 0.0001	0.99903 0.0001	-0.99827 0.0001	-0.99823 0.0001	0.99811 0.0001
0.99958 0.0001	-0.99989 0.0001	-0.98899 0.0001	-0.99984 0.0001	-0.99967 0.0001	0.99995 0.0001	0.99993 0.0001	-0.99995 0.0001
1.00000 0.0001	-0.99972 0.0001	-0.99251 0.0001	-0.99995 0.0001	-0.99998 0.0001	0.99979 0.0001	0.99981 0.0001	-0.99983 0.0001
1.00000 0.0000	-0.99966 0.0001	-0.99284 0.0001	-0.99992 0.0001	-0.99997 0.0001	0.99974 0.0001	0.99976 0.0001	-0.99977 0.0001
-0.99966 0.0001	1.00000 0.0000	0.98975 0.0001	0.99990 0.0001	0.99980 0.0001	-0.99998 0.0001	-0.99995 0.0001	0.99989 0.0001
-0.99284 0.0001	0.98975 0.0001	1.00000 0.0000	0.99138 0.0001	0.99230 0.0001	-0.98996 0.0001	-0.99007 0.0001	0.99013 0.0001
-0.99992 0.0001	0.99990 0.0001	0.99138 0.0001	1.00000 0.0000	0.99997 0.0001	-0.99994 0.0001	-0.99994 0.0001	0.99993 0.0001
-0.99997 0.0001	0.99980 0.0001	0.99230 0.0001	0.99997 0.0001	1.00000 0.0000	-0.99984 0.0001	-0.99985 0.0001	0.99982 0.0001
0.99974 0.0001	-0.99998 0.0001	-0.98996 0.0001	-0.99994 0.0001	-0.99984 0.0001	1.00000 0.0000	0.99999 0.0001	-0.99996 0.0001
0.99976 0.0001	-0.99995 0.0001	-0.99007 0.0001	-0.99994 0.0001	-0.99985 0.0001	0.99999 0.0001	1.00000 0.0000	-0.99995 0.0001
-0.99977 0.0001	0.99989 0.0001	0.99013 0.0001	0.99993 0.0001	0.99982 0.0001	-0.99996 0.0001	-0.99995 0.0001	1.00000 0.0000

APPENDIX C

COMPILED LISTING OF COMPUTER PROGRAMS

```
*LEVEL 2.3.0 (JUNE 78)                  OS/360  FORTRAN H EXTENDED              DATE 81.153/21.05.15        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

  ISN 0002              SUBROUTINE FDCT(A,NUM)                                               00000690
                C        DCT TRANSFORM USING FFT(IBM VERSION : FFTRC)                        00000700
                C        NUM    :   NUMBER OF DATA POINTS TO BE TRANSFORMED                  00000710
                C        A      :   INPUT ARRAY OF FFT AND OUTPUT ARRAY OF DCT               00000720
                C        IWK    :   WORK AREA OF FFT                                         00000730
                C        WK     :   WORK AREA OF FFT                                         00000740
                C        X      :   OUTPUT ARRAY OF FFT                                      00000750
  ISN 0003              DIMENSION IWK(2600),WK(2600),A(1)                                    00000760
  ISN 0004              COMPLEX X(4750)                                                      00000770
  ISN 0005              NUM2=NUM/2                                                           00000780
  ISN 0006              WRWP=3.141592/FLOAT(2*NUM)                                           00000790
  ISN 0007              J=0                                                                  00000800
  ISN 0008              CALL FFTRC(A,NUM,X,IWK,WK)                                           00000810
  ISN 0009              DO 10 I=2,NUM2                                                       00000820
  ISN 0010          10  X(NUM+2-I)=CONJG(X(I))                                               00000830
  ISN 0011              DO 20 I=1,NUM                                                        00000840
  ISN 0012              ARG=WRWP*FLOAT(I-1)                                                  00000850
  ISN 0013              X(I)=CMPLX(COS(ARG),SIN(ARG))*(X(I))                                 00000860
  ISN 0014          20  A(I)=REAL(X(I))/NUM2                                                 00000870
  ISN 0015              A(1)=A(1)/2.0                                                        00000880
  ISN 0016              RETURN                                                               00000890
  ISN 0017              END                                                                  00000900

                        *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
A        0002  0003  0008  0014  0015  0015
I        0009  0010  0010  0011  0012  0013  0013  0014  0014
J        0007
X        0004  0008  0010  0010  0013  0013  0014
WK       0003  0008
ARG      0012  0013  0013
COS      0013
IWK      0003  0008
NUM      0002  0005  0006  0008  0010  0011
SIN      0013
FDCT     0002
NUM2     0005  0009  0014
REAL     0014
WRWP     0006  0012
CMPLX    0013
CONJG    0010
FFTRC    0008
FLOAT    0006  0012

                        *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
 LABEL    DEFINED    REFERENCES
   10     0010       0009
   20     0014       0011

                     000000  47 F0 F 00C          FDCT        FC     15.12(0.15)
```

```
                    000004   07                                   DC     XL1'07'
                    000005   C6C4C3E3404C40                       DC     CL7'FDCT   '
                    00000C   90 EC D 00C                          STM    14,12,12(13)
                    000010   18 4D                                LR     4,13
                    000012   98 CD F 020                          LM     12,13,32(15)
                    000016   50 40 D 004                          ST     4,4(0,13)
                    00001A   50 D0 4 008                          ST     13,8(0,4)
                    00001E   07 FC                                BCR    15,12

TEMPORARY FOR FIX/FLOAT
                    000098   4E000000                             DC     XL4'4E000000'
                    00009C   00000000                             DC     XL4'00000000'
CONSTANTS
                    0000A0   4E000000                             DC     XL4'4E000000'
                    0000A4   80000000                             DC     XL4'80000000'
                    0000A8   00000000                             DC     XL4'00000000'
                    0000AC   00000001                             DC     XL4'00000001'
                    0000B0   00000002                             DC     XL4'00000002'
                    0000B4   41200000                             DC     XL4'41200000'
                    0000B8   413243F6                             DC     XL4'413243F6'
                    0000BC   00000000                             DC     XL4'00000000'
                    0000C0   00000000                             DC     XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
                    00E6A0   00002580                             DC     XL4'00002580'
                    00E6A4   00005220                             DC     XL4'00005220'
ADCONS FOR EXTERNAL REFERENCES
                    00E6A8   00000000                             DC     XL4'00000000'                  A
                    00E6B0   00000000                             DC     XL4'00000000'                COS
                    00E6B4   00000000                             DC     XL4'00000000'                SIN
                    00E6B8   00000000                             DC     XL4'00000000'              FFTFC
                    00E6BC   00000000                             DC     XL4'00000000'              CMPY#
                    00E6F0   58 50 C 008                 100001   L        5,   8( 0,12)
                    00E6F4   58 90 C 004                          L        9,   4( 0,12)
                    00E6F8   58 B0 C 000                          L       11,   0( 0,12)
                    00E6FC   58 A0 D 084                          L       10, 132( 0,13)                  I
                    00E700   58 80 C 028                          L        8,  40( 0,12)                  8
                    00E704   58 70 D 088                          L        7, 136( 0,13)                  2
                    00E708   58 20 D 0A8                          L        2, 168( 0,13)                NUM
                    00E70C   8E 20 0 020                          SRDA     2,  32
                    00E710   1D 27                                DR       2,  7
                    00E712   50 30 D 0B0                          ST       3, 176( 0,13)               NUM2
                    00E716   58 40 D 0A8                          L        4, 168( 0,13)                NUM
                    00E71A   89 40 0 001                          SLL      4,   1
                    00E71E   18 04                                LR       0,  4
                    00E720   57 00 D 07C                          X        0, 124( 0,13)   4E00000080000000
                    00E724   50 00 D 074                          ST       0, 116( 0,13)
                    00E728   68 20 D 070                          LD       2, 112( 0,13)
                    00E72C   6B 20 D 078                          SD       2, 120( 0,13)   4E00000000000000
                    00E730   78 00 D 090                          LE       0, 144( 0,13)           413243F6
                    00E734   3D 02                                DER      0,  2
                    00E736   70 00 D 0B4                          STE      0, 180( 0,13)               WRWF
                    00E73A   58 F0 C 018                          L       15,  24( 0,12)              FFTFC
                    00E73E   41 10 D 04C                          LA       1,  76( 0,13)
                    00E742   05 EF                                BALR    14,15
                    00E744   47 00 0 008                          BC       0,   8( 0, 0)
                    00E748   18 48                                LR       4,  8
                    00E74A   58 60 D 0A8                          L        6, 168( 0,13)                NUM
                    00E74E   58 60 C 034                          L        6,  52( 0,12)                 1/
```

```
00E752  18 B3                  LR     11, 3
00E754  78 28 9 000        10  LE     2,    0( 8, 9)              X
00E758  78 48 9 004            LE     4,    4( 8, 9)              X
00E75C  33 44                  LCER   4, 4
00E75E  18 26                  LR     2, 6
00E760  1B 27                  SR     2, 7
00E762  89 20 0 003            SLL    2,    3
00E766  70 42 9 014            STE    4,   20( 2, 9)              X
00E76A  70 22 9 010            STE    2,   16( 2, 9)              X
00E76E  1A 84                  AR     8, 4
00E770  87 7A C 0E4            BXLE   7,10, 180(12)               10
00E774  58 B0 C 000    100002  L      11,    0( 0,12)
00E778  58 80 C 028            L      8,   40( 0,12)              P
00E77C  58 70 D 088            L      7, 136( 0,13)               2
00E780  58 00 D 0B0            L      0, 176( 0,13)               NUM2
00E784  57 00 D 07C            X      0, 124( 0,13)   4E00000080000000
00E788  50 00 D 074            ST     0, 116( 0,13)
00E78C  68 C0 D 070            LD     0, 112( 0,13)
00E790  6B 00 D 078            SD     0, 120( 0,13)   4E00000080000000
00E794  70 00 C 024            STE    0,   36( 0,12)              .002
00E798  18 28                  LR     2, 8
00E79A  58 00 C 02C            L      0,   44( 0,12)              4
00E79E  50 00 C 030            ST     0,   48( 0,12)              .003
00E7A2  58 30 C 02C            L      3,   44( 0,12)              4
00E7A6  18 4E                  LR     4, 8
00E7A8  58 60 C 030            L      6,   48( 0,12)              .003
00E7AC  18 7A                  LR     7,10
00E7AE  18 82                  LR     8, 2
00E7B0  58 B0 D 0A8            L      11, 168( 0,13)              NUM
00E7B4  18 27          100003  LR     2, 7
00E7B6  1B 2A                  SR     2,10
00E7B8  18 02                  LR     0, 2
00E7BA  57 00 D 07C            X      0, 124( 0,13)   4E00000080000000
00E7BE  50 00 D 074            ST     0, 116( 0,13)
00E7C2  68 20 D 070            LD     2, 112( 0,13)
00E7C6  6B 20 D 078            SD     2, 120( 0,13)   4E00000080000000
00E7CA  7C 20 D 0B4            ME     2, 180( 0,13)               WEWF
00E7CE  70 20 D 0A4            STE    2, 164( 0,13)               ARG
00E7D2  58 F0 C 010            L      15,  16( 0,12)              COS
00E7D6  41 10 D 060            LA     1,   96( 0,13)
00E7DA  05 EF                  BALR   14,15
00E7DC  47 00 0 000            BC     0,   13( 0, 0)
00E7E0  70 00 C 038            STE    0,   56( 0,12)              .100
00E7E4  58 F0 C 014            L      15,  20( 0,12)              SIN
00E7E8  41 10 D 060            LA     1,   96( 0,13)
00E7EC  05 EF                  BALR   14,15
00E7EE  47 00 0 000            BC     0,   13( 0, 0)
00E7F2  70 00 C 03C            STE    0,   60( 0,12)              .101
00E7F6  78 00 C 038            LE     0,   56( 0,12)              .100
00E7FA  70 00 C 040            STE    0,   64( 0,12)              .102
00E7FE  78 00 C 03C            LE     0,   60( 0,12)              .101
00E802  70 00 C 044            STE    0,   68( 0,12)              .103
00E806  78 08 9 000            LE     0,    0( 8, 9)              X
00E80A  70 00 C 038            STE    0,   56( 0,12)              .100
00E80E  78 08 9 004            LE     0,    4( 8, 9)              X
00E812  70 00 C 03C            STE    0,   60( 0,12)              .101
00E816  58 F0 C 01C            L      15,  28( 0,12)              CMPY4
00E81A  41 10 D 064            LA     1, 100( 0,13)
```

```
                    00E81E   05 EF                                 BALR   14,15
                    00E820   47 00 0 000                           BC     0,  13( 0, 0)
                    00E824   70 00 C C48                           STE    0,  72( 0,12)                     .104
                    00E828   70 28 9 004                           STE    2,   4( 8, 9)                        X
                    00E82C   78 00 C C48                           LE     0,  72( 0,12)                     .104
                    00E830   70 08 9 000                           STE    0,   0( 8, 9)                        X
                    00E834   78 08 9 004                       20  LE     0,   4( 8, 9)                        X
                    00E838   78 28 9 000                           LE     2,   0( 8, 9)                        X
                    00E83C   7D 20 C 024                           DE     2,  36( 0,12)                     .602
                    00E840   70 26 5 000                           STE    2,   0( 6, 5)                        A
                    00E844   1A 63                                 AR     6, 3
                    00E846   1A 64                                 AR     6, 4
                    00E848   87 7A C 114                           BXLE   7,10, 276(12)                   100C03
                    00E84C   58 B0 C 000                   100C04  L      11,   0( 0,12)
                    00E850   58 80 C 028                           L      8,  40( 0,12)                        B
                    00E854   58 70 D 0E8                           L      7, 136( 0,13)                        Z
                    00E858   78 20 5 004                           LE     2,   4( 0, 5)                        A
                    00E85C   7D 20 D 08C                           DE     2, 140( 0,13)                 4120000C
                    00E860   70 20 5 004                           STE    2,   4( 0, 5)                        A
                    00E864   1B FF                                 SR     15,15
                    00E866   58 E0 D 000                           L      14,   0( 0,13)
                    00E86A   07 FE                                 BCR    15,14
ADDRESS OF EPILOGUE
                    00E86C   58 A0 D 004                           L      10,   4( 0,13)
                    00E870   58 E0 A 00C                           L      14,  12( 0,10)
                    00E874   58 B0 A 018                           L      11,  24( 0,10)
                    00E878   58 10 B 004                           L      1,   4( 0,11)
                    00E87C   58 20 D 0A8                           L      2, 168( 0,13)                      NUM
                    00E880   50 20 1 000                           ST     2,   0( 0, 1)
                    00E884   18 DA                                 LR     13,10
                    00E886   92 FF A 00C                           MVI     12(10),255
                    00E88A   98 2C A 01C                           LM     2,12,  28(10)
                    00E88E   07 FE                                 BCR    15,14
ADDRESS OF PROLOGUE
                    00E890   58 C0 D 048                           L      12,  72( 0,13)
                    00E894   58 70 1 004                           L      7,   4( 0, 1)
                    00E898   58 20 7 000                           L      2,   0( 0, 7)
                    00E89C   50 20 D 0A8                           ST     2, 168( 0,13)                      NUM
                    00E8A0   58 20 1 000                           L      2,   0( 0, 1)
                    00E8A4   41 30 2 000                           LA     3,   0( 0, 2)
                    00E8A8   41 50 0 004                           LA     5,   4
                    00E8AC   1B 25                                 SR     2, 5
                    00E8AE   50 20 C 008                           ST     2,   8( 0,12)
                    00E8B2   50 30 C 00C                           ST     3,  12( 0,12)                        A
                    00E8B6   50 30 D 04C                           ST     3,  76( 0,13)
                    00E8BA   47 F0 C 050                           BC     15,  80( 0,12)
ADCON FOR PROLOGUE
                    000020   0000E890                              DC     XL4'0000E890'
ADCON FOR SAVE AREA
                    000024   00000028                              DC     XL4'00000028'
ADCON FOR EPILOGUE
                    000028   0000E86C                              DC     XL4'0000E86C'
ADCON FOR REG 12
                    000070   0000E6A0                              DC     XL4'0000E6A0'
ADCONS FOR PARAMETER LISTS
                    000078   000000D0                              DC     XL4'000000D0'                      NUM
                    00007C   00005228                              DC     XL4'00005228'                        X
                    000080   000029E4                              DC     XL4'000029E4'                      IWK
```

156

```
        000084   E0C000E0        DC    XL4'800000E0'         WK
        000088   80C000CC        DC    XL4'ECC0C0CC'         ARG
        00008C   00C0E6F0        DC    XL4'0000E6E0'         .T02
        000090   8000E6D0        DC    XL4'E000E6D8'         .T00
TEMPORARIES AND GENERATED CONSTANTS
        00E6C0   0CCC0000        DC    XL4'00000000'
        00E6C4   00000000        DC    XL4'C0000CCC'
        00E6C8   00C0000E        DC    XL4'0000000E'
        00E6CC   00C00004        DC    XL4'00000004'
        00E6D0   00C00000        DC    XL4'00CCC0C0'
        00E6D4   00C00010        DC    XL4'00000010'
        00E6D8   00C00000        DC    XL4'C0C0C0C0'
        00E6DC   00C00000        DC    XL4'C0000000'
        00E6E0   00CC0000        DC    XL4'00000000'
        00E6E4   00C00000        DC    XL4'C00000C0'
        00E6E8   00C00000        DC    XL4'00000000'
        00E6EC   0CC40006        DC    XL4'00C40006'
```

```
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =      16, PROGRAM SIZE =     59502, SUBPROGRAM NAME =  FDCT

*STATISTICS*  NO DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    316K BYTES OF CORE NOT USED
```

```
*LEVEL 2.3.0 (JUNE 78)                    OS/360  FORTRAN H EXTENDED              DATE 81.166/14.56.34        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

    ISN 0002              SUBROUTINE SELECT(A,B,FMAX,NUM,EPSLON,FMEU)                    00001390
    ISN 0003              DIMENSION A(1),B(1)                                            00001400
    ISN 0004              FMAX=0.0                                                       00001410
    ISN 0005              DO 10 I=1,NUM                                                  00001420
    ISN 0006              STD=STD+A(I)*A(I)                                              00001430
    ISN 0007         10   IF (FMAX .LT. ABS(A(I))) FMAX=ABS(A(I))                        00001440
    ISN 0009              ICOUNT=0                                                       00001450
    ISN 0010              STD=STD/FLOAT(NUM)                                             00001460
    ISN 0011              STD=SQRT(STD)                                                  00001470
    ISN 0012              EPSLON=.05*STD                                                 00001480
    ISN 0013              DO 15 J=1,NUM                                                  00001490
    ISN 0014              IF(ABS(A(J)) .LE.EPSLON) GO TO 15                              00001500
    ISN 0016              ICOUNT=ICOUNT+1                                                00001510
    ISN 0017              IF (A(J) .LT. -EPSLON) B(ICOUNT)=A(J)+EPSLON                   00001520
    ISN 0019              IF (A(J) .GT. EPSLON)  B(ICOUNT)=A(J)-EPSLON                   00001530
    ISN 0021         15   CONTINUE                                                       00001540
    ISN 0022              RATIO=FMAX/STD                                                 00001550
    ISN 0023              IF(RATIO .LT. 4.0) FMEU=0.0                                    00001560
    ISN 0025              IF(RATIO .LT. 15.0 .AND. RATIO .GE. 4.0) FMEU=10.0             00001570
    ISN 0027              IF(RATIO .LT. 20.0 .AND. RATIO .GE. 15.0) FMEU=30.0            00001580
    ISN 0029              IF(RATIO .LT. 25.0 .AND. RATIO .GE. 20.0) FMEU=50.0            00001590
    ISN 0031              IF(RATIO .LT. 35.0 .AND. RATIO .GE. 25.0) FMEU=100.0           00001600
    ISN 0033              IF(RATIO .GE. 35.0) FMEU=200.0                                 00001610
    ISN 0035              FMAX=FMAX-EPSLON                                               00001620
    ISN 0036              NUM=ICOUNT                                                     00001630
    ISN 0037              RETURN                                                         00001640
    ISN 0038              END                                                            00001650

                 *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
A        0002  0003  0006  0006  0007  0007  0014  0017  0017  0019  0019
B        0002  0003  0017  0019
I        0005  0006  0006  0007  0007
J        0013  0014  0017  0017  0019  0019
ABS      0007  0007  0014
NUM      0002  0005  0010  0013  0036
STD      0006  0006  0010  0010  0011  0011  0012  0022
FMAX     0002  0004  0007  0007  0022  0035  0035
FMEU     0002  0023  0025  0027  0029  0031  0033
SQRT     0011
FLOAT    0010
RATIO    0022  0023  0025  0025  0027  0027  0029  0031  0031  0033
RATIO    0029
EPSLON   0002  0012  0014  0017  0017  0019  0019  0035
ICOUNT   0009  0016  0016  0017  0019  0036
SELECT   0002

                 *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
 LABEL   DEFINED   REFERENCES
   10    0007      0005
   15    0021      0013  0014
```

```
                    000000  47 F0 F 00C          SELECT   BC     15,12(0,15)
                    000004  07                            DC     XL1'C7'
                    000005  E2C5D3C5C3E340                DC     CL7'SELECT '
                    00000C  90 EC D 00C                   STM    14,12,12(13)
                    000010  18 4D                         LR     4,13
                    000012  98 CD F 020                   LM     12,13,32(15)
                    000016  50 40 D 004                   ST     4,4(0,13)
                    00001A  50 D0 4 008                   ST     13,8(0,4)
                    00001E  07 FC                         BCR    15,12

TEMPORARY FOR FIX/FLOAT
                    000078  4E000000                      DC     XL4'4E000000'
                    00007C  00000000                      DC     XL4'00000000'
CONSTANTS
                    000080  4E000000                      DC     XL4'4E000000'
                    000084  80000000                      DC     XL4'80000000'
                    000088  00000000                      DC     XL4'00000000'
                    00008C  00000000                      DC     XL4'00000000'
                    000090  00000001                      DC     XL4'00000001'
                    000094  3FCCCCCD                      DC     XL4'3FCCCCCD'
                    000098  41400000                      DC     XL4'41400000'
                    00009C  41A00000                      DC     XL4'41A00000'
                    0000A0  41F00000                      DC     XL4'41F00000'
                    0000A4  42140000                      DC     XL4'42140000'
                    0000A8  42190000                      DC     XL4'42190000'
                    0000AC  421E0000                      DC     XL4'421E0000'
                    0000B0  42230000                      DC     XL4'42230000'
                    0000B4  42320000                      DC     XL4'42320000'
                    0000B8  42640000                      DC     XL4'42640000'
                    0000BC  42C80000                      DC     XL4'42C80000'
                    0000C0  00000000                      DC     XL4'00000000'
                    0000C4  00000000                      DC     XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                    0000F8  00000000                      DC     XL4'00000000'                        A
                    000100  00000000                      DC     XL4'00000000'                        E
                    000108  00000000                      DC     XL4'00000000'                     SQRT
                    000138  58 40 D 0D0          100001   L       4, 208( 0,13)
                    00013C  58 60 D 0D8                   L       6, 216( 0,13)
                    000140  58 B0 D 060                   L      11,  96( 0,13)                       O
                    000144  58 A0 D 0EC                   L      10, 236( 0,13)                       4
                    000148  58 30 D 068                   L       3, 104( 0,13)                       1
                    00014C  78 00 D 064                   LE      0, 100( 0,13)                       0
                    000150  70 00 D 0B0                   STE     0, 176( 0,13)                    FMAX
                    000154  58 20 D 0A8                   L       2, 168( 0,13)                     NUM
                    000158  89 20 0 002                   SLL     2,   2
                    00015C  50 20 D 104                   ST      2, 260( 0,13)                    .COE
                    000160  18 8A                         LR      8,10
                    000162  18 B2                         LR     11, 2
                    000164  78 68 A 000          100002   LE      6,   0( 8, 4)                       A
                    000168  38 46                         LER     4, 6
                    00016A  3C 46                         MER     4, 6
                    00016C  7A 40 D 0AC                   AE      4, 172( 0,13)                     STD
                    000170  70 40 D 0AC                   STE     4, 172( 0,13)                     STD
                    000174  30 26                    10   LPER    2, 6
                    000176  70 20 D 0E4                   STE     2, 228( 0,13)                    .COI
                    00017A  79 20 D 0B0                   CE      2, 176( 0,13)                    FMAX
```

```
00017E  47 C0 D 15E               BC     12, 350( 0,13)            100004
000182  7C 20 D 0B0       100003  STE     2, 176( 0,13)              FMAX
000186  87 8A D 13C       100C04  BXLE    8,10, 316(13)            100002
00018A  58 B0 D 060       100C03  L      11,  96( 0,13)                 0
00018E  18 2B                     LR      2,11
000190  50 B0 D 0C4               ST     11, 196( 0,13)            ICOUNT
000194  58 00 D 0A8               L       0, 168( 0,13)               NUM
000198  57 00 D 05C               X       0,  92( 0,13)  4E00000080000000
00019C  50 00 D 054               ST      0,  84( 0,13)
0001A0  68 20 D 050               LD      2,  80( 0,13)
0001A4  6E 20 D 058               SD      2,  88( 0,13)  4E00000000000000
0001A8  78 00 D 0AC               LE      0, 172( 0,13)               STD
0001AC  3D 02                     DER     0, 2
0001AE  70 00 D 0AC               STE     0, 172( 0,13)               STD
0001B2  58 F0 D 0E0               L      15, 224( 0,13)              SQRT
0001B6  41 10 D 04C               LA      1,  76( 0,13)
0001BA  05 EF                     BALR   14,15
0001BC  47 00 0 008               BC      0,  11( 0, 0)
0001C0  70 00 D 108               STE     0, 264( 0,13)              .100
0001C4  70 00 D 0AC               STE     0, 172( 0,13)               STD
0001C8  78 20 D 06C               LE      2, 108( 0,13)           3FCCCCCC
0001CC  7C 20 D 108               ME      2, 264( 0,13)              .100
0001D0  70 20 D 0C0               STE     2, 192( 0,13)            EPSLON
0001D4  33 22                     LCER    2, 2
0001D6  70 20 D 0E8               STE     2, 232( 0,13)              .C02
0001DA  18 52                     LR      5, 2
0001DC  18 7B                     LR      7,11
0001DE  18 8B                     LR      8,11
0001E0  18 9A                     LR      9,10
0001E2  58 B0 D 104               L      11, 260( 0,13)              .C08
0001E6  78 69 A 000       100C06  LE      6,   0( 9,10)                 A
0001EA  30 46                     LPER    4, 6
0001EC  79 40 D 0C0               CE      4, 192( 0,13)            EPSLON
0001F0  47 C0 D 1F6               BC     12, 502( 0,13)                15
0001F4  1A 53             100C07  AR      5, 3
0001F6  1A 7A                     AR      7,10
0001F8  1A 8A                     AR      8,10
0001FA  79 60 D 0E8               CE      6, 232( 0,13)              .C02
0001FE  47 A0 D 1E4               BC     10, 484( 0,13)            100C09
000202  38 26             100C08  LER     2, 6
000204  7A 20 D 0C0               AE      2, 192( 0,13)            EPSLON
000208  70 28 6 000               STE     2,   0( 8, 6)                 E
00020C  79 60 D 0C0       100C09  CE      6, 192( 0,13)            EPSLON
000210  47 C0 D 1F6               BC     12, 502( 0,13)                15
000214  38 26             100C10  LER     2, 6
000216  7B 20 D 0C0               SE      2, 192( 0,13)            EPSLON
00021A  70 27 6 000               STE     2,   0( 7, 6)                 P
00021E  87 9A D 1BE            15 BXLE    9,10, 446(13)            100C06
000222  50 50 D 0C4               ST      5, 196( 0,13)            ICOUNT
000226  58 B0 D 060       100C11  L      11,  96( 0,13)                 0
00022A  78 20 D 0B0               LE      2, 176( 0,13)              FMAX
00022E  70 20 D 0AC               CE      2, 172( 0,13)               STD
000232  70 20 D 0B8               STE     2, 184( 0,13)             RATIO
000236  79 20 D 070               CE      2, 112( 0,13)           41400000
00023A  47 A0 D 21E               BC     10, 542( 0,13)            100013
00023E  78 00 D 064       100C12  LE      0, 100( 0,13)                 0
000242  70 00 D 0B4               STE     0, 180( 0,13)              EMEL
000246  78 00 D 0B8       100C13  LE      0, 184( 0,13)             RATIO
```

```
        00024A  79 00 D 078                   CE    0, 120( 0,13)             41F00000
        00024E  47 A0 D 23E                   BC   10, 574( 0,13)               100015
        000252  78 00 D 0B8          200001   LE    0, 184( 0,13)                RATIO
        000256  79 00 D 070                   CE    0, 112( 0,13)             41400000
        00025A  47 50 D 23E                   BC    5, 574( 0,13)               100015
        00025E  78 00 D 074          100014   LE    0, 116( 0,13)             41A00000
        000262  70 00 D 0B4                   STE   0, 180( 0,13)                 FNEU
        000266  78 00 D 0B8          100015   LE    0, 184( 0,13)                RATIO
        00026A  79 00 D 07C                   CE    0, 124( 0,13)             42140000
        00026E  47 A0 D 25E                   BC   10, 606( 0,13)               100017
        000272  78 00 D 0B8          200002   LE    0, 184( 0,13)                RATIO
        000276  79 00 D 078                   CE    0, 120( 0,13)             41F00000
        00027A  47 50 D 25E                   BC    5, 606( 0,13)               100017
        00027E  78 00 D 084          100016   LE    0, 132( 0,13)             421E0000
        000282  70 00 D 0B4                   STE   0, 180( 0,13)                 FNEU
        000286  78 00 D 0B8          100017   LE    0, 184( 0,13)                RATIO
        00028A  79 00 D 080                   CE    0, 128( 0,13)             42190000
        00028E  47 A0 D 27E                   BC   10, 638( 0,13)               100019
        000292  78 00 D 0B8          200003   LE    0, 188( 0,13)                RATIO
        000296  79 00 D 07C                   CE    0, 124( 0,13)             4214C000
        00029A  47 50 D 27E                   BC    5, 638( 0,13)               100019
        00029E  78 00 D 08C          100018   LE    0, 140( 0,13)             42320000
        0002A2  70 00 D 0B4                   STE   0, 180( 0,13)                 FNEU
        0002A6  78 00 D 0B8          100019   LE    0, 184( 0,13)                RATIO
        0002AA  79 00 D 088                   CE    0, 136( 0,13)             42230000
        0002AE  47 A0 D 29E                   BC   10, 670( 0,13)               100021
        0002B2  78 00 D 0B8          200001   LE    0, 184( 0,13)                RATIO
        0002B6  79 00 D 080                   CE    0, 128( 0,13)             42190000
        0002BA  47 50 D 29E                   BC    5, 670( 0,13)               100021
        0002BE  78 00 D 090          100020   LE    0, 144( 0,13)             42640000
        0002C2  70 00 D 0B4                   STE   0, 180( 0,13)                 FNEU
        0002C6  78 00 D 0B8          100021   LE    0, 184( 0,13)                RATIO
        0002CA  79 00 D 088                   CE    0, 136( 0,13)             42230000
        0002CE  47 50 D 2B2                   BC    5, 690( 0,13)               100023
        0002D2  78 00 D 094          100022   LE    0, 148( 0,13)             42CCCCCC
        0002D6  70 00 D 0B4                   STE   0, 180( 0,13)                 FNEU
        0002DA  78 00 D 0B0          100023   LE    0, 176( 0,13)                 FMAX
        0002DE  7B 00 D 0C0                   SE    0, 192( 0,13)               EPSLON
        0002E2  70 00 D 0B0                   STE   0, 176( 0,13)                 FMAX
        0002E6  58 00 D 0C4                   L     0, 196( 0,13)               ICOUNT
        0002EA  50 00 D 0A8                   ST    0, 168( 0,13)                  NUM
        0002EE  1B FF                         SR   15,15
        0002F0  58 E0 D 000                   L    14,   0( 0,13)
        0002F4  07 FE                         BCR  15,14
ADDRESS OF EPILOGUE
        0002F6  58 A0 D 004                   L    10,   4( 0,13)
        0002FA  58 E0 A 00C                   L    14,  12( 0,10)
        0002FE  58 B0 A 018                   L    11,  24( 0,10)
        000302  58 10 B 00E                   L     1,   8( 0,11)
        000306  78 20 D 0B0                   LE    2, 176( 0,13)                 FMAX
        00030A  70 20 1 000                   STE   2,   0( 0, 1)
        00030E  58 20 B 00C                   L     2,  12( 0,11)
        000312  58 30 D 0A8                   L     3, 168( 0,13)                  NUM
        000316  50 30 2 000                   ST    3,   0( 0, 2)
        00031A  58 40 B 010                   L     4,  16( 0,11)
        00031E  78 40 D 0C0                   LE    4, 192( 0,13)               EPSLON
        000322  70 40 4 000                   STE   4,   0( 0, 4)
        000326  58 50 B 014                   L     5,  20( 0,11)
```

```
*LEVEL 2.3.0 (JUNE 78)                      OS/360  FORTRAN H EXTENDED           DATE 81.166/14.56.34         PAGE   5
                     00032A  78 60 D 0B4                      LE      6, 180( 0,13)                         FMEU
                     00032E  70 60 5 000                      STE     6,   0( 0, 5)
                     000332  18 DA                            LR     13,10
                     000334  92 FF A 00C                      MVI      12(10),255
                     000338  98 2C A 01C                      LM      2,12,  28(10)
                     00033C  07 FE                            BCR    15,14
ADDRESS OF PROLOGUE
                     00033E  98 7A 1 008                      LM      7,10,   8( 1)
                     000342  78 20 7 000                      LE      2,   0( 0, 7)
                     000346  70 20 D 0B0                      STE     2, 176( 0,13)                         RMAX
                     00034A  58 20 8 000                      L       2,   0( 0, 8)
                     00034E  50 20 D 0A8                      ST      2, 168( 0,13)                          NUM
                     000352  78 20 9 000                      LE      2,   0( 0, 9)
                     000356  70 20 D 0C0                      STE     2, 192( 0,13)                       EPSLON
                     00035A  78 20 A 000                      LE      2,   0( 0,10)
                     00035E  70 20 D 0B4                      STE     2, 180( 0,13)                         FMEU
                     000362  58 20 1 000                      L       2,   0( 0, 1)
                     000366  41 30 2 000                      LA      3,   0( 0, 2)
                     00036A  41 50 0 004                      LA      5,   4
                     00036E  1B 25                            SR      2, 5
                     000370  50 20 D 0D0                      ST      2, 208( 0,13)
                     000374  50 30 D 0D4                      ST      3, 212( 0,13)                            A
                     000378  58 20 1 004                      L       2,   4( 0, 1)
                     00037C  41 30 2 000                      LA      3,   0( 0, 2)
                     000380  41 50 0 004                      LA      5,   4
                     000384  1B 25                            SR      2, 5
                     000386  50 20 D 0D8                      ST      2, 216( 0,13)
                     00038A  50 30 D 0DC                      ST      3, 220( 0,13)                            E
                     00038E  47 F0 D 110                      BC     15, 272( 0,13)
ADCON FOR PROLOGUE
                     000020  0000033E                         DC      XL4'0000033E'
ADCON FOR SAVE AREA
                     000024  00000028                         DC      XL4'00000028'
ADCON FOR EPILOGUE
                     000028  000002FE                         DC      XL4'000002FE'
ADCONS FOR PARAMETER LISTS
                     000074  800000D4                         DC      XL4'800000D4'                          STD
TEMPORARIES AND GENERATED CONSTANTS
                     00010C  00000000                         DC      XL4'00000000'
                     000110  00000000                         DC      XL4'00000000'
                     000114  00000004                         DC      XL4'00000004'
                     000118  00000000                         DC      XL4'00000000'
                     00011C  00000000                         DC      XL4'00000000'
                     000120  00000000                         DC      XL4'00000000'
                     000124  00000000                         DC      XL4'00000000'
                     000128  00000000                         DC      XL4'00000000'
                     00012C  00000000                         DC      XL4'00000000'
                     000130  00000000                         DC      XL4'00000000'
                     000134  00000000                         DC      XL4'00000000'

*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =       37, PROGRAM SIZE =       914, SUBPROGRAM NAME =SELECT
```

```
*LEVEL 2.3.0 (JUNE 78)                    OS/360  FORTRAN H EXTENDED              DATE 81.153/21.05.18        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

   ISN 0002              SUBROUTINE CONMEU(RDATA,NUM,EPSLON,XMAX,RMEU)                       00000910
               C          MEU-LAW CONVERTER                                                  00000920
               C                                                                             00000930
               C          RDATA   :   INPUT ARRAY DCT COEFFICIENTS OF SEISMIC DATA TRACE     00000940
               C          RMEU    :   MEU-VALUE SET AS 500                                   00000950
               C          XMAX    :   ABSOLUTE MAXIMUM VALUE OF RDATA ARRAY                  00000960
               C          NUM     :   NO. OF DATA POINTS PER SWEEPS                          00000970
               C          EPSLON  :   THRESHOLD VALUE OF INSIGNIFICANT DCT COEFFICIENTS      00000980
               C                                                                             00000990
   ISN 0003               DIMENSION RDATA(1)                                                 00001000
               C          APPLY MEU-LAW                                                      00001010
   ISN 0004              RMEU1=RMEU+1.0                                                      00001020
   ISN 0005              DEN=ALOG(RMEU1)                                                     00001030
   ISN 0006              EPSLON=EPSLON/XMAX                                                  00001040
   ISN 0007              EPSLON=1.0+RMEU*EPSLON                                              00001050
   ISN 0008              EPSLON=XMAX*ALOG(EPSLON)                                            00001060
   ISN 0009              EPSLON=(EPSLON/DEN)                                                 00001070
   ISN 0010              DO 10 I=1,NUM                                                       00001080
   ISN 0011              RDATA(I)=0.0                                                        00001090
   ISN 0012              SIGN=1.0                                                            00001100
   ISN 0013              ABSR=ABS(RDATA(I))                                                  00001110
   ISN 0014              IF (RDATA(I).LT.0.0) SIGN=-1.0                                      00001120
   ISN 0016              ABSR=ABSR/XMAX                                                      00001130
   ISN 0017              ABSR=1.0+RMEU*ABSR                                                  00001140
   ISN 0018              ABSR=XMAX*ALOG(ABSR)                                                00001150
   ISN 0019              ABSR=(ABSR/DEN)*SIGN                                                00001160
   ISN 0020              RDATA(I)=ABSR                                                       00001170
   ISN 0021          10  CONTINUE                                                            00001180
   ISN 0022          20  RETURN                                                              00001190
   ISN 0023              END                                                                 00001200

                         *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
I        0010  0011  0013  0014  0020
ABS      0013
DEN      0005  0009  0019
NUM      0002  0010
ABSR     0013  0016  0016  0017  0017  0018  0018  0019  0019  0020
ALOG     0005  0008  0018
RMEU     0002  0004  0007  0017
SIGN     0012  0014  0019
XMAX     0002  0006  0008  0016  0018
RDATA    0002  0003  0011  0013  0014  0020
RMEU1    0004  0005
CONMEU   0002
EPSLON   0002  0006  0006  0007  0007  0008  0008  0009  0009

                         *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
 LABEL    DEFINED    REFERENCES
   10      0021       0010
   20      0022
```

```
                    000000  47 F0 F 00C          CONMEU    BC      15,12(0,15)
                    000004  07                             DC      XL1'07'
                    000005  C3D6D5D4C5E440                 DC      CL7'CONMEU '
                    00000C  90 EC D 00C                    STM     14,12,12(13)
                    000010  18 4D                          LR      4,13
                    000012  98 CD F 020                    LM      12,13,32(15)
                    000016  50 40 D 004                    ST      4,4(0,13)
                    00001A  50 D0 4 008                    ST      13,8(0,4)
                    00001E  07 FC                          BCR     15,12

CONSTANTS
                    000080  00000000                       DC      XL4'00000000'
                    000084  00000001                       DC      XL4'00000001'
                    000088  41100000                       DC      XL4'41100000'
                    00008C  00000000                       DC      XL4'00000000'
                    000090  00000000                       DC      XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                    0000C8  00000000                       DC      XL4'00000000'                          ALOG
                    0000CC  00000000                       DC      XL4'00000000'                          RDATA
                    0000EC  58 80 D 0A4          100001    L        8, 164( 0,13)
                    0000F0  58 A0 D 0B4                    L       10, 180( 0,13)                              4
                    0000F4  58 70 D 074                    L        7, 116( 0,13)                            NUM
                    0000F8  78 00 D 060                    LE       0,  96( 0,13)                        41100000
                    0000FC  7A 00 D 07C                    AE       0, 124( 0,13)                           FREQ
                    000100  70 00 D 088                    STE      0, 136( 0,13)                          RMFUI
                    000104  58 F0 D 0A0                    L       15, 160( 0,13)                           ALOG
                    000108  41 10 D 04C                    LA       1,  76( 0,13)
                    00010C  05 EF                          BALR    14,15
                    00010E  47 00 0 005                    BC       0,   5( 0, 0)
                    000112  70 00 D 0BC                    STE      0, 188( 0,13)                           .100
                    000116  70 00 D 070                    STE      0, 112( 0,13)                            DEN
                    00011A  78 20 D 090                    LE       2, 144( 0,13)                         EPSLON
                    00011E  7D 20 D 084                    DE       2, 132( 0,13)                           XMAX
                    000122  70 20 D 090                    STE      2, 144( 0,13)                         EPSLON
                    000126  7C 20 D 07C                    ME       2, 124( 0,13)                           FREQ
                    00012A  7A 20 D 060                    AE       2,  96( 0,13)                       41100000
                    00012E  70 20 D 090                    STE      2, 144( 0,13)                         EPSLON
                    000132  58 F0 D 0A0                    L       15, 160( 0,13)                           ALOG
                    000136  41 10 D 050                    LA       1,  80( 0,13)
                    00013A  05 EF                          BALR    14,15
                    00013C  47 00 0 008                    BC       0,   8( 0, 0)
                    000140  78 20 D 084                    LE       2, 132( 0,13)                           XMAX
                    000144  3C 20                          MER      2, 0
                    000146  70 20 D 090                    STE      2, 144( 0,13)                         EPSLON
                    00014A  7D 20 D 0BC                    DE       2, 188( 0,13)                           .100
                    00014E  70 20 D 090                    STE      2, 144( 0,13)                         EPSLON
                    000152  78 00 D 060                    LE       0,  96( 0,13)                       41100000
                    000156  33 00                          LCER     0, 0
                    000158  70 00 D 0B0                    STE      0, 176( 0,13)                           .002
                    00015C  18 B7                          LR      11, 7
                    00015E  89 B0 0 002                    SLL     11,   2
                    000162  18 9A                          LR       9,10
                    000164  78 00 D 058          100002    LE       0,  88( 0,13)                              0
                    000168  70 09 B 000                    STE      0,   0( 9,11)                          RDATA
                    00016C  78 00 D 060                    LE       0,  96( 0,13)                       41100000
                    000170  70 00 D 080                    STE      0, 128( 0,13)                           SIGN
```

```
            000174  78 29 8 000              LE     2,   0( 9, 8)             FDATA
            000178  30 02                    LPER   0, 2
            00017A  70 00 D 07E              STE    0, 120( 0,13)             ABSF
            00017E  32 22                    LTER   2, 2
            000180  47 A0 D 164              BC     10, 356( 0,13)            10000A
            000184  78 00 D 0B0      100003  LE     0, 176( 0,13)             .002
            000188  70 00 D 080              STE    0, 128( 0,13)             SIGN
            00018C  78 20 D 078      100004  LE     2, 120( 0,13)             ABSF
            000190  7D 20 D 084              DE     2, 132( 0,13)             XMAX
            000194  7C 20 D 07C              ME     2, 124( 0,13)             RMEL
            000198  7A 20 D 060              AE     2,  96( 0,13)             41100000
            00019C  70 20 D 078              STE    2, 120( 0,13)             ABSF
            0001A0  58 F0 D 0A0              L      15, 160( 0,13)            ALOG
            0001A4  41 10 D 054              LA     1,  84( 0,13)
            0001A8  05 EF                    BALR   14,15
            0001AA  47 00 0 012              BC     0,  18( 0, 0)
            0001AE  78 20 D 084              LE     2, 132( 0,13)             XMAX
            0001B2  3C 20                    MER    2, 0
            0001B4  7D 20 D 070              DE     2, 112( 0,13)             DEN
            0001B8  7C 20 D 080              ME     2, 128( 0,13)             SIGN
            0001BC  70 29 8 000              STE    2,   0( 9, 8)             FDATA
            0001C0  87 9A D 13C          10  BXLE   9,10, 316(13)             100002
            0001C4  1D FF                20  SR     15,15
            0001C6  58 E0 D 000              L      14,   0( 0,13)
            0001CA  07 FE                    BCR    15,14
ADDRESS OF EPILOGUE
            0001CC  58 A0 D 004              L      10,   4( 0,13)
            0001D0  58 E0 A 00C              L      14,  12( 0,10)
            0001D4  58 B0 A 018              L      11,  24( 0,10)
            0001D8  58 10 B 008              L      1,   8( 0,11)
            0001DC  78 20 D 090              LE     2, 144( 0,13)             EPSLON
            0001E0  70 20 1 000              STE    2,   0( 0, 1)
            0001E4  18 DA                    LR     13,10
            0001E6  92 FF A 00C              MVI    12(10),255
            0001EA  98 2C A 01C              LM     2,12,  28(10)
            0001EE  07 FE                    BCR    15,14
ADDRESS OF PROLOGUE
            0001F0  98 7A 1 004              LM     7,10,   4( 1)
            0001F4  58 20 7 000              L      2,   0( 0, 7)
            0001F8  50 20 D 074              ST     2, 116( 0,13)             NUM
            0001FC  78 2C 8 000              LE     2,   0( 0, 8)
            000200  70 20 D 090              STE    2, 144( 0,13)             EPSLON
            000204  78 20 9 000              LE     2,   0( 0, 9)
            000208  70 20 D 084              STE    2, 132( 0,13)             XMAX
            00020C  78 20 A 000              LE     2,   0( 0,10)
            000210  70 20 D 07C              STE    2, 124( 0,13)             RMEL
            000214  58 20 1 000              L      2,   0( 0, 1)
            000218  41 30 2 000              LA     3,   0( 0, 2)
            00021C  41 50 0 004              LA     5,   4
            000220  1E 25                    SR     2, 5
            000222  50 20 D 0A4              ST     2, 164( 0,13)
            000226  50 30 D 0A8              ST     3, 168( 0,13)             FDATA
            00022A  47 F0 D 0C4              BC     15, 196( 0,13)
ADCON FOR PROLOGUE
            000020  000001F0                 DC     XL4'000001F0'
ADCON FOR SAVE AREA
            000024  00000028                 DC     XL4'00000028'
ADCON FOR EPILOGUE
```

```
                     000028   000001CC                        DC     XL4'000001CC'
ADCONS FOR PARAMETER LISTS
                     000074   800000B0                        DC     XL4'800000B0'                  RMEU1
                     000078   000000E8                        DC     XL4'000000E8'                 EPSLON
                     00007C   800000A0                        DC     XL4'800000A0'                   ABSF
TEMPORARIES AND GENERATED CONSTANTS
                     0000D4   00000000                        DC     XL4'00000000'
                     0000D8   00000000                        DC     XL4'00000000'
                     0000DC   00000004                        DC     XL4'00000004'
                     0000E0   00000000                        DC     XL4'00000000'
                     0000E4   00000000                        DC     XL4'00000000'
                     0000E8   00000000                        DC     XL4'00000000'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =       22, PROGRAM SIZE =       556, SUBPROGRAM NAME =CONMEU
_______________________________________________________________________________________________________
*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                          316K BYTES OF CORE NOT USED
```

```
*LEVEL 2.3.0 (JUNE 78)                    OS/360  FORTRAN H EXTENDED             DATE 81.153/21.05.20        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

   ISN 0002                SUBROUTINE CODER(RDATA,EPSLON,XMAX,ICODE,NUM)                          00001210
                 C                                                                                00001220
                 C          RDATA(I)      :      INPUT  ARRAY                                     00001230
                 C          EPSLON        :      THRESHOLD LEVEL                                  00001240
                 C          XMAX          :      MAXIMUM INPUT VALUE                              00001250
                 C          ICODE         :      OUTPUT ARRAY                                     00001260
                 C          NUM           :      NUMBER OF DATA IN THE INPUT ARRAY                00001270
                 C          IULVL         :      UPPER LEVEL LIMIT                                00001280
                 C          ILLVL         :      LOWER LEVEL LIMIT                                00001290
                 C                                                                                00001300
   ISN 0003                DIMENSION RDATA(1), ICODE(1)                                           00001310
   ISN 0004                DELTA=XMAX/64.0                                                        00001320
   ISN 0005                IULVL=63                                                               00001330
   ISN 0006                ILLVL=-64                                                              00001340
                 C                                                                                00001350
   ISN 0007                I=0                                                                    00001360
   ISN 0008                DO 10 J=1,NUM                                                          00001370
   ISN 0009                I=I+1                                                                  00001380
   ISN 0010                IF(RDATA(J).LT.0.0) GO TO 15                                           00001390
   ISN 0012                CODE=RDATA(I)/DELTA                                                    00001400
   ISN 0013                ICODE(I)=INT(CODE)                                                     00001410
   ISN 0014                GO TO 20                                                               00001420
   ISN 0015             15 CODE=RDATA(I)/DELTA-1.0                                                00001430
   ISN 0016                ICODE(I)=INT(CODE)                                                     00001440
   ISN 0017             20 IF(ICODE(I). GT. IULVL) ICODE(I)=IULVL                                 00001450
   ISN 0019                IF(ICODE(I) .LT.ILLVL) ICODE(I)=ILLVL                                  00001460
   ISN 0021             10 CONTINUE                                                               00001470
   ISN 0022                RETURN                                                                 00001480
   ISN 0023                END                                                                    00001490

                          *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
I        0007  0009  0009  0012  0013  0015  0016  0017  0017  0019  0019
J        0008  0010
INT      0013  0016
NUM      0002  0008
CODE     0012  0013  0015  0016
XMAX     0002  0004
CODER    0002
DELTA    0004  0012  0015
ICODE    0002  0003  0013  0016  0017  0017  0019  0019
ILLVL    0006  0019  0019
IULVL    0005  0017  0017
RDATA    0002  0003  0010  0012  0015
EPSLON   0002

                          *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
 LABEL    DEFINED    REFERENCES
   10      0021       0008
   15      0015       0010
   20      0017       0014
```

```
                000000  47 F0 F 00C         CODER     BC      15,12(0,15)
                000004  07                            DC      XL1'07'
                000005  C3D6C4C5D94040                DC      CL7'CODER  '
                00000C  90 EC D 00C                   STM     14,12,12(13)
                000010  18 4D                         LR      4,13
                000012  98 CD F 020                   LM      12,13,32(15)
                000016  50 40 D 004                   ST      4,4(0,13)
                00001A  50 D0 4 008                   ST      13,8(0,4)
                00001E  07 FC                         BCR     15,12

TEMPORARY FOR FIX/FLOAT
                000078  00000000                      DC      XL4'00000000'
                00007C  00000000                      DC      XL4'00000000'
CONSTANTS
                000080  4E000000                      DC      XL4'4E000000'
                000084  00000000                      DC      XL4'00000000'
                000088  00000000                      DC      XL4'00000000'
                00008C  00000000                      DC      XL4'00000000'
                000090  00000001                      DC      XL4'00000001'
                000094  0000003F                      DC      XL4'0000003F'
                000098  00000040                      DC      XL4'00000040'
                00009C  41100000                      DC      XL4'41100000'
                0000A0  42400000                      DC      XL4'42400000'
                0000A4  00000000                      DC      XL4'00000000'
                0000A8  00000000                      DC      XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                0000E0  00000000                      DC      XL4'00000000'                    ICODE
                0000E8  00000000                      DC      XL4'00000000'                    DDATA
                000108  58 60 D 0C0         100001    L        6, 192( 0,13)
                00010C  58 90 D 0B8                   L        9, 184( 0,13)
                000110  78 60 D 094                   LE       6, 148( 0,13)                   XMAX
                000114  58 B0 D 060                   L       11,  96( 0,13)                   0
                000118  58 A0 D 0CC                   L       10, 204( 0,13)                   4
                00011C  38 46                         LER      4, 6
                00011E  7D 40 D 078                   DE       4, 120( 0,13)            42400000
                000122  58 00 D 06C                   L        0, 108( 0,13)                   63
                000126  50 00 D 0A4                   ST       0, 164( 0,13)               IULVL
                00012A  58 00 D 070                   L        0, 112( 0,13)                   64
                00012E  13 00                         LCR      0, 0
                000130  50 00 D 0A0                   ST       0, 160( 0,13)               ILLVL
                000134  58 20 D 08C                   L        2, 140( 0,13)                 NUM
                000138  89 20 0 002                   SLL      2,    2
                00013C  18 4B                         LR       4,11
                00013E  18 5B                         LR       5,11
                000140  18 7A                         LR       7,10
                000142  18 8B                         LR       8,11
                000144  18 B2                         LR      11, 2
                000146  1A 8A               100002    AR       8,10
                000148  1A 4A                         AR       4,10
                00014A  1A 5A                         AR       5,10
                00014C  78 07 6 000                   LE       0,    0( 7, 6)              FDATA
                000150  32 00                         LTER     0, 0
                000152  47 50 D 14C                   BC       5, 332( 0,13)                  15
                000156  78 65 6 000         100003    LE       6,    0( 5, 6)              FDATA
                00015A  3D 64                         DER      6, 4
                00015C  2B 00                         SDR      0, 0
```

```
        00015E  38 06                         LER    0,6
        000160  6A 00 D 058                   AD     0, 88( 0,13)          4F08000000000000
        000164  60 00 D 050                   STD    0, 80( 0,13)
        000168  58 20 D 054                   L      2, 84( 0,13)
        00016C  50 25 9 000                   ST     2,  0( 5, 9)                      ICODE
        000170  47 F0 D 16C                   BC     15,364( 0,13)                        20
        000174  78 24 6 000              15   LE     2,  0( 4, 6)                      RDATA
        000178  30 24                         CER    2,4
        00017A  38 62                         LER    6,2
        00017C  7B 60 D 074                   SE     6,116( 0,13)                   41100000
        000180  2B 00                         SDR    0,0
        000182  38 06                         LER    0,6
        000184  6A 00 D 058                   AD     0, 88( 0,13)          4F08000000000000
        000188  60 00 D 050                   STD    0, 80( 0,13)
        00018C  58 20 D 054                   L      2, 84( 0,13)
        000190  50 24 9 000                   ST     2,  0( 4, 9)                      ICODE
        000194  58 08 9 000              20   L      0,  0( 8, 9)                      ICODE
        000198  59 00 D 0A4                   C      0,164( 0,13)                      IULVL
        00019C  47 C0 D 180                   BC     12,384( 0,13)                    100005
        0001A0  58 00 D 0A4          100004   L      0,164( 0,13)                      IULVL
        0001A4  50 08 9 000                   ST     0,  0( 8, 9)                      ICODE
        0001A8  58 08 9 000          100005   L      0,  0( 8, 9)                      ICODE
        0001AC  59 00 D 0A0                   C      0,160( 0,13)                      ILLVL
        0001B0  47 A0 D 194                   BC     10,404( 0,13)                        10
        0001B4  58 00 D 0A0          100006   L      0,160( 0,13)                      ILLVL
        0001B8  50 08 9 000                   ST     0,  0( 8, 9)                      ICODE
        0001BC  87 7A D 11E              10   BXLE   7,10, 286(13)                    100002
        0001C0  78 60 D 094          100007   LE     6,148( 0,13)                       XMAX
        0001C4  58 B0 D 060                   L      11, 96( 0,13)                         C
        0001C8  1B FF                         SR     15,15
        0001CA  58 E0 D 000                   L      14,  0( 0,13)
        0001CE  07 FE                         BCR    15,14
ADDRESS OF EPILOGUE
        0001D0  58 D0 D 004                   L      13,  4( 0,13)
        0001D4  58 E0 D 00C                   L      14, 12( 0,13)
        0001D8  92 FF D 00C                   MVI     12(13),255
        0001DC  98 2C D 01C                   LM     2,12,  28(13)
        0001E0  07 FE                         BCR    15,14
ADDRESS OF PROLOGUE
        0001E2  98 7A 1 004                   LM     7,10,   4( 1)
        0001E6  78 20 7 000                   LE     2,  0( 0, 7)
        0001EA  70 20 D 0A8                   STE    2,168( 0,13)                     EPSLON
        0001EE  78 20 8 000                   LE     2,  0( 0, 8)
        0001F2  70 20 D 094                   STE    2,148( 0,13)                       XMAX
        0001F6  58 20 A 000                   L      2,  0( 0,10)
        0001FA  50 20 D 08C                   ST     2,140( 0,13)                        NUM
        0001FE  58 20 1 000                   L      2,  0( 0, 1)
        000202  41 30 2 000                   LA     3,  0( 0, 2)
        000206  41 50 0 004                   LA     5,  4
        00020A  1B 25                         SR     2,5
        00020C  50 20 D 0C0                   ST     2,192( 0,13)
        000210  50 30 D 0C4                   ST     3,196( 0,13)                      RDATA
        000214  58 20 1 00C                   L      2, 12( 0, 1)
        000218  41 30 2 000                   LA     3,  0( 0, 2)
        00021C  41 50 0 004                   LA     5,  4
        000220  1B 25                         SR     2,5
        000222  50 20 D 0B8                   ST     2,184( 0,13)
        000226  50 30 D 0BC                   ST     3,188( 0,13)                      ICODE
```

```
*LEVEL 2.3.0 (JUNE 78)                 OS/360  FORTRAN H  EXTENDED          DATE 81.153/21.05.20       PAGE   4
                000022A  47 F0 C 0E0                        BC      15, 224( 0,12)
ADCON FOR PROLOGUE
                000020   000001F2                           DC      XL4'000001F2'
ADCON FOR SAVE AREA
                000024   00000028                           DC      XL4'00000028'
ADCON FOR EPILOGUE
                000028   000001D0                           DC      XL4'000001D0'
TEMPORARIES AND GENERATED CONSTANTS
                0000F0   00000000                           DC      XL4'00000000'
                0000F4   00000004                           DC      XL4'00000004'
                0000F8   00000000                           DC      XL4'00000000'
                0000FC   00000000                           DC      XL4'00000000'
                000100   00000000                           DC      XL4'00000000'
                000104   00000000                           DC      XL4'00000000'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =      22, PROGRAM SIZE =      558, SUBPROGRAM NAME = CODER

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                        216K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
```

```
*LEVEL 2.3.0 (JUNE 78)                 OS/360  FORTRAN H EXTENDED              DATE 81.153/21.05.49        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

  ISN 0002              SUBROUTINE DECODE(ICODE,MAPPER,DELTA,RDATA,NUM)                  00000280
                 C      VARIABLE DESCRIPTION                                              00000290
                 C      ICODE   :   ENCODED DCT TRANSFORM COEF. OF SEISMIC DATA           00000300
                 C      MAPPER  :   COMPRESSION FLAG                                      00000310
                 C      DELTA   :   STEP SIZE                                             00000320
                 C      RDATA   :   DECODED DATA ARRAY                                    00000330
                 C                                                                        00000340
  ISN 0003              DIMENSION ICODE(1),MAPPER(1),RDATA(1)                             00000350
  ISN 0004              DO 10 I=1,NUM                                                     00000360
  ISN 0005              RDATA(I)=0.0                                                      00000370
  ISN 0006              IF (MAPPER(I) .EQ. 0) GO TO 10                                    00000380
  ISN 0008              CODE=ICODE(I)                                                     00000390
  ISN 0009              RDATA(I)=DELTA*CODE                                               00000400
  ISN 0010          10  CONTINUE                                                          00000410
  ISN 0011              RETURN                                                            00000420
  ISN 0012              END                                                               00000430

                      *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
I        0004  0005  0006  0008  0009
NUM      0002  0004
CODE     0008  0009
DELTA    0002  0009
ICODE    0002  0003  0008
RDATA    0002  0003  0005  0009
DECODE   0002
MAPPER   0002  0003  0006

                      *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
 LABEL    DEFINED     REFERENCES
   10     0010        0004  0006

                      000000  47 F0 F 00C          DECODE      BC      15,12(0,15)
                      000004  07                               DC      XL1'07'
                      000005  C4C5C3D6C4C540                   DC      CL7'DECODE '
                      00000C  90 EC D 00C                      STM     14,12,12(13)
                      000010  18 4D                            LR      4,13
                      000012  98 CD F 020                      LM      12,13,32(15)
                      000016  50 40 D 004                      ST      4,4(0,13)
                      00001A  50 D0 4 008                      ST      13,8(0,4)
                      00001E  07 FC                            BCR     15,12

TEMPORARY FOR FIX/FLOAT
                      000078  4E000000                         DC      XL4'4E000000'
                      00007C  00000000                         DC      XL4'00000000'
CONSTANTS
                      000080  4E000000                         DC      XL4'4E000000'
                      000084  80000000                         DC      XL4'80000000'
                      000088  00000000                         DC      XL4'00000000'
                      00008C  00000000                         DC      XL4'00000000'
```

```
              000090  00000001                     DC    XL4'00000001'
              000094  00000000                     DC    XL4'00000000'
              000098  00000000                     DC    XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
              0000B8  00000000                     DC    XL4'00000000'                ICODE
              0000C0  00000000                     DC    XL4'00000000'                RDATA
              0000C8  00000000                     DC    XL4'00000000'                MAFFER
              0000DC  58 60 D 0A0          100001  L      6, 160( 0,13)
              0000E0  58 70 D 090                  L      7, 144( 0,13)
              0000E4  58 80 D 098                  L      8, 152( 0,13)
              0000E8  78 40 D 080                  LE     4, 128( 0,13)               DELTA
              0000EC  58 A0 D 0AC                  L     10, 172( 0,13)                   4
              0000F0  58 50 D 078                  L      5, 120( 0,13)                 NUM
              0000F4  18 B5                        LR    11, 5
              0000F6  89 B0 0 002                  SLL   11,   2
              0000FA  18 9A                        LR     9,10
              0000FC  78 00 D 064          100002  LE     0, 100( 0,13)                   0
              000100  70 09 B 000                  STE    0,   0( 9,11)               RDATA
              000104  58 09 6 000                  L      0,   0( 9, 6)              MAFFER
              000108  12 00                        LTR    0, 0
              00010A  47 E0 D 102                  BC    14, 258( 0,13)                  10
              00010E  58 09 7 000          100003  L      0,   0( 9, 7)               ICODE
              000112  57 00 D 05C                  X      0,  92( 0,13)    4E00000080000000
              000116  50 00 D 054                  ST     0,  84( 0,13)
              00011A  68 60 D 050                  LD     6,  80( 0,13)
              00011E  6B 60 D 058                  SD     6,  88( 0,13)    4E00000000000000
              000122  38 26                        LER    2, 6
              000124  3C 24                        MER    2, 4
              000126  70 29 8 000                  STE    2,   0( 9, 8)               FDATA
              00012A  87 9A D 0D4              10  BXLE   9,10, 212(13)              100002
              00012E  18 FF                100004  SR    15,15
              000130  58 E0 D 000                  L     14,   0( 0,13)
              000134  07 FE                        BCR   15,14
ADDRESS OF EPILOGUE
              000136  58 D0 D 004                  L     13,   4( 0,13)
              00013A  58 E0 D 00C                  L     14,  12( 0,13)
              00013E  92 FF D 00C                  MVI     12(13),255
              000142  98 2C D 01C                  LM     2,12,  28(13)
              000146  07 FE                        BCR   15,14
ADDRESS OF PROLOGUE
              000148  98 79 1 008                  LM     7, 9,   8( 1)
              00014C  78 20 7 000                  LE     2,   0( 0, 7)
              000150  70 20 D 080                  STE    2, 128( 0,13)               DELTA
              000154  58 20 9 000                  L      2,   0( 0, 9)
              000158  50 20 D 078                  ST     2, 120( 0,13)                 NUM
              00015C  58 20 1 000                  L      2,   0( 0, 1)
              000160  41 30 2 000                  LA     3,   0( 0, 2)
              000164  41 50 0 004                  LA     5,   4
              000168  1B 25                        SR     2, 5
              00016A  50 20 D 090                  ST     2, 144( 0,13)
              00016E  50 30 D 094                  ST     3, 148( 0,13)               ICODE
              000172  58 20 1 004                  L      2,   4( 0, 1)
              000176  41 30 2 000                  LA     3,   0( 0, 2)
              00017A  41 50 0 004                  LA     5,   4
              00017E  1B 25                        SR     2, 5
              000180  50 20 D 0A0                  ST     2, 160( 0,13)
              000184  50 30 D 0A4                  ST     3, 164( 0,13)              MAFFER
```

172

```
*LEVEL 2.3.0 (JUNE 78)                      OS/360  FORTRAN H EXTENDED              DATE 81.153/21.05.44        PAGE   2

                 000188   58 20 1 00C                          L        2,  12( 0, 1)
                 00018C   41 30 2 000                          LA       3,   0( 0, 2)
                 000190   41 50 0 004                          LA       5,   4
                 000194   1B 25                                SR       2, 5
                 000196   50 20 D 098                          ST       2, 152( 0,13)
                 00019A   50 30 D 09C                          ST       3, 156( 0,13)                    BDATA
                 00019E   47 F0 D 0B4                          BC      15, 180( 0,13)
ADCON FOR PROLOGUE
                 000020   00000148                             DC      XL4'00000148'
ADCON FOR SAVE AREA
                 000024   00000028                             DC      XL4'00000028'
ADCON FOR EPILOGUE
                 000028   00000136                             DC      XL4'00000136'
TEMPORARIES AND GENERATED CONSTANTS
                 000000   00000000                             DC      XL4'00000000'
                 000004   00000004                             DC      XL4'00000004'
                 000008   00000000                             DC      XL4'00000000'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =      11, PROGRAM SIZE =      416, SUBPROGRAM NAME =DECODE

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                       316K BYTES OF CORE NOT USED
```

```
*LEVEL 2.3.0 (JUNE 78)                    OS/360  FORTRAN H EXTENDED                 DATE 81.153/21.05.46        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

   ISN 0002                SUBROUTINE INVMEU(RDATA,NUM,XMAX,RMEU,EPSLON)                          00000440
                   C       MEU-LAW INVERTER                                                       00000450
                   C        RDATA      :   INPUT ARRAY OF MEU-LAW CONVERTED TRACE DATA            00000460
                   C        RMEU       :   MEU-VALUE SET AS 500                                   00000470
                   C        XMAX       :   ABSOLUTE MAXIMUM VALUE OF INPUT ARRAY                  00000480
                   C        NUM        :   NUMBER OF DATA POINTS TO BE INVERTED                   00000490
                   C        EPSLON     :   THRESHOLD VALUE FOR THE INSIGNIFICANT DCT COEF.        00000500
                   C                                                                              00000510
   ISN 0003                 DIMENSION RDATA(1)                                                    00000520
   ISN 0004                COEF=ALOG(RMEU+1)/XMAX                                                 00000530
   ISN 0005                COEF1=XMAX/RMEU                                                        00000540
   ISN 0006                DO 10 I=1,NUM                                                          00000550
                   C        IGNORE COMPRESSED VALUE                                               00000560
   ISN 0007                IF(RDATA(I) .EQ. 0.0) GO TO 10                                         00000570
   ISN 0009                RVAL=RDATA(I)*COEF                                                     00000580
   ISN 0010                SIGN=1.0                                                               00000590
   ISN 0011                IF(RVAL .LT. 0.0) SIGN=-1.0                                            00000600
   ISN 0013                RVAL=ABS(RVAL)                                                         00000610
   ISN 0014                RVAL=EXP(RVAL)                                                         00000620
   ISN 0015                RVAL=RVAL - 1.0                                                        00000630
   ISN 0016                RVAL=RVAL*COEF1                                                        00000640
   ISN 0017                RDATA(I)=RVAL*SIGN                                                     00000650
   ISN 0018                IF(RDATA(I) .LT. 0.0) RDATA(I)=RDATA(I)-EPSLON                         00000660
   ISN 0020                IF(RDATA(I) .GE. 0.0) RDATA(I)=RDATA(I)+EPSLON                         00000670
   ISN 0022          10    CONTINUE                                                               00000680
   ISN 0023                RETURN                                                                 00000690
   ISN 0024                END                                                                    00000700

                           *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
I        0006  0007  0009  0017  0018  0018  0018  0020  0020  0020
ABS      0013
EXP      0014
NUM      0002  0006
ALOG     0004
COEF     0004  0009
RMEU     0002  0004  0005
RVAL     0009  0011  0013  0013  0014  0014  0015  0015  0016  0016  0017
SIGN     0010  0011  0017
XMAX     0002  0004  0005
COEF1    0005  0016
EPSON    0002
RDATA    0002  0003  0007  0009  0017  0018  0018  0018  0020  0020  0020
EPSLON   0018  0020
INVMEU   0002

                           *****F O R T R A N    C R O S S    R E F E R E N C E    L I S T I N G*****
 LABEL    DEFINED    REFERENCES
   10     0022       0006  0007
```

```
          000000  47 F0 F 00C             INVMEU     BC     15,12(0,15)
          000004  07                                 DC     XL1'07'
          000005  C9D5E5D4C5E440                     DC     CL7'INVMEU '
          00000C  90 EC D 00C                        STM    14,12,12(13)
          000010  18 4D                              LR     4,13
          000012  98 CD F 020                        LM     12,13,32(15)
          000016  50 40 D 004                        ST     4,4(0,13)
          00001A  50 D0 4 008                        ST     13,8(0,4)
          00001E  07 FC                              BCR    15,12

CONSTANTS
          000080  00000000                           DC     XL4'00000000'
          000084  00000001                           DC     XL4'00000001'
          000088  41100000                           DC     XL4'41100000'
          00008C  00000000                           DC     XL4'00000000'
          000090  00000000                           DC     XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
          0000C8  00000000                           DC     XL4'00000000'                 EXP
          0000CC  00000000                           DC     XL4'00000000'                 ALOG
          0000D0  00000000                           DC     XL4'00000000'                 RDATA
          0000F8  58 80 D 0A8             100001     L      8, 168( 0,13)
          0000FC  58 A0 D 0C0                        L      10, 192( 0,13)                N
          000100  58 70 D 070                        L      7, 112( 0,13)                 NUM
          000104  78 00 D 060                        LE     0,  96( 0,13)                 41100000
          000108  7A 00 D 078                        AE     0, 120( 0,13)                 DMEU
          00010C  70 00 D 0C8                        STE    0, 200( 0,13)                 .T00
          000110  58 F0 D 0A4                        L      15, 164( 0,13)                ALOG
          000114  41 10 D 04C                        LA     1,  76( 0,13)
          000118  05 EF                              BALR   14,15
          00011A  47 00 0 004                        BC     0,   4( 0, 0)
          00011E  7D 00 D 0E4                        DE     0, 132( 0,13)                 XMAX
          000122  70 00 D 074                        STE    0, 116( 0,13)                 COEF
          000126  78 00 D 0E4                        LE     0, 132( 0,13)                 XMAX
          00012A  7D 00 D 078                        DE     0, 120( 0,13)                 EMEU
          00012E  70 00 D 088                        STE    0, 136( 0,13)                 COEF1
          000132  78 00 D 060                        LE     0,  96( 0,13)                 41100000
          000136  33 00                              LCER   0, 0
          000138  70 00 D 0BC                        STE    0, 188( 0,13)                 .C04
          00013C  18 B7                              LR     11, 7
          00013E  89 B0 0 002                        SLL    11,   2
          000142  18 5A                              LR     5,10
          000144  78 29 8 000             100002     LE     2,   0( 9, 8)                 FDATA
          000148  70 20 D 0B0                        STE    2, 176( 0,13)                 .C01
          00014C  32 22                              LTER   2, 2
          00014E  47 80 D 19A                        BC     8, 410( 0,13)                 10
          000152  7C 20 D 074             100003     ME     2, 116( 0,13)                 COEF
          000156  70 20 D 07C                        STE    2, 124( 0,13)                 FVAL
          00015A  78 00 D 060                        LE     0,  96( 0,13)                 41100000
          00015E  70 00 D 080                        STE    0, 128( 0,13)                 SIGN
          000162  32 22                              LTER   2, 2
          000164  47 A0 D 148                        BC     10, 328( 0,13)                100005
          000168  78 00 D 0BC             100004     LE     0, 188( 0,13)                 .C04
          00016C  70 00 D 080                        STE    0, 128( 0,13)                 SIGN
          000170  78 00 D 07C             100005     LE     0, 124( 0,13)                 FVAL
          000174  30 00                              LPER   0, 0
          000176  70 00 D 07C                        STE    0, 124( 0,13)                 FVAL
          00017A  58 F0 D 0A0                        L      15, 160( 0,13)                EXP
```

```
            00017E   41 10 D 050                  LA     1,  80( 0,13)
            000182   05 EF                        BALR   14,15
            000184   47 00 0 00E                  BC     0,  14( 0, 0)
            000188   38 20                        LER    2, 0
            00018A   7B 20 D 060                  SE     2,  96( 0,13)                 41100000
            00018E   7C 20 D 088                  ME     2, 136( 0,13)                    COEF1
            000192   7C 20 D 080                  ME     2, 128( 0,13)                     SIGN
            000196   70 29 8 000                  STE    2,   0( 9, 8)                    RDATA
            00019A   32 22                        LTER   2, 2
            00019C   47 A0 D 1B4                  BC     10, 308( 0,13)                  100007
            0001A0   78 29 8 000        100006    LE     2,   0( 9, 8)                    RDATA
            0001A4   7B 20 D 090                  SE     2, 144( 0,13)                   EPSLON
            0001A8   70 29 8 000                  STE    2,   0( 9, 8)                    RDATA
            0001AC   78 29 8 000        100007    LE     2,   0( 9, 8)                    RDATA
            0001B0   70 20 D 0B8                  STE    2, 184( 0,13)                     .C03
            0001B4   32 22                        LTER   2, 2
            0001B6   47 50 D 19A                  BC     5, 410( 0,13)                       10
            0001BA   7A 20 D 090        100008    AE     2, 144( 0,13)                   EPSLON
            0001BE   70 29 8 000                  STE    2,   0( 9, 8)                    RDATA
            0001C2   87 9A D 11C            10    BXLE   9,10, 284(13)                   100002
            0001C6   1E FF              100009    SR     15,15
            0001C8   58 E0 D 000                  L      14,   0( 0,13)
            0001CC   07 FE                        BCR    15,14
ADDRESS OF EPILOGUE
            0001CE   58 A0 D 004                  L      10,   4( 0,13)
            0001D2   58 E0 A 00C                  L      14,  12( 0,10)
            0001D6   58 B0 A 018                  L      11,  24( 0,10)
            0001DA   58 10 B 00C                  L      1,  12( 0,11)
            0001DE   78 20 D 078                  LE     2, 120( 0,13)                     RMEL
            0001E2   70 20 1 000                  STE    2,   0( 0, 1)
            0001E6   18 DA                        LR     13,10
            0001E8   92 FF A 00C                  MVI     12(10),255
            0001EC   98 2C A 01C                  LM     2,12,  28(10)
            0001F0   07 FE                        BCR    15,14
ADDRESS OF PROLOGUE
            0001F2   98 7A 1 004                  LM     7,10,   4( 1)
            0001F6   58 20 7 000                  L      2,   0( 0, 7)
            0001FA   50 20 D 070                  ST     2, 112( 0,13)                      NUM
            0001FE   78 20 8 000                  LE     2,   0( 0, 8)
            000202   70 20 D 084                  STE    2, 132( 0,13)                     XMAX
            000206   78 20 9 000                  LE     2,   0( 0, 9)
            00020A   70 20 D 078                  STE    2, 120( 0,13)                     RMEL
            00020E   78 20 A 000                  LE     2,   0( 0,10)
            000212   70 20 D 08C                  STE    2, 140( 0,13)                    EPSON
            000216   58 20 1 000                  L      2,   0( 0, 1)
            00021A   41 30 2 000                  LA     3,   0( 0, 2)
            00021E   41 50 0 004                  LA     5,   4
            000222   1B 25                        SR     2, 5
            000224   50 20 D 0A8                  ST     2, 168( 0,13)
            000228   50 30 D 0AC                  ST     3, 172( 0,13)                    RDATA
            00022C   47 F0 D 0D0                  BC     15, 208( 0,13)
ADCON FOR PROLOGUE
            000020   000001F2                     DC     XL4'000001F2'
ADCON FOR SAVE AREA
            000024   00000028                     DC     XL4'00000028'
ADCON FOR EPILOGUE
            000028   000001CE                     DC     XL4'000001CE'
ADCONS FOR PARAMETER LISTS
```

```
                   000074  800000F0                     DC      XL4'E00000F0'                      .IOC
                   000078  800000A4                     DC      XL4'E00000A4'                      FVAL
TEMPORARIES AND GENERATED CONSTANTS
                   0000D8  00000000                     DC      XL4'00000000'
                   0000DC  00000000                     DC      XL4'00000000'
                   0000E0  00000000                     DC      XL4'00000000'
                   0000E4  00000000                     DC      XL4'00000000'
                   0000E8  00000004                     DC      XL4'00000004'
                   0000EC  00000000                     DC      XL4'00000000'
                   0000F0  00000000                     DC      XL4'00000000'
                   0000F4  00000000                     DC      XL4'00000000'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =      23, PROGRAM SIZE =      560, SUBPROGRAM NAME =INVMEU
________________________________________________________________________________________
*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                       316K BYTES OF CORE NOT USED
```

```
*LEVEL 2.3.0 (JUNE 78)                         OS/360  FORTRAN H EXTENDED                    DATE 81.153/21.05.48        PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

                  C
    ISN 0002            SUBROUTINE FIDCT(A,NUM)
                  C      INVERSE DCT USING FFTCC(IBM MATH PACKAGE)
                  C      NUM    :   NUMBER OF DATA POINTS
                  C      A      :   DATA TO BE TRANSFORMED
                  C      IWK    :   WORKING AREA OF FFTCC
                  C      WK     :   WORKING AREA OF FFTCC
                  C      X      :   INPUT AND OUTPUT ARRAY OF FFTCC
                  C
    ISN 0003            DIMENSION IWK(2600),WK(2600),A(1)
    ISN 0004            COMPLEX X(4750)
    ISN 0005            WRWP=3.141592/FLOAT(2*NUM)
    ISN 0006            DO 10 I=1,NUM
    ISN 0007            ARG=WRWP*FLOAT(I-1)
    ISN 0008            X(I)=CMPLX(A(I),0.0)*CMPLX(COS(ARG),SIN(ARG))
    ISN 0009         10 CONTINUE
    ISN 0010            CALL FFTCC(X,NUM,IWK,WK)
    ISN 0011            A(I)=REAL(X(I))
    ISN 0012         20 CONTINUE
    ISN 0013            RETURN
    ISN 0014            END

                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
A        0002  0003  0008  0011
I        0006  0007  0008  0008  0011  0011
X        0004  0008  0010  0011
WK       0003  0010
ARG      0007  0008  0008
COS      0008
IWK      0003  0010
NUM      0002  0005  0006  0010
SIN      0008
REAL     0011
WRWP     0005  0007
CMPLX    0008  0008
FFTCC    0010
FIDCT    0002
FLOAT    0005  0007

                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
 LABEL    DEFINED   REFERENCES
   10      0009      0006
   20      0012

                 000000  47 F0 F 00C          FIDCT      BC    15,12(0,15)
                 000004  07                              DC    XL1'07'
                 000005  C6C9C4C3E34040                  DC    CL7'FIDCT  '
                 00000C  90 EC D 00C                     STM   14,12,12(13)
                 000010  18 4D                           LR    4,13
```

```
              000012  98 CD F 020                   LM     12,13,32(15)
              000016  50 40 D 004                   ST     4,4(0,13)
              00001A  50 D0 4 008                   ST     13,8(0,4)
              00001E  07 FC                         BCR    15,12

TEMPORARY FOR FIX/FLOAT
              000090  4E000000                      DC     XL4'4E000000'
              000094  00000000                      DC     XL4'00000000'
CONSTANTS
              000098  4E000000                      DC     XL4'4E000000'
              00009C  80000000                      DC     XL4'80000000'
              0000A0  00000000                      DC     XL4'00000000'
              0000A4  00000001                      DC     XL4'00000001'
              0000A8  00000002                      DC     XL4'00000002'
              0000AC  413243F6                      DC     XL4'413243F6'
              0000B0  00000000                      DC     XL4'00000000'
              0000B4  000000C0                      DC     XL4'000000C0'
ADCONS FOR VARIABLES AND CONSTANTS
              00E680  00002568                      DC     XL4'00002568'
              00E684  00005208                      DC     XL4'00005208'
ADCONS FOR EXTERNAL REFERENCES
              00E688  00000000                      DC     XL4'00000000'                                 A
              00E690  00000000                      DC     XL4'00000000'                               COS
              00E694  00000000                      DC     XL4'00000000'                               SIN
              00E698  00000000                      DC     XL4'00000000'                             FFTCC
              00E69C  00000000                      DC     XL4'00000000'                             CHFY#
              00E6D4  58 50 C 008          100001   L       5,   8( 0,12)
              00E6D8  58 60 C 004                   L       6,   4( 0,12)
              00E6DC  58 B0 C 000                   L      11,   0( 0,12)
              00E6E0  58 A0 D 07C                   L      10, 124( 0,13)                                I
              00E6E4  58 40 C 024                   L       4,  36( 0,12)                                E
              00E6E8  58 30 C 02C                   L       3,  44( 0,12)                                4
              00E6EC  58 20 D 098                   L       2, 152( 0,13)                              NUM
              00E6F0  89 20 0 001                   SLL     2,   1
              00E6F4  18 02                         LR      0,  2
              00E6F6  57 00 D 074                   X       0, 116( 0,13)                4E00000080000000
              00E6FA  50 00 D 06C                   ST      0, 108( 0,13)
              00E6FE  68 20 D 068                   LD      2, 104( 0,13)
              00E702  6B 20 D 070                   SD      2, 112( 0,13)                4E00000080000000
              00E706  78 00 D 084                   LE      0, 132( 0,13)                        413243F6
              00E70A  3D 02                         DER     0,  2
              00E70C  70 00 D 09C                   STE     0, 156( 0,13)                            WFWF
              00E710  19 2A                         LR      2,10
              00E712  50 A0 D 090                   ST     10, 144( 0,13)                                I
              00E716  78 00 D 078                   LE      0, 120( 0,13)                                0
              00E71A  70 00 C 020                   STE     0,  32( 0,12)                             .C01
              00E71E  50 40 C 028                   ST      4,  40( 0,12)                             .C02
              00E722  50 30 C 030                   ST      3,  48( 0,12)                             .C03
              00E726  58 70 C 030                   L       7,  48( 0,12)                             .C03
              00E72A  58 80 C 028                   L       8,  40( 0,12)                             .C02
              00E72E  18 92                         LR      9,  2
              00E730  58 B0 D 098                   L      11, 152( 0,13)                              NUM
              00E734  18 29                100002   LR      2,  9
              00E736  1B 2A                         SR      2,10
              00E738  18 02                         LR      0,  2
              00E73A  57 00 D 074                   X       0, 116( 0,13)                4E00000080000000
              00E73E  50 00 D 06C                   ST      0, 108( 0,13)
              00E742  68 20 D 068                   LD      2, 104( 0,13)
```

```
            00E746   6B 20 D 070                   SD     2, 112( 0,13)               4E00000080000000
            00E74A   7C 20 D 09C                   ME     2, 156( 0,13)                           MRMF
            00E74E   70 20 D 094                   STE    2, 148( 0,13)                            ARG
            00E752   78 27 5 000                   LE     2,   0( 7, 5)                              A
            00E756   70 20 C 038                   STE    2,  56( 0,12)                           .T01
            00E75A   58 F0 C 010                   L     15,  16( 0,12)                            COS
            00E75E   41 10 D 04C                   LA     1,  76( 0,13)
            00E762   05 EF                         BALR  14,15
            00E764   47 00 0 008                   BC     0,   8( 0, 0)
            00E768   70 00 C 034                   STE    0,  52( 0,12)                           .T00
            00E76C   58 F0 C 014                   L     15,  20( 0,12)                            SIN
            00E770   41 10 D 04C                   LA     1,  76( 0,13)
            00E774   05 EF                         BALR  14,15
            00E776   47 00 0 008                   BC     0,   8( 0, 0)
            00E77A   70 00 C 040                   STE    0,  64( 0,12)                           .T03
            00E77E   78 00 C 034                   LE     0,  52( 0,12)                           .T00
            00E782   70 00 C 048                   STE    0,  72( 0,12)                           .T05
            00E786   78 00 C 040                   LE     0,  64( 0,12)                           .T03
            00E78A   70 00 C 04C                   STE    0,  76( 0,12)                           .T06
            00E78E   78 00 C 020                   LE     0,  32( 0,12)                           .C01
            00E792   70 00 C 03C                   STE    0,  60( 0,12)                           .T02
            00E796   58 F0 C 01C                   L     15,  28( 0,12)                          CMPY#
            00E79A   41 10 D 050                   LA     1,  80( 0,13)
            00E79E   05 EF                         BALR  14,15
            00E7A0   47 00 0 008                   BC     0,   8( 0, 0)
            00E7A4   70 00 C 034                   STE    0,  52( 0,12)                           .T00
            00E7A8   70 28 6 004                   STE    2,   4( 8, 6)                              X
            00E7AC   78 00 C 034                   LE     0,  52( 0,12)                           .T00
            00E7B0   70 08 6 000                   STE    0,   0( 8, 6)                              X
            00E7B4   1A 73                   10    AR     7, 3
            00E7B6   1A 84                         AR     8, 4
            00E7B8   87 9A C 0B4                   BXLE   9,10, 180(12)                         100002
            00E7BC   50 90 D 090                   ST     9, 144( 0,13)                              I
            00E7C0   58 B0 C 000             100003 L    11,   0( 0,12)
            00E7C4   58 F0 C 018                   L     15,  24( 0,12)                          FFTCC
            00E7C8   41 10 D 058                   LA     1,  88( 0,13)
            00E7CC   05 EF                         BALR  14,15
            00E7CE   47 00 0 00A                   BC     0,  10( 0, 0)
            00E7D2   58 20 D 090                   L      2, 144( 0,13)                              I
            00E7D6   89 20 0 003                   SLL    2,   3
            00E7DA   78 22 6 000                   LE     2,   0( 2, 6)                              X
            00E7DE   78 02 6 004                   LE     0,   4( 2, 6)                              X
            00E7E2   58 20 D 090                   L      2, 144( 0,13)                              I
            00E7E6   89 20 0 002                   SLL    2,   2
            00E7EA   70 22 5 000                   STE    2,   0( 2, 5)                              /
            00E7EE   1B FF                   20    SR    15,15
            00E7F0   58 E0 D 000                   L     14,   0( 0,13)
            00E7F4   07 FE                         BCR   15,14
ADDRESS OF EPILOGUE
            00E7F6   58 A0 D 004                   L     10,   4( 0,13)
            00E7FA   58 E0 A 00C                   L     14,  12( 0,10)
            00E7FE   58 B0 A 018                   L     11,  24( 0,10)
            00E802   58 10 D 004                   L      1,   4( 0,11)
            00E806   58 20 D 098                   L      2, 152( 0,13)                            NLK
            00E80A   50 20 1 000                   ST     2,   0( 0, 1)
            00E80E   18 DA                         LR    13,10
            00E810   92 FF A 00C                   MVI    12(10),255
            00E814   98 2C A 01C                   LM     2,12,  28(10)
```

```
                    00E818   07 FE                        BCR     15,14
ADDRESS OF PROLOGUE
                    00E81A   58 C0 D 048                  L       12,  72( 0,13)
                    00E81E   58 70 1 004                  L        7,   4( 0, 1)
                    00E822   58 20 7 000                  L        2,   0( 0, 7)
                    00E826   50 20 D 098                  ST       2, 152( 0,13)              NUM
                    00E82A   58 20 1 000                  L        2,   0( 0, 1)
                    00E82E   41 30 2 000                  LA       3,   0( 0, 2)
                    00E832   41 50 0 004                  LA       5,   4
                    00E836   1B 25                        SR       2, 5
                    00E838   50 20 C 008                  ST       2,   8( 0,12)
                    00E83C   50 30 C 00C                  ST       3,  12( 0,12)              A
                    00E840   47 F0 C 054                  BC      15,  84( 0,12)
ADCON FOR PROLOGUE
                    000020   0000E81A                     DC      XL4'0000E81A'
ADCON FOR SAVE AREA
                    000024   00000028                     DC      XL4'00000028'
ADCON FOR EPILOGUE
                    000028   0000E7F6                     DC      XL4'0000E7F6'
ADCON FOR REG 12
                    000070   0000E6B0                     DC      XL4'0000E6B0'
ADCONS FOR PARAMETER LISTS
                    000074   800000EC                     DC      XL4'800000EC'               ARG
                    000078   0000E6B8                     DC      XL4'0000E6B8'              .T01
                    00007C   8000E6C8                     DC      XL4'8000E6C8'              .T05
                    000080   00005210                     DC      XL4'00005210'                 X
                    000084   000000C0                     DC      XL4'000000C0'               NUM
                    000088   0000296C                     DC      XL4'0000296C'               IWK
                    00008C   800000CC                     DC      XL4'800000CC'                WK
TEMPORARIES AND GENERATED CONSTANTS
                    00E6A0   00000000                     DC      XL4'00000000'
                    00E6A4   00000008                     DC      XL4'00000008'
                    00E6A8   00000000                     DC      XL4'00000000'
                    00E6AC   00000004                     DC      XL4'00000004'
                    00E6B0   00000000                     DC      XL4'00000000'
                    00E6B4   00000000                     DC      XL4'00000000'
                    00E6B8   00000000                     DC      XL4'00000000'
                    00E6BC   00000000                     DC      XL4'00000000'
                    00E6C0   00000000                     DC      XL4'00000000'
                    00E6C4   00080005                     DC      XL4'00080005'
                    00E6C8   00580005                     DC      XL4'00580005'
                    00E6CC   00000000                     DC      XL4'00000000'
                    00E6D0   00000006                     DC      XL4'00000006'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*      SOURCE STATEMENTS =       13, PROGRAM SIZE =     59600, SUBPROGRAM NAME = FIDCT
_____________________________________________________________________________________________________

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                           216K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
```

```
LEVEL 2.3.0 (JUNE 78)                      OS/360  FORTRAN H EXTENDED                DATE 81.155/14.58.30         PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

              C                                                                              00001720
              C                                                                              00001730
              C                                                                              00001740
  ISN 0002                  SUBROUTINE AUTC(N,X,MM,R,A,ALPHA,RC)                              00001750
              C                                                                              00001760
              C             THIS PROGRAM CALCULATES THE FILTER COEFFICIENTS FOR              00001770
              C             A LINEAR PREDICTOR OF ORDER 'MM'.  THE REFLECTION COEFFICIENTS00001780
              C             ARE SAVED FOR A LATTICE IMPLEMENTATION OF THE INVERSE FILTER. 00001790
              C             THIS ROUTINE IS GIVEN BY MARKEL AND GRAY (LINEAR PREDICTION OF00001800
              C             SPEECH).                                                         00001810
              C                                                                              00001820
              C                                                                              00001830
              C             N - NO. OF POINTS                                                00001840
              C             X - VECTOR OF SAMPLED SPEECH PTS                                 00001850
              C             M - ORDER OF INVERS FILTER                                       00001860
              C             A - VECTOR OF INVERSE FILTER COEFFICIENTS                        00001870
              C             ALPHA - VECTOR OF CROSS CORRELATION COEFFICIENTS                 00001880
              C             RC - VECTOR OF REFLECTION COEFFICIENTS                           00001890
              C             R - AUTOCORRELATION COEFFICIENTS                                 00001900
              C             ARRAY - VECTOR TO HOUSE ALL COEFFICIENTS CALCULATED              00001910
              C                                                                              00001920
              C                                                                              00001930
  ISN 0003                  INTEGER WNDOWF,AUTOF,LF                                          00001940
  ISN 0004                  DATA LP/6/,WNDOWF/8/,AUTOF/9/                                    00001950
  ISN 0005                  DIMENSION  R(20),IX(256),X(256),A(20),ALPHA(20),RC(20),          00001960
                   $             ARRAY(44)                                                   00001970
  ISN 0006                  M=MM                                                             00001980
  ISN 0007       11         MP = M + 1                                                       00001990
              C                                                                              00002000
  ISN 0008                  DO 15 K = 1,MP                                                   00002010
              C                                                                              00002020
  ISN 0009                       R(K) = 0.0                                                  00002030
  ISN 0010                       L = N - K + 1                                               00002040
              C                                                                              00002050
  ISN 0011                       DO 10 NP = 1,L                                              00002060
  ISN 0012                            NPK =NP+K-1                                            00002070
  ISN 0013                            R(K) = R(K)+X(NP)*X(NPK)                               00002080
  ISN 0014       10              CONTINUE                                                    00002090
              C                                                                              00002100
  ISN 0015       15         CONTINUE                                                         00002110
              C                                                                              00002120
  ISN 0016                  A(1) = 1.                                                        00002130
  ISN 0017                  ALPHA(1) = R(1)                                                  00002140
  ISN 0018                  IF(M.EQ.0) GO TO 60                                              00002150
  ISN 0020                  RC(1) = -R(2)/R(1)                                               00002160
  ISN 0021                  A(2) = RC(1)                                                     00002170
  ISN 0022                  ALPHA(2) = R(1) + R(2)*RC(1)                                     00002180
  ISN 0023                  IF(M.EQ.1) GO TO 60                                              00002190
              C                                                                              00002200
              C                                                                              00002210
  ISN 0025                  DO 40 MINC = 2,M                                                 00002220
              C                                                                              00002230
  ISN 0026                       S = 0.0                                                     00002240
```

```
                C                                                                   00002250
   ISN 0027                DO 20 IP = 1,MINC                                        00002260
   ISN 0028                     MNC=MINC-IP+2                                       00002270
   ISN 0029                     S = S + R(MNC)*A(IP)                                00002280
   ISN 0030      20        CONTINUE                                                 00002290
                C                                                                   00002300
   ISN 0031                RC(MINC) = -S/ALPHA(MINC)                                00002310
   ISN 0032                MH = MINC/2 + 1                                          00002320
                C                                                                   00002330
   ISN 0033                DO 30 IP = 2,MH                                          00002340
   ISN 0034                     IB = MINC - IP + 2                                  00002350
   ISN 0035                     AT = A(IP) + RC(MINC)*A(IB)                         00002360
   ISN 0036                     A(IB) = A(IB) + RC(MINC)*A(IP)                      00002370
   ISN 0037                     A(IP) = AT                                          00002380
   ISN 0038      30        CONTINUE                                                 00002390
                C                                                                   00002400
   ISN 0039                A(MINC+1) = RC(MINC)                                     00002410
   ISN 0040                ALPHA(MINC+1) = ALPHA(MINC)-ALPHA(MINC)*RC(MINC)*RC(MINC)00002420
                C                                                                   00002430
   ISN 0041                IF(ALPHA(MINC)) 60,60,40                                 00002440
                C                                                                   00002450
   ISN 0042      40     CONTINUE                                                    00002460
                C                                                                   00002470
                C                                                                   00002480
   ISN 0043      60     CONTINUE                                                    00002490
                C                                                                   00002500
   ISN 0044             RETURN                                                      00002510
   ISN 0045             END                                                         00002520
```

```
                 *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
A        0002  0003  0016  0021  0029  0035  0035  0036  0036  0036  0037  0039
K        0008  0009  0010  0012  0013  0013
L        0010  0011
M        0006  0007  0018  0023  0025
N        0002  0010
R        0002  0005  0009  0013  0013  0017  0020  0020  0022  0022  0029
S        0026  0029  0029  0031
A        0002  0005  0013  0013
AT       0035  0037
IB       0034  0035  0036  0036
IP       0027  0028  0029  0033  0034  0035  0036  0037
IX       0005
LP       0003  0004
MH       0032  0033
MM       0002  0006
MP       0007  0008
NP       0011  0012  0013
RC       0002  0005  0020  0021  0022  0031  0035  0036  0039  0040  0040
MNC      0028  0029
NPK      0012  0013
AUTO     0002
MINC     0025  0027  0028  0031  0031  0032  0034  0035  0036  0039  0039  0040  0040  0040  0040  0040  0041
ALPHA    0002  0005  0017  0022  0031  0040  0040  0040  0041
ARRAY    0005
AUTOF    0003  0004
WNDOW    0003  0004
```

```
                    *****F C R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
LABEL   DEFINED   REFERENCES
  10    0014      0011
  11    0007
  15    0015      0008
  20    0030      0027
  30    0038      0033
  40    0042      0025  0041
  60    0043      0018  0023  0041  0041

                  000000  47 F0 F 00C          AUTO     BC     15,12(0,15)
                  000004  C7                            DC     XL1'07'
                  000005  C1E4E3D6404040                DC     CL7'AUTO   '
                  00000C  90 EC D 00C                   STM    14,12,12(13)
                  000010  18 4D                         LR     4,13
                  000012  98 CD F 020                   LM     12,13,32(15)
                  000016  50 40 D 004                   ST     4,4(0,13)
                  00001A  50 DC 4 008                   ST     13,8(0,4)
                  00001E  07 FC                         BCR    15,12

CONSTANTS
                  000078  00000000                      DC     XL4'00000000'
                  00007C  00000000                      DC     XL4'00000000'
                  000080  00000001                      DC     XL4'00000001'
                  000084  00000002                      DC     XL4'00000002'
                  000088  41100000                      DC     XL4'41100000'
                  00008C  00000000                      DC     XL4'00000000'
                  000090  00000000                      DC     XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                  0000E0  00000000                      DC     XL4'00000000'                A
                  0000E8  00000000                      DC     XL4'00000000'                F
                  0000F0  00000000                      DC     XL4'00000000'                X
                  0000F8  00000000                      DC     XL4'00000000'                HC
                  000100  00000000                      DC     XL4'00000000'                ALPHA
                  000120  58 70 D 0D8        100001     L       7, 216( 0,13)
                  000124  58 EC D 0D0                   L       E, 208( 0,13)
                  000128  58 90 D 0B8                   L       9, 184( 0,13)
                  00012C  58 E0 D 0C0                   L      11, 192( 0,13)
                  000130  58 A0 D 058                   L      10,  88( 0,13)              I
                  000134  58 60 D 0E4                   L       6, 228( 0,13)              4
                  000138  58 20 D 090                   L       2, 144( 0,13)              NN
                  00013C  50 20 D 074                   ST      2, 116( 0,13)              N
                  000140  1A 2A              11         AR      2,10
                  000142  50 20 D 094                   ST      2, 148( 0,13)              NF
                  000146  50 60 D 0F4                   ST      6, 244( 0,13)              .C04
                  00014A  18 3A                         LR      3,10
                  00014C  58 70 D 078                   L       7, 120( 0,13)              N
                  000150  18 E2                         LR      E, 2
                  000152  18 56                         LR      5, 6
                  000154  78 60 D 054                   LE      6,  84( 0,13)              0
                  000158  18 5B                         LR      5,11
                  00015A  58 E0 D 0F4        100002     L      14, 244( 0,13)             .004
                  00015E  70 6E 5 000                   STE     6,   0(14, 5)              F
                  000162  18 27                         LR      2, 7
                  000164  1B 23                         SR      2, 3
```

```
000166   18 EA                         LR      11,10
000168   1A B2                         AR      11, 2
00016A   58 40 D 0F4                   L        4, 244( 0,13)          .C04
00016E   18 89                         LR      8, 9
000170   18 9A                         LR      9,10
000172   58 70 D 0C8                   L        7, 200( 0,13)
000176   18 29                 100003  LR      2, 9
000178   1A 23                         AR      2, 3
00017A   18 62                         LR      6, 2
00017C   1B 6A                         SR      6,10
00017E   78 28 7 000                   LE      2,    0( 8, 7)          X
000182   18 26                         LR      2, 6
000184   89 20 0 002                   SLL     2,    2
000188   7C 22 7 000                   ME      2,    0( 2, 7)          X
00018C   7A 24 5 000                   AE      2,    0( 4, 5)          R
000190   70 24 5 000                   STE     2,    0( 4, 5)          R
000194   5A E0 D 0E4               10  A       6, 228( 0,13)           4
000198   87 9A D 14E                   BXLE    9,10, 334(13)           100003
00019C   58 50 D 0E4               15  L       5, 228( 0,13)           4
0001A0   58 80 D 0C4                   L       8, 196( 0,13)           MF
0001A4   58 70 D 078                   L       7, 120( 0,13)           N
0001A8   58 00 D 0F4                   L       0, 244( 0,13)           .C04
0001AC   1A 09                         AR      0, 9
0001AE   50 00 D 0F4                   ST      0, 244( 0,13)           .C04
0001B2   1A 3A                         AR      3,10
0001B4   19 38                         CR      3, 8
0001B6   47 C0 D 132                   BC      12, 306( 0,13)          100002
0001BA   58 70 D 0D8           100005  L       7, 216( 0,13)
0001BE   58 80 D 0D0                   L       8, 208( 0,13)
0001C2   58 90 D 0B8                   L       9, 184( 0,13)
0001C6   58 E0 D 0C0                   L      11, 192( 0,13)
0001CA   58 60 D 0E4                   L       6, 228( 0,13)           4
0001CE   78 C0 D 06C                   LE      0,   96( 0,13)          41100000
0001D2   70 00 9 004                   STE     0,    4( 0, 9)          A
0001D6   78 20 B 004                   LE      2,    4( 0,11)          F
0001DA   70 20 7 004                   STE     2,    4( 0, 7)          ALPHA
0001DE   58 00 D 074                   L       0, 116( 0,13)           N
0001E2   12 00                         LTR     0, 0
0001E4   47 80 D 226                   BC      8, 606( 0,13)           60
0001E8   78 20 B 008           100006  LE      2,    8( 0,11)          F
0001EC   78 40 B 004                   LE      4,    4( 0,11)          F
0001F0   38 62                         LER     6, 2
0001F2   3D 64                         DER     6, 4
0001F4   33 06                         LCER    0, 6
0001F6   70 0C 8 004                   STE     0,    4( 0, 8)          RC
0001FA   7E 6C 8 004                   LE      6,    4( 0, 8)          RC
0001FE   70 60 9 008                   STE     6,    8( 0, 9)          A
000202   3C 26                         MER     2, 6
000204   3A 24                         AER     2, 4
000206   70 20 7 008                   STE     2,    8( 0, 7)          ALPHA
00020A   59 A0 D 074                   C      10, 116( 0,13)           N
00020E   47 80 D 226                   BC      8, 606( 0,13)           60
000212   58 00 D 05C           100007  L       0,   92( 0,13)          2
000216   50 00 D 0A8                   ST      0, 168( 0,13)           MINC
00021A   58 00 D 0F0                   L       0, 240( 0,13)           B
00021E   50 00 D 0EC                   ST      0, 236( 0,13)           .C03
000222   58 30 D 05C                   L       3,   92( 0,13)          2
000226   19 96                         LR      9, 6
```

```
000228   18 B7                       LR     11, 7
00022A   58 60 D 0B8                 L      6, 184( 0,13)
00022E   58 70 D 0D0                 L      7, 208( 0,13)
000232   78 20 D 054         100009  LE     2,  84( 0,13)          C
000236   70 20 D 07C                 STE    2, 124( 0,13)          S
00023A   18 29                       LR     2, 9
00023C   18 49                       LR     4, 9
00023E   18 72                       LR     7, 2
000240   18 EA                       LR     E,10
000242   58 B0 D 0A8                 L      11, 168( 0,13)         MINC
000246   38 62                       LER    6, 2
000248   58 60 D 0B8                 L      6, 184( 0,13)
00024C   58 50 D 0C0                 L      5, 192( 0,13)
000250   18 2B               100009  LR     2,11
000252   1B 2E                       SR     2, E
000254   18 52                       LR     5, 2
000256   1A 93                       AR     9, 3
000258   18 29                       LR     2, 9
00025A   89 20 0 002                 SLL    2,    2
00025E   7E 22 5 000                 LE     2,    0( 2, 5)         F
000262   7C 27 6 000                 ME     2,    0( 7, 6)         A
000266   3A 62                       AER    6, 2
000268   1A 74                   20  AR     7, 4
00026A   87 8A D 228                 BXLE   8,10, 552(13)          100009
00026E   7C 60 D 07C                 STE    6, 124( 0,13)          S
000272   58 70 D 0D0         100010  L      7, 208( 0,13)
000276   58 80 D 0B8                 L      8, 184( 0,13)
00027A   58 B0 D 0D8                 L      11, 216( 0,13)
00027E   58 90 D 0E4                 L      9, 228( 0,13)          4
000282   58 E0 D 0EC                 L      14, 236( 0,13)         .C03
000286   78 20 D 07C                 LE     2, 124( 0,13)          S
00028A   70 2E B 000                 CE     2,    0(14,11)         ALFHA
00028E   33 02                       LCER   0, 2
000290   70 0E 7 000                 STE    0,    0(14, 7)         RC
000294   58 40 D 0A8                 L      4, 168( 0,13)          MINC
000298   8E 40 0 020                 SRDA   4,   32
00029C   1D 43                       DR     4, 3
00029E   18 2A                       LR     2,10
0002A0   1A 25                       AR     2, 5
0002A2   50 30 D 088                 ST     3, 136( 0,13)          IF
0002A6   78 0E 7 000                 LE     0,    0(14, 7)         RC
0002AA   70 00 D 0E0                 STE    0, 224( 0,13)          .C01
0002AE   18 49                       LR     4, 9
0002B0   58 50 D 0A8                 L      5, 168( 0,13)          MINC
0002B4   58 70 D 0F0                 L      7, 240( 0,13)          P
0002B8   58 E0 D 088                 L      E, 136( 0,13)          IF
0002BC   18 B2                       LR     11, 2
0002BE   58 90 D 0B8                 L      9, 184( 0,13)
0002C2   18 25               100011  LR     2, 5
0002C4   1B 28                       SR     2, E
0002C6   18 62                       LR     6, 2
0002C8   1A 63                       AR     6, 3
0002CA   18 26                       LR     2, 6
0002CC   89 20 0 002                 SLL    2,    2
0002D0   78 62 9 000                 LE     6,    0( 2, 9)         A
0002D4   38 26                       LER    2, 6
0002D6   7C 20 D 0E0                 ME     2, 224( 0,13)          .C01
0002DA   78 47 5 000                 LE     4,    0( 7, 5)         F
```

```
              0002DE   3A 24                        AER    2, 4
              0002E0   7C 40 D 0E0                  ME     4, 224( 0,13)          .C01
              0002E4   3A 46                        AER    4, 6
              0002E6   70 42 9 000                  STE    4,   0( 2, 9)              A
              0002EA   70 27 9 000                  STE    2,   0( 7, 9)              A
              0002EE   1A 74                   30   AR     7, 4
              0002F0   87 6A D 29A                  BXLE   6,10, 666(13)         100C11
              0002F4   58 70 D 0D0          100C12  L      7, 208( 0,13)
              0002F8   58 80 D 0B8                  L      8, 184( 0,13)
              0002FC   58 B0 D 0D8                  L     11, 216( 0,13)
              000300   58 90 D 0E4                  L      9, 228( 0,13)              4
              000304   58 E0 D 0EC                  L     14, 236( 0,13)           .C03
              000308   78 00 D 0E0                  LE     0, 224( 0,13)           .C01
              00030C   70 0E B 004                  STE    0,   4(14,11)              A
              000310   78 2E B 000                  LE     2,   0(14,11)          ALPHA
              000314   38 42                        LER    4, 2
              000316   7C 40 D 0E0                  ME     4, 224( 0,13)           .C01
              00031A   7C 40 D 0E0                  ME     4, 224( 0,13)           .C01
              00031E   3B 24                        SER    2, 4
              000320   70 2E B 004                  STE    2,   4(14,11)          ALPHA
              000324   78 0E B 000                  LE     0,   0(14,11)          ALPHA
              000328   32 00                        LTER   0, 0
              00032A   47 30 D 30A                  BC     3, 778( 0,13)             4C
              00032E   47 F0 D 326                  BC    15, 806( 0,13)             6C
              000332   58 00 D 0EC             40   L      0, 236( 0,13)           .C03
              000336   1A 05                        AR     0, 5
              000338   50 00 D 0EC                  ST     0, 236( 0,13)           .C03
              00033C   58 20 D 0A8                  L      2, 168( 0,13)           MINC
              000340   1A 2A                        AR     2,10
              000342   50 20 D 0A8                  ST     2, 168( 0,13)           MINC
              000346   59 20 D 074                  C      2, 116( 0,13)              M
              00034A   47 C0 D 20A                  BC    12, 522( 0,13)         100C06
              00034E   58 70 D 0D8             60   L      7, 216( 0,13)
              000352   58 80 D 0D0                  L      8, 208( 0,13)
              000356   58 90 D 0B8                  L      9, 184( 0,13)
              00035A   58 B0 D 0C0                  L     11, 192( 0,13)
              00035E   58 60 D 0E4                  L      6, 228( 0,13)              A
              000362   1B FF                        SR    15,15
              000364   58 E0 D 000                  L     14,   0( 0,13)
              000368   07 FE                        BCR   15,14
ADDRESS OF EPILOGUE
              00036A   58 D0 D 004                  L     13,   4( 0,13)
              00036E   58 E0 D 00C                  L     14,  12( 0,13)
              000372   92 FF D 00C                  MVI    12(13),255
              000376   98 2C D 01C                  LM     2,12,  28(13)
              00037A   07 FE                        BCR   15,14
ADDRESS OF PROLOGUE
              00037C   98 7B 1 000                  LM     7,11,   0( 1)
              000380   58 20 7 000                  L      2,   0( 0, 7)
              000384   50 20 D 078                  ST     2, 120( 0,13)              M
              000388   58 20 9 000                  L      2,   0( 0, 9)
              00038C   50 20 D 090                  ST     2, 144( 0,13)             MA
              000390   58 20 1 004                  L      2,   4( 0, 1)
              000394   41 30 2 000                  LA     3,   0( 0, 2)
              000398   41 50 0 004                  LA     5,   4
              00039C   1B 25                        SR     2, 5
              00039E   50 20 D 0C8                  ST     2, 200( 0,13)
              0003A2   50 30 D 0CC                  ST     3, 204( 0,13)              X
```

```
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =       44, PROGRAM SIZE =      1026, SUBPROGRAM NAME =  AUTO

*STATISTICS*    3 DIAGNOSTICS GENERATED, HIGHEST SEVERITY CODE IS  4

****** END OF COMPILATION ******                                       308K BYTES OF CORE NOT USED
```

```
*LEVEL 2.3.0 (JUNE 78)                 OS/360  FORTRAN H EXTENDED            DATE 81.155/14.56.33        PAGE    1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

              C
              C
              C
   ISN 0002                 SUBROUTINE INVERS(N,X,M,R,A,RC,FC)
              C
              C
              C             THIS ROUTINE IMPLEMENTS THE LATTICE FILTER.  THE OUTPUT OF
              C             THE FILTER IS THE PREDICTION RESIDUAL.
              C
              C
              C             X - INPUT OF SPEECH SAMPLES
              C             N - NO. OF POINTS
              C             M - ORDER OF FILTER
              C             RC - REFLECTION COEFFICIENTS
              C             FC - RESIDUAL OF SPEECH PTS OUTPUT
              C             B - VECTOR OF BACKWARD PREDICTED SAMPLES
              C             C - TEMPORARY VECTOR FOR SAMPLES
              C
              C
   ISN 0003                 DIMENSION X(256),A(20),B(20),RC(20)
   ISN 0004                 DIMENSION FC(256),R(20)
              C
   ISN 0005                 MM=M+1
              C
   ISN 0006                 DO 10 J=1,MM
   ISN 0007                      B(J)=0.
   ISN 0008       10        CONTINUE
   ISN 0009                 DO 20 J=1,N
              C
              C
   ISN 0010                      A(1)=X(J)
   ISN 0011                 DO 30 I=1,M
   ISN 0012                 A(I+1)=A(I)+B(I)*RC(I)
   ISN 0013        30       CONTINUE
   ISN 0014                 DO 40 I=1,M
   ISN 0015        40       B(I+1)=B(I)+A(I)*RC(I)
   ISN 0016                      B(1)=A(1)
   ISN 0017                      FC(J)=A(MM)
   ISN 0018       20        CONTINUE
   ISN 0019                 RETURN
   ISN 0020                 END

                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
A        0002  0003  0010  0012  0012  0015  0016  0017
B        0003  0007  0012  0015  0015  0016
I        0011  0012  0012  0012  0012  0014  0015  0015  0015  0015
J        0006  0007  0009  0010  0017
M        0002  0005  0011  0014
N        0002  0009
R        0002  0004
X        0002  0003  0010
```

```
                         *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
MM       0005  0006  0017
NC       0002  0003  0012  0015
ND       0002  0004  0017
INVERS   0002

                         *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
 LABEL    DEFINED    REFERENCES
   10      0008       0006
   20      0010       0009
   30      0013       0011
   40      0015       0014

                  000000  47 F0 F 00C            INVERS    BC     15,12(0,15)
                  000004  07                               DC     XL1'07'
                  000005  C9D5E5C5D9E240                   DC     CL7'INVERS '
                  00000C  90 EC D 00C                      STM    14,12,12(13)
                  000010  18 4D                            LR     4,13
                  000012  98 CD F 020                      LM     12,13,32(15)
                  000016  50 40 D 004                      ST     4,4(0,13)
                  00001A  50 D0 4 008                      ST     13,8(0,4)
                  00001E  07 FC                            BCR    15,12

CONSTANTS
                  000078  00000000                         DC     XL4'00000000'
                  00007C  00000001                         DC     XL4'00000001'
                  000080  00000000                         DC     XL4'00000000'
                  000084  00000000                         DC     XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                  0000F0  00000000                         DC     XL4'00000000'                       A
                  0000F8  00000000                         DC     XL4'00000000'                       F
                  000100  00000000                         DC     XL4'00000000'                       X
                  000108  00000000                         DC     XL4'00000000'                      RC
                  000110  00000000                         DC     XL4'00000000'                      RC
                  000138  58 70 D 0E0           100001     L       7, 224( 0,13)
                  00013C  58 80 D 0C8                      L       8, 200( 0,13)
                  000140  78 60 D 050                      LE      6,  80( 0,13)                      C
                  000144  58 B0 D 068                      L      11, 104( 0,13)                      N
                  000148  58 A0 D 0F0                      L      10, 240( 0,13)                      A
                  00014C  58 20 D 054                      L       2,  84( 0,13)                      I
                  000150  1A 2B                            AR      2,11
                  000152  50 20 D 070                      ST      2, 112( 0,13)                     MA
                  000156  89 20 0 002                      SLL     2,   2
                  00015A  50 20 D 0F8                      ST      2, 248( 0,13)                   .C02
                  00015E  18 5A                            LR      5,10
                  000160  18 B2                            LR     11, 2
                  000162  70 69 D 074           100002     STE     6, 116( 5,13)                      F
                  000166  87 5A D 13A               10     BXLE    5,10, 314(13)                 100002
                  00016A  58 B0 D 068           100003     L      11, 104( 0,13)                      N
                  00016E  18 2B                            LR      2,11
                  000170  89 20 0 002                      SLL     2,   2
                  000174  50 20 D 104                      ST      2, 260( 0,13)                   .C05
                  000178  50 20 D 0FC                      ST      2, 252( 0,13)                   .C03
```

190

```
          00017C  58 00 D 0F8              L      0, 248( 0,13)          .C02
          000180  50 00 D 108              ST     0, 264( 0,13)          .C06
          000184  58 50 D 06C              L      5, 108( 0,13)          K
          000188  89 50 0 002              SLL    5,   2
          00018C  18 2A                    LR     2,10
          00018E  18 4A                    LR     4,10
          000190  18 62                    LR     6, 2
          000192  58 30 D 0D8              L      3, 216( 0,13)
          000196  78 26 3 000      100004  LE     2,   0( 6, 3)          X
          00019A  70 20 8 004              STE    2,   4( 0, 8)          A
          00019E  18 94                    LR     9, 4
          0001A0  18 A4                    LR    10, 4
          0001A2  58 B0 D 104              L     11, 260( 0,13)          .C05
          0001A6  78 29 D 074      100005  LE     2, 116( 9,13)          E
          0001AA  7C 29 7 000              ME     2,   0( 9, 7)          RC
          0001AE  7A 29 8 000              AE     2,   0( 9, 8)          A
          0001B2  70 29 8 004              STE    2,   4( 9, 8)          A
          0001B6  87 9A D 17E          30  BXLE   9,10, 382(13)          100005
          0001BA  18 94            100006  LR     9, 4
          0001BC  18 A4                    LR    10, 4
          0001BE  58 B0 D 0FC              L     11, 252( 0,13)          .C03
          0001C2  78 29 8 000          40  LE     2,   0( 9, 8)          A
          0001C6  7C 29 7 000              ME     2,   0( 9, 7)          RC
          0001CA  7A 29 D 074              AE     2, 116( 9,13)          E
          0001CE  70 29 D 078              STE    2, 120( 9,13)          B
          0001D2  87 9A D 19A              BXLE   9,10, 410(13)          40
          0001D6  78 20 8 004      100007  LE     2,   4( 0, 8)          A
          0001DA  70 20 D 078              STE    2, 120( 0,13)          E
          0001DE  58 E0 D 108              L     14, 264( 0,13)          .C06
          0001E2  78 2E 8 000              LE     2,   0(14, 8)          A
          0001E6  58 F0 D 0E8              L     15, 232( 0,13)
          0001EA  70 26 F 000              STE    2,   0( 6,15)          RC
          0001EE  87 64 D 16E          20  BXLE   6, 4, 366(13)          100004
          0001F2  58 B0 D 068      100009  L     11, 104( 0,13)          M
          0001F6  1B FF                    SR    15,15
          0001F8  58 E0 D 000              L     14,   0( 0,13)
          0001FC  07 FE                    BCR   15,14
ADDRESS OF EPILOGUE
          0001FE  58 D0 D 004              L     13,   4( 0,13)
          000202  58 E0 D 00C              L     14,  12( 0,13)
          000206  92 FF D 00C              MVI     12(13),255
          00020A  98 2C D 01C              LM     2,12,  28(13)
          00020E  07 FE                    BCR   15,14
ADDRESS OF PROLOGUE
          000210  98 7B 1 000              LM     7,11,   0( 1)
          000214  58 20 7 000              L      2,   0( 0, 7)
          000218  50 20 D 06C              ST     2, 108( 0,13)          K
          00021C  58 20 9 000              L      2,   0( 0, 9)
          000220  50 20 D 068              ST     2, 104( 0,13)          M
          000224  58 20 1 004              L      2,   4( 0, 1)
          000228  41 30 2 000              LA     3,   0( 0, 2)
          00022C  41 50 0 004              LA     5,   4
          000230  1B 25                    SR     2, 5
          000232  50 20 D 0D8              ST     2, 216( 0,13)
          000236  50 30 D 0DC              ST     3, 220( 0,13)          X
          00023A  58 20 1 00C              L      2,  12( 0, 1)
          00023E  41 30 2 000              LA     3,   0( 0, 2)
          000242  41 50 0 004              LA     5,   4
```

```
*LEVEL 2.3.0 (JUNE 78)          INVERS           OS/360  FORTRAN H EXTENDED                DATE 81.155/14.58.33        PAGE
                    000246  1B 25                               SR     2,5
                    000248  50 20 D 0D0                         ST     2,208(0,13)
                    00024C  50 30 D 0D4                         ST     3,212(0,13)                    R
                    000250  58 20 1 01C                         L      2,  1C(0, 1)
                    000254  41 30 2 000                         LA     3,   0(0, 2)
                    000258  41 50 0 004                         LA     5,   4
                    00025C  1B 25                               SR     2,5
                    00025E  50 20 D 0C8                         ST     2,200(0,13)
                    000262  50 30 D 0CC                         ST     3,204(0,13)                    A
                    000266  58 20 1 014                         L      2,  20(0, 1)
                    00026A  41 30 2 000                         LA     3,   0(0, 2)
                    00026E  41 50 0 004                         LA     5,   4
                    000272  1B 25                               SR     2,5
                    000274  50 20 D 0E0                         ST     2,224(0,13)
                    000278  50 30 D 0E4                         ST     3,228(0,13)                    RC
                    00027C  58 20 1 018                         L      2,  24(0, 1)
                    000280  41 30 2 000                         LA     3,   0(0, 2)
                    000284  41 50 0 004                         LA     5,   4
                    000288  1B 25                               SR     2,5
                    00028A  50 20 D 0E8                         ST     2,232(0,13)
                    00028E  50 30 D 0EC                         ST     3,236(0,13)                    RC
                    000292  47 F0 D 110                         BC    15,272(0,13)
ADCON FOR PROLOGUE
                    000020  00000210                            DC     XL4'00000210'
ADCON FOR SAVE AREA
                    000024  00000028                            DC     XL4'00000028'
ADCON FOR EPILOGUE
                    000028  000001FE                            DC     XL4'000001FE'
TEMPORARIES AND GENERATED CONSTANTS
                    000118  00000004                            DC     XL4'00000004'
                    00011C  00000000                            DC     XL4'00000000'
                    000120  00000000                            DC     XL4'00000000'
                    000124  00000000                            DC     XL4'00000000'
                    000128  00000000                            DC     XL4'00000000'
                    00012C  00000000                            DC     XL4'00000000'
                    000130  00000000                            DC     XL4'00000000'
                    000134  00000000                            DC     XL4'00000000'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =       15, PROGRAM SIZE =       672, SUBPROGRAM NAME =INVERS

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                           21?K BYTES OF CORE NOT USED
```

```
*LEVEL 2.3.0 (JUNE 78)                    OS/360  FORTRAN H EXTENDED              DATE 81.155/14.58.26          PAGE   1

REQUESTED OPTIONS: OPT=2,FORMAT,XREF,LIST,MAP,SIZE(750K)

OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)
                   SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

                 C
                 C
   ISN 0002                SUBROUTINE SYNTHZ(N,M,RC,RO,Y)
                 C
                 C               THIS ROUTINE IMPLEMENTS THE SYNTHESIS LATTICE FILTER.
                 C               ITS OUTPUT IS THE ORIGINAL INPUT RECONSTRUCTED FROM THE
                 C               PREDICTION RESIDUAL.
                 C
                 C               RC - REFLECTION COEFFICIENTS
                 C               RO - PREDICTION RESIDUAL
                 C               M - ORDER OF THE FILTER
                 C               N - NUMBER OF SAMPLES OF THE PRED. RESIDUAL
                 C               Y - RECONSTRUCTED SIGNAL
                 C
                 C
                 C
   ISN 0003                DIMENSION A(20),B(20),RC(20),RO(256),Y(256)
                 C
                 C
   ISN 0004                MM=M+1
                 C
   ISN 0005                DO 100 J=1,MM
   ISN 0006                   B(J)=0.
   ISN 0007      100       CONTINUE
                 C
   ISN 0008                DO 200 J=1,N
   ISN 0009             A(MM)=RO(J)
   ISN 0010             DO 300 I=1,M
   ISN 0011             IP1=M-I+1
   ISN 0012             A(IP1)=A(IP1+1)-B(IP1)*RC(IP1)
   ISN 0013       300   CONTINUE
   ISN 0014             DO 400 I=1,M
   ISN 0015        400  B(I+1)=B(I)+A(I)*RC(I)
   ISN 0016                   B(1)=A(1)
   ISN 0017                   Y(J)=A(1)
   ISN 0018      200       CONTINUE
   ISN 0019                RETURN
   ISN 0020                END

                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL   INTERNAL STATEMENT NUMBERS
A           0003  0009  0012  0012  0015  0016  0017
B           0003  0006  0012  0015  0015  0016
I           0010  0011  0014  0015  0015  0015  0015
J           0005  0006  0008  0009  0017
M           0002  0004  0010  0011  0014
N           0002  0008
Y           0002  0003  0017
MM          0004  0005  0009
RC          0002  0003  0012  0015
RO          0002  0003  0009
IP1         0011  0012  0012  0012  0012
```

```
                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
SYMBOL  INTERNAL STATEMENT NUMBERS
SYNTHZ  0002

                    *****F O R T R A N   C R O S S   R E F E R E N C E   L I S T I N G*****
 LABEL    DEFINED    REFERENCES
  100      0007       0005
  200      0018       0008
  300      0013       0010
  400      0015       0014

                     000000  47 F0 F 00C          SYNTHZ   BC    15,12(0,15)
                     000004  07                            DC    XL1'07'
                     000005  E2E8D5E3C8E940                DC    CL7'SYNTHZ '
                     00000C  90 EC D 00C                   STM   14,12,12(13)
                     000010  18 4D                         LR    4,13
                     000012  98 CD F 020                   LM    12,13,32(15)
                     000016  50 40 D 0C4                   ST    4,4(0,13)
                     00001A  50 D0 4 008                   ST    13,8(0,4)
                     00001E  07 FC                         BCR   15,12

CONSTANTS
                     000078  00000000                      DC    XL4'00000000'
                     00007C  00000001                      DC    XL4'00000001'
                     000080  00000000                      DC    XL4'00000000'
                     000084  00000000                      DC    XL4'00000000'
ADCONS FOR VARIABLES AND CONSTANTS
ADCONS FOR EXTERNAL REFERENCES
                     000148  00000000                      DC    XL4'00000000'                      Y
                     000150  00000000                      DC    XL4'00000000'                     RC
                     000158  00000000                      DC    XL4'00000000'                     RC
                     00017C  58 70 D 128          100001   L      7, 296( 0,13)
                     000180  78 60 D 050                   LE     6,  80( 0,13)    I               0
                     000184  58 B0 D 068                   L     11, 104( 0,13)                    N
                     000188  58 40 D 138                   L      4, 312( 0,13)                    4
                     00018C  58 30 D 054                   L      3,  84( 0,13)                    1
                     000190  18 23                         LR     2, 3
                     000192  1A 2B                         AR     2,11
                     000194  50 20 D 070                   ST     2, 112( 0,13)                   MA
                     000198  89 20 0 002                   SLL    2,    2
                     00019C  50 20 D 150                   ST     2, 336( 0,13)                 .C06
                     0001A0  18 54                         LR     5, 4
                     0001A2  18 A4                         LR    10, 4
                     0001A4  18 B2                         LR    11, 2
                     0001A6  70 69 D 0C8          100002   STE    6, 200( 9,13)                    B
                     0001AA  87 9A C 17E             100   BXLE   9,10, 382(12)               100002
                     0001AE  58 B0 D 068          100003   L     11, 104( 0,13)                    N
                     0001B2  58 00 D 150                   L      0, 336( 0,13)                 .C06
                     0001B6  50 00 D 148                   ST     0, 328( 0,13)                 .C04
                     0001BA  18 0B                         LR     0,11
                     0001BC  89 00 0 002                   SLL    0,    2
                     0001C0  50 00 D 140                   ST     0, 320( 0,13)                 .C02
                     0001C4  58 50 D 06C                   L      5, 108( 0,13)                    N
                     0001C8  89 50 0 002                   SLL    5,    2
                     0001CC  18 24                         LR     2, 4
```

```
        0001CE   18 62                       LR     6, 2
        0001D0   58 F0 D 130         100C04  L      15, 304( 0,13)
        0001D4   78 26 F 000                 LE     2,   0( 6,15)          RC
        0001D8   58 E0 D 1E4                 L      14, 228( 0,13)        .C04
        0001DC   70 2E D 078                 STE    2, 120(14,13)           A
        0001E0   18 53                       LR     5, 3
        0001E2   18 A3                       LR     10, 3
        0001E4   58 E0 D 068                 L      11, 104( 0,13)          N
        0001E8   18 2B               100005  LR     2,11
        0001EA   1B 25                       SR     2, 5
        0001EC   18 82                       LR     8, 2
        0001EE   1A 8A                       AR     8,10
        0001F0   18 28                       LR     2, 8
        0001F2   89 20 0 002                 SLL    2,   2
        0001F6   78 22 D 0C8                 LE     2, 200( 2,13)           B
        0001FA   7C 22 7 000                 ME     2,   0( 2, 7)          RC
        0001FE   33 22                       LCER   2, 2
        000200   7A 22 D 07C                 AE     2, 124( 2,13)           A
        000204   70 22 D 078                 STE    2, 120( 2,13)           A
        000208   87 5A D 1C0            200  BXLE   5,10, 448(13)       100C05
        00020C   18 54               100C06  LR     5, 4
        00020E   18 A4                       LR     10, 4
        000210   58 B0 D 140                 L      11, 320( 0,13)        .C02
        000214   18 E7                       LR     8, 7
        000216   78 29 D 078            400  LE     2, 120( 5,13)           A
        00021A   7C 29 8 000                 ME     2,   0( 9, 8)          RC
        00021E   7A 29 D 0C8                 AE     2, 200( 9,13)           E
        000222   70 29 D 0CC                 STE    2, 204( 9,13)           E
        000226   87 5A D 1EE                 BXLE   5,10, 494(13)          400
        00022A   78 20 D 07C         100C07  LE     2, 124( 0,13)           A
        00022E   70 20 D 0CC                 STE    2, 204( 0,13)           E
        000232   58 F0 D 120                 L      15, 288( 0,13)
        000236   70 26 F 000                 STE    2,   0( 6,15)           Y
        00023A   87 64 D 1A8            200  BXLE   6, 4, 424(13)       100C04
        00023E   58 B0 D 068         100C08  L      11, 104( 0,13)          N
        000242   1B FF                       SR     15,15
        000244   58 E0 D 000                 L      14,   0( 0,13)
        000248   07 FE                       BCR    15,14
ADDRESS OF EPILOGUE
        00024A   58 D0 D 004                 L      13,   4( 0,13)
        00024E   58 E0 D 00C                 L      14,  12( 0,13)
        000252   92 FF D 00C                 MVI    12(13),255
        000256   98 2C D 01C                 LM     2,12,  28(13)
        00025A   07 FE                       BCR    15,14
ADDRESS OF PROLOGUE
        00025C   98 7B 1 000                 LM     7,11,    0( 1)
        000260   58 20 7 000                 L      2,   0( 0, 7)
        000264   50 20 D 06C                 ST     2, 108( 0,13)           N
        000268   58 20 8 000                 L      2,   0( 0, 8)
        00026C   50 20 D 068                 ST     2, 104( 0,13)           M
        000270   58 20 1 008                 L      2,   8( 0, 1)
        000274   41 30 2 000                 LA     3,   0( 0, 2)
        000278   41 50 0 004                 LA     5,   4
        00027C   1B 25                       SR     2, 5
        00027E   50 20 D 128                 ST     2, 296( 0,13)
        000282   50 30 D 12C                 ST     3, 300( 0,13)          RC
        000286   58 20 1 00C                 L      2,  12( 0, 1)
        00028A   41 30 2 000                 LA     3,   0( 0, 2)
```

/

```
*LEVEL 2.3.0 (JUNE 78)        SYNTH2          OS/360  FORTRAN H EXTENDED           DATE 81.155/14.58.36        PAGE    4

                   00028E   41 50 0 004                    LA      5,   4
                   000292   1B 25                          SR      2, 5
                   000294   50 20 D 130                    ST      2, 304( 0,13)
                   000298   50 30 D 134                    ST      3, 308( 0,13)                       PC
                   00029C   58 20 1 010                    L       2,  16( 0, 1)
                   0002A0   41 30 2 000                    LA      3,   0( 0, 2)
                   0002A4   41 50 0 004                    LA      5,   4
                   0002A8   1B 25                          SR      2, 5
                   0002AA   50 20 D 120                    ST      2, 288( 0,13)
                   0002AE   50 30 D 124                    ST      3, 292( 0,13)                        Y
                   0002B2   47 F0 D 154                    BC     15, 340( 0,13)
ADCON FOR PROLOGUE
                   000020   0000025C                       DC      XL4'0000025C'
ADCON FOR SAVE AREA
                   000024   00000028                       DC      XL4'00000028'
ADCON FOR EPILOGUE
                   000028   0000024A                       DC      XL4'0000024A'
TEMPORARIES AND GENERATED CONSTANTS
                   000160   00000004                       DC      XL4'00000004'
                   000164   00000000                       DC      XL4'00000000'
                   000168   00000000                       DC      XL4'00000000'
                   00016C   00000000                       DC      XL4'00000000'
                   000170   00000000                       DC      XL4'00000000'
                   000174   00000000                       DC      XL4'00000000'
                   000178   00000000                       DC      XL4'00000000'


*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(0750K) AUTODBL(NONE)

*OPTIONS IN EFFECT*SOURCE EBCDIC LIST NODECK OBJECT MAP FORMAT GOSTMT XREF NOALC NOANSF TERM IBM FLAG(I)

*STATISTICS*     SOURCE STATEMENTS =       15, PROGRAM SIZE =       694, SUBPROGRAM NAME =SYNTH2

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    316K BYTES OF CORE NOT USED
```

APPENDIX D

SATELLITE COMMUNICATION TERMINOLOGIES

Transponder. The equipment which receives a signal, amplifies it, changes its frequency, and retransmits it. This process is necessary in order to avoid interfering the weak incoming signal with the powerful transmitted signal. Most satellites have more than one transponder, and the bandwidth of most transponders is 36 MHz, which can carry one televised signal.

Earth Station. A large dish-shaped antenna pointed toward a satellite. The size of the dish usually varies with the size of the beam angle. Most earth stations simply transmit and receive the telecommunication signals with a fixed antenna. The most inexpensive channels operate with a UHF channel.

Channel Capacity (C). The maximum rate at which nearby errorless data transmission is theoretically possible. For certain types of communication channels it has been shown that [14]

$$C = B \log_2 (1 + S/N)$$

where B is the bandwidth, S is the signal power, and N is the noise power. For example, for a 3000 Hz of bandwidth and $S/N = 10^3$, the capacity of channel needs to be approximately 30 k bits/second. At the present time, the actual data rate on such channels ranges from 150 to 9000 bits/second [23].

Multiplexing. Any technique which permits more than one independent signal to share one physical facility. This may include space, frequency, and/or time division multiplexing. In a satellite, a high level of multiplexing is needed so that many signals can share the large bandwidth.

Access Methods of Satellite Links [34, 35]. A satellite interconnects large numbers of earth stations scattered over thousands of miles.

An efficient solution to allocate subchannels to many users (multiple-access) is required. The simplest way to subdivide satellite capacity by frequency is to give different users different transponders, simply referred to as the multiple-transponder technique. This approach is less satisfactory for the users who need much smaller capacity and/or variable channel assignment. For this reason, techniques which allow for sharing the same transponder among many earth stations have been developed. They are frequency division multiple access (FDMA) and time division multiple access (TDMA).

FDMA. With FDMA the transponder bandwidth is divided into smaller bandwidths. An earth station transmits on one or more of these divisions. The signal is used to modulate a carrier and multiple carriers are used so that signals can be spaced from each other. Figure 40 illustrates one example of FDMA, where 800 channel carriers are spaced 45 KHz apart. The first channel is used to control the allocation of voice carriers to earth stations. A carrier at the center of each slot is modulated with the voice channel. The more carriers a transponder shares with this scheme the lower the overall capacity. This is due to the effect of guard bands between the carrier's bands and intermodulation.

TDMA. One of the objectives of TDMA is to employ a single carrier for the transmission via one transponder. With TDMA, each earth station is allowed to transmit a high-speed burst of bits for a brief period of time. The times of bursts are carefully controlled so that no two bursts overlap. For the period of its bursts the earth station has the entire transponder bandwidth available to it. The set of bursts is illustrated in Figure 41. The first burst in a frame contains no

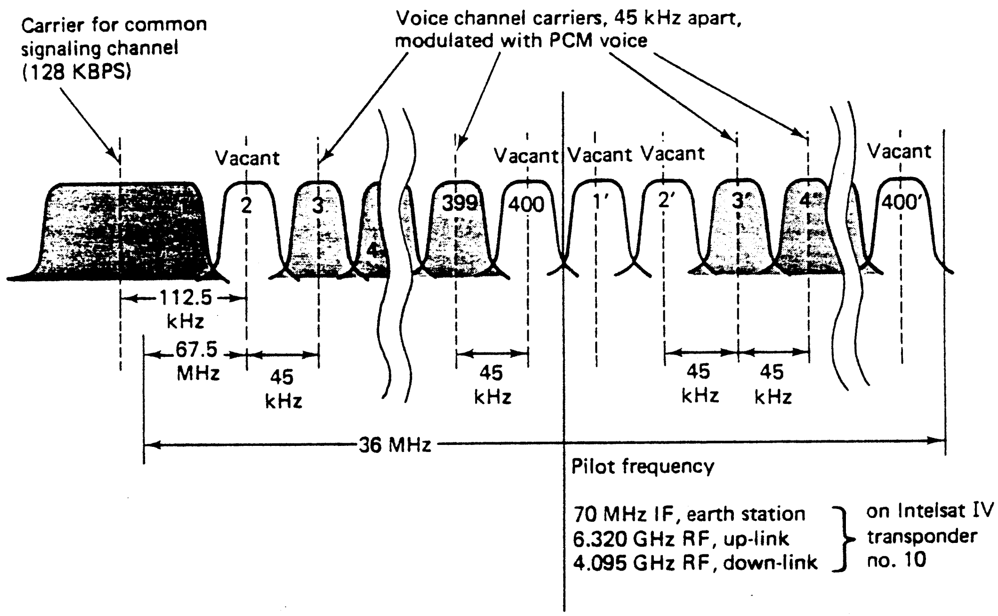


Figure 40. Frequency Multiple Access Method Example
(After Martin [35])

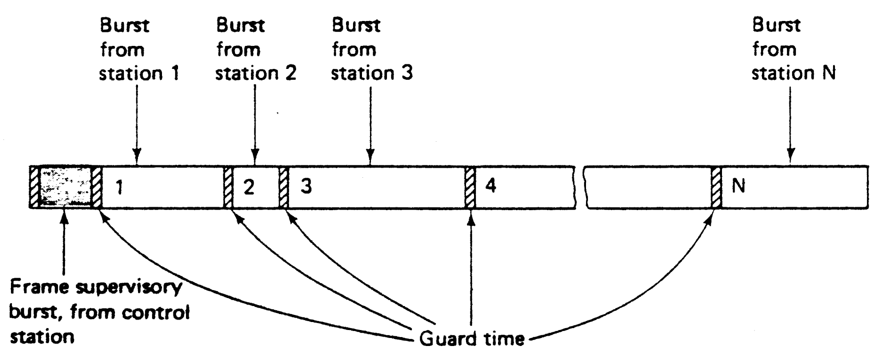


Figure 41. Time Division Multiple Access Method Example
(After Martin [35])

traffic but serves to synchronize and identify a frame. This method is superior to FDMA in such aspects as flexibility in channel capacity, no intermodulation interference, and no transponder saturation. However, TDMA has other types of problems associated with the synchronization and control of the high-speed digital bit stream.

2

VITA

Meemong Lee

Candidate for the Degree of

Doctor of Philosophy

Thesis: REVERSIBLE SIESMIC DATA COMPRESSION

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Junjoo, Korea, January 10, 1953, the daughter of Mr. and Mrs. Pooyung Lee.

Education: Graduated from Sookmyung Girl's High School, Seoul, Korea, in February, 1971; received the Bachelor of Science degree in Electronic Engineering from Sogang University, Seoul, Korea, in February, 1975; received the Master of Science degree in Information and Computing Science from Oklahoma State University in July, 1979; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in December, 1981.

Professional Experience: Assistant, Information and Computing Science Department, Oklahoma State University, from February, 1977, to May, 1978; Programmer, S.E.T.A.C., Stillwater, Oklahoma, from March, 1978, to May, 1979; Program Analyst, Applied Data Service Corp., Houston, Texas, from June, 1979, to December, 1979; Research Assistant, School of Electrical Engineering, Oklahoma State University, from January, 1980, to present.