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STUDY OF ON-BOARD COMPRESSION OF EARTH RESOURCES DATA

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EXECUTIVE SUMMARY

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This report is an Executive Summary of the Final Report on the Study of On-Board Compression of Earth Resources Data. The study was performed by TRW for NASA-Ames Research Center under contract NAS2-8394. Only highlights of the study are presented here. The reader is referred to the Final Report for more detailed treatments.

1. INTRODUCTION

NASA's LANDSAT (ERTS) program has provided a wide variety of users the opportunity to explore the utility of satellite-based earth resources observation. Although the full range of applications has not yet been addressed, the potential of such systems to earth resource management has been definitely established. Even at this early stage, many commercial and governmental agencies have expressed strong interest in the operational use of earth observations. The LANDSAT experiment has also shown that converting this potential into an operational system in which practical earth resource management can be accomplished requires extensive investments in communications, data handling, and data processing. These investments are continually increasing along with user requirements for increased spatial and spectral resolution, earth coverage, and data timeliness which imply sensor output and data processing rates of hundreds of megabits per second.

The objective of on-board data compression (source encoding) is to reduce costs and/or systems constraints incurred by high data rates in the sensor-to-ultimate user data handling chain. When the data rate and volume are reduced at the sensor, obvious benefits result. These include reduced on-board storage, simpler data transmission, simpler ground data recording, and fewer data tapes to archive. This is accomplished by exploiting statistical dependencies which exist between data samples in order to reduce the information rate.

Data compression has been the subject of much research and a large number of papers over many years. In spite of the progress made in this field, few spacecraft missions have been able to justify on-board data compression with its attendant risks in reliability and data alteration, and its cost in terms of size, weight, and power. The situation, however, has changed recently. Digital logic has become smaller, more reliable, less expensive, and much less power consuming for a given amount of processing. It now appears practical to actually implement an operational data compression system.

One of the principal considerations in selecting the most feasible data compression technique is the need for broadbased applicability. Earth observation experiments are charactized by general purpose sensors which are used by hundreds of investigators for many different purposes. Such a variety of users requires that the designer provide an information management system as broadly useful as possible within the cost constraints. Achievement of this maximum utility in terms of cost benefits and cost avoidance is a major tradeoff item.

1.1 NEED FOR DATA COMPRESSION OF EARTH RESOURCES DATA

By surveying the almost continuous studies of user needs for earth resources data, it is possible to judge trends in data requirements. One recent survey of these studies related data types, such as ocean survey, meteorology, agriculture, forestry, geology, and mineral resources to user community uses ranging from sea surface effects (temperature, roughness, etc.) to terrain mapping, atmospheric pollution, and severe storm warning. Additional factors such as data uses, data destination, data perishability, frequency of observation, and resolution can then be used to form candidate missions and sensor groupings to meet emerging needs. Figure 1 presents a summary of typical sensor/mission groupings.

SENSORS → MISSION ↓	IMAGING SENSORS	SPECTROMETERS	VISIBLE AND INFRARED RADIOMETERS	PASSIVE MICROWAVE RADIOMETERS	SYNTHETIC APERTURE RADAR
TERRESTRIAL SURVEY ENVIRONMENTAL QUALITY	x	x			
OCEAN SURVEY METEOROLOGICAL	x	x	x		
TERRESTRIAL SURVEY/ ENVIRONMENTAL QUALITY	x	x			x
OCEAN SURVEY/ METEOROLOGICAL			x	x	
TRANSIENT ENVIRONMENT PHENOMENA MONITORING			x		
TERRESTRIAL SURVEY ENVIRONMENTAL QUALITY	x	x			x
OCEAN SURVEY/ METEOROLOGICAL		x		x	
METEOROLOGICAL			x	x	x

Figure 1. Mission/Sensor Grouping

The sensors listed are typical of the major classes of earth resources sensors to be used in the post 1975 time frame. Among these, the highest data rates are achieved by the imaging sensors, which are often multispectral, and the synthetic aperture radar. One convenient way to look at the data rates of imagers is from the standpoint of the user oriented requirements shown in Figure 2. When projected into the 1980's these sensors lead to spacecraft missions with instantaneous composite data rates in excess of 700 Mbps and data volumes approaching 10^{12} bits per orbit. These high rate requirements are solidly based on known earth resources user community needs. Economic and/or political vicissitudes notwithstanding, the necessity of considering data compression tradeoffs in future earth resources mission studies is obvious. This report seeks to provide concrete results on multispectral data compression upon which to base such tradeoffs.

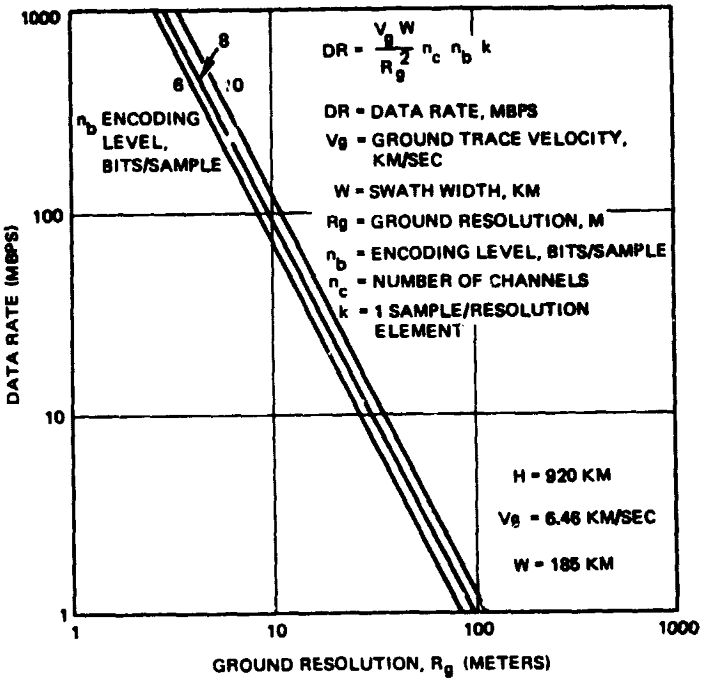


Figure 2. Data Rate vs Ground Resolution for Imagery Sensors

1.2 EXPECTED BENEFITS OF DATA COMPRESSION IN NASA EARTH RESOURCES PROGRAMS

The ultimate aim of data compression is to increase the cost-effectiveness of data management in operating earth resources systems. In most cases, the incremental cost of adding data compression is modest. Benefits, however, are usually realized by designing the data management system with integral data compression, not as an add on. There is little impact, for example, in reducing the data rate on an existing communications link if the released capacity cannot be used elsewhere to reduce cost. Cost benefits, in general, are quantitatively related to the compression ratio which is achievable within fidelity constraints. Although the exact relationships and demonstrability of cost savings may be complex, reductions substantially related to the compression ratio are expected. Some of the more obvious cases in which data compression will yield immediate benefits to NASA operating data management systems are:

- High data rate recording at low cost ground stations
- Relaying of data at moderate to high rates, via common carriers (e.g., domestic satellite) for quick look or fast reaction needs
- Maintenance of digital data bases on image analysis computer systems (disks, tapes, drums, etc.)
- Handling, transportation, and capital costs associated with digital (computer) tape distribution and recovery.

It must be recognized that the compression scheme used should be carefully matched to the application. General user applications, such as data archiving, will usually attain only modest compression (factors of 2 to 5). Specific users, however, who require only data subsets with specific characteristics, or who are satisfied with some loss of resolution either spectrally or spatially, can realize cost benefit ratios of 10 to 100. Achievement of some gains is immediately possible in the former case. Information preserving techniques developed under previous NASA studies can be implemented to reduce the cost of archiving and recalling data. In this case, special care is taken that the cost associated with reconstructing compressed data files is minimum because this operation will be repeated often. Compression, on the other hand, is performed only once, upon archiving, and can thus be more complex.

Two examples of data compression benefits to NASA programs are as follows:

Earth Observatory Satellite

One feature of this program is the ability to directly transmit imagery data to low cost user stations for their own processing. Cost considerations, however, dictate a reduced data rate from the 240 Mbps provided to primary stations. A 12 to 1 compression on-board the spacecraft would allow reception of full resolution data at a reduced rate. The only alternatives are various subsampling approaches such as sending 1/4 resolution in each spatial direction. This decreased resolution would severely limit the utility of the imagery to users, even to the point of jeopardizing the practicality of low cost stations.

Goddard Space Flight Center to Sioux Falls Link

The EOS system can produce imagery totaling 10^{12} bits per day. After GSFC processing, this data must be transmitted to the EOS data center at Sioux Falls, S.D. A continuous 10 Mbps link would be required for this transmission for which costs via domestic comsat can exceed $1,000,000 per year. A 4 to 1 compression ratio could provide approximately $750,000 in annual savings.

2. PURPOSE OF THE STUDY

The purpose of the study was to provide NASA with comprehensive tradeoff data and specific recommended methods of on-board data compression for use in planning and configuring both present and future earth resources programs. This study forms a natural second step to previous NASA funded studies of data compression techniques for multispectral imagery which were more limited in scope and considered only a few specific algorithms. General Electric and Philco-Ford restricted their investigations to rather elementary schemes which were very simply implementable for on-board use. Purdue University considered more complex (transform) techniques and demonstrated their performance on both aircraft and satellite multispectral scanner data. TRW Systems and Purdue University performed parallel studies under the ERTS (now LANDSAT) program to compress multispectral scanner imagery using errorless codes for both archiving and on-board application.

These studies exhibited a number of very basic differences. For one, they were forced to use different data bases due to the sequencing of NASA programs and thus a meaningful comparison of results was difficult. Furthermore, they did not, in general, include important systems parameters such as the effects of channel noise and sensor peculiarities on individual algorithm performance. And finally, the use of differing criteria of optimality and fidelity caused difficulty in applying their results to on-going NASA programs.

The present study is much more comprehensive and unified. It applies a common set of data, criteria, and system parameters and considers a broad range of data compression techniques. The aim was to find the techniques most suitable for multispectral imagery and which inject minimum distortion as measured by a variety of fidelity criteria. Most unique among the criteria was classification accuracy which recognized that many end users employ only specific processing of their data products. Subjective evaluation of typical imagery products was also used. An additional objective was to obtain parametric results which could be used by NASA in future program planning. This included a requirement to deliver all computer simulations to both the Ames and Marshall NASA Centers.

3. STUDY APPROACH

The basic study approach taken is summarized in Figure 3. The study began with a survey of the current literature on image bandwidth compression and selection of those methods relevant to compression of multispectral imagery. Typical satellite multispectral data was then analyzed statistically and the results used to select a smaller set of candidate bandwidth compression techniques particularly relevant to earth resources data. These were compared using both theoretical analysis and simulation, under various criteria of optimality such as mean square error (MSE), signal-to-noise ratio, classification accuracy, and computational complexity. By concatenating some of the most promising techniques, three multispectral data compression systems were synthesized which appear well suited to current and future NASA earth resources applications. The performance of these three recommended systems was then examined in detail by all of the above criteria. Finally, merits and deficiencies were summarized and a number of recommendations for future NASA activities in data compression proposed.

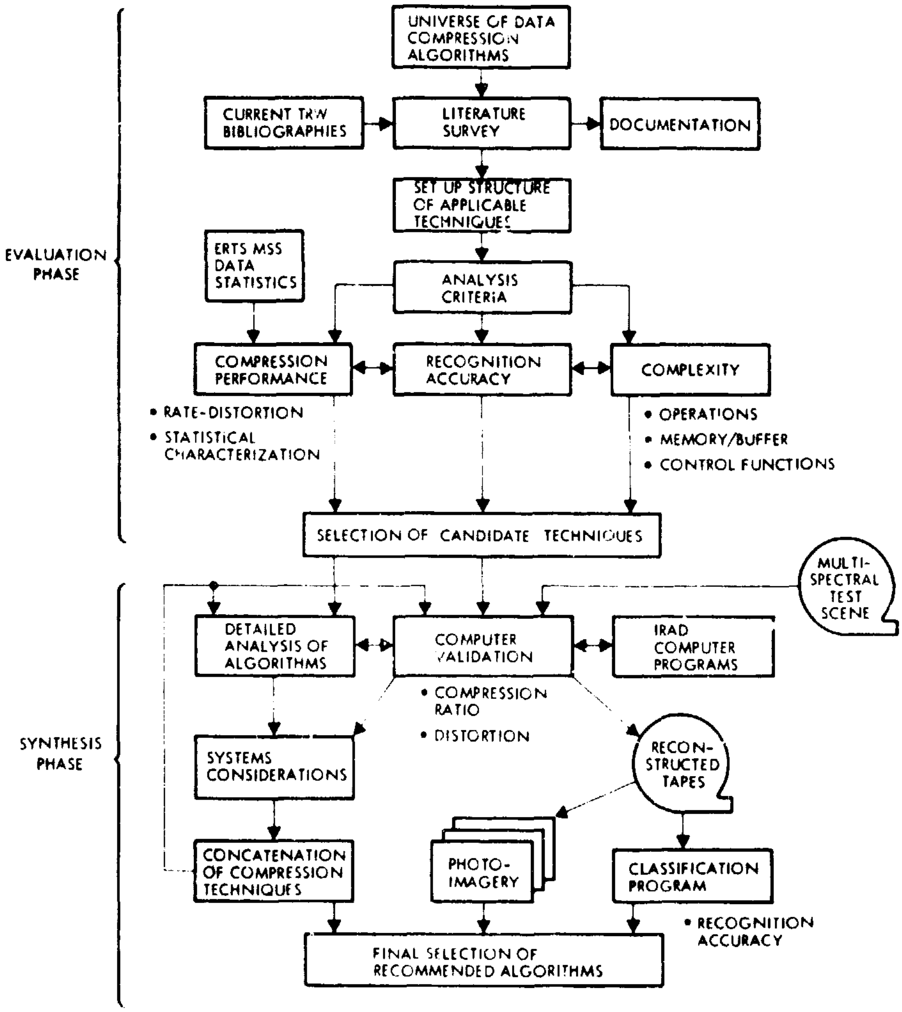


Figure 3. Flow Diagram of the Study

Several comments are relevant to assumptions and limitations pertinent to this study:

(1) Only two sets of multispectral data were used in analysis and simulation of the various data compression algorithms. One four-band LANDSAT MSS image was relied upon heavily in arriving at data statistics and determining relative performance. This scene (Imperial Valley, California), which is quite representative of earth resources data, has been intensively studied by other investigators, and contains a rich mixture of high and low detail, brightness levels, and colors. A second, entirely different type, 12-channel multispectral image was used to verify the generality of major results and conclusions. It was supplied by the Laboratory for Applications of Remote Sensing (LARS).

(2) The study considers largely nonadaptive, rather than adaptive, methods for compressing multispectral image data. Nonadaptive image coding methods are better established and tested, are easier to implement, and in general are less data dependent. However, in the past year (1975) a number of adaptive algorithms for coding images have been developed which deserve further consideration in specific application studies.

(3) The study includes computational complexity of the various compression methods and presents tables for comparison in terms of number of arithmetic operations and storage requirements. However, hardware implementation tradeoffs specifying design complexity were considered beyond the scope of this study.

4. MAJOR CONSIDERATIONS IN DATA COMPRESSION FOR EARTH RESOURCES DATA

4.1 NATURE OF MULTISPECTRAL IMAGE DATA

As indicated above, this study concentrated on the compression of multispectral imagery because, of all earth resources data types, it has by far the greatest potential for cost savings. This results from the high data rates and volumes involved. Figure 4 illustrates typical multispectral image digital data as produced by a multispectral scanner (MSS). Each spectral band is a separate image of the same exact ground area made up of discrete sampled points called picture elements (pixels). Pixels corresponding to the same ground point are precisely aligned from one spectral image to another as indicated. This registration is inherent in most MSS's and is important for good data compression because it maximizes the correlation of data intensity between adjacent pixels.

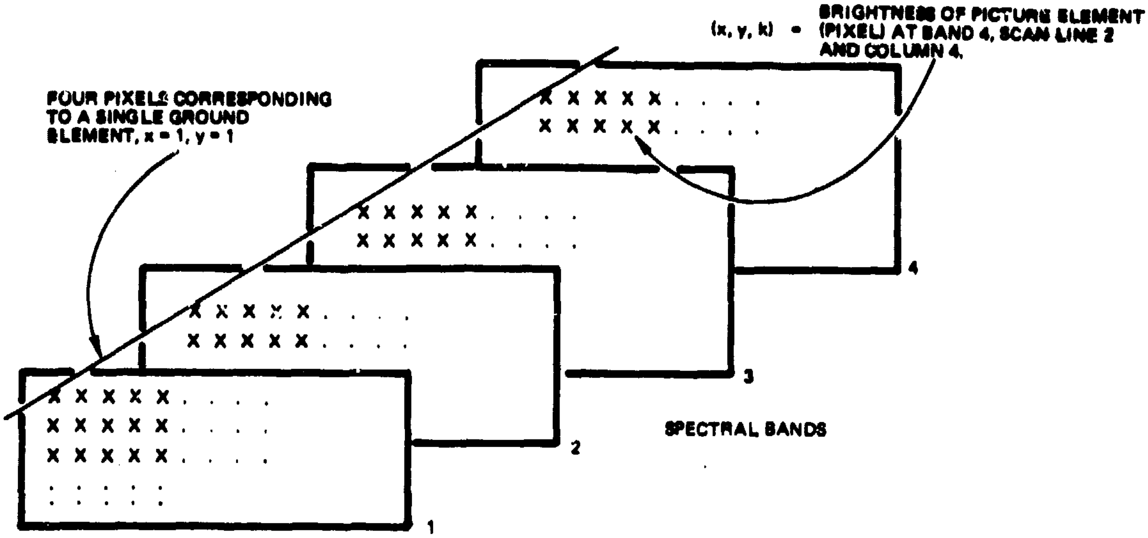


Figure 4. Illustration of Typical Multispectral Image Data

A typical image size in earth resources applications is 4000 x 4000 pixels (which in LANDSAT was some 100 nmi x 100 nmi). If each pixel is quantized to 8-bit accuracy and there are four bands, one multispectral image requires 4000 x 4000 x 8 x 4 = 512 million bits for full representation. Note that each ground element can be considered as represented by a four element vector which is a unique point in four-dimensional multispectral space. Many processing and compression schemes involve manipulation of these vectors.

4.2 CRITERIA FOR COMPARING BANDWIDTH COMPRESSION TECHNIQUES

For data compression to be possible, one or both of two conditions must be satisfied. The first is that the data have some structure or redundancy. By knowing something about the data structure, data compression can be accomplished without losing any of the information the data contains. Data compression that relies solely on knowledge of data structure is called information preserving or error free data compression. The second condition is that the image user have interest in only limited accuracy or a particular aspect of the data collected. In this case, the data of low value to the user can be discarded, resulting in data compression. Since information discarded is permanently lost, compression based on user interest is called information destroying data compression.

Information discarded by the compression process causes differences in the original and reconstructed images. The fundamental theoretical problem in data compression is to choose a technique which drives this distortion as low as possible at a given transmission rate. However other factors, such as susceptibility to channel errors and complexity of the compressor, are also important in practical systems. Several pertinent comparison criteria are discussed below.

The clustering method serves well for measuring how well classification accuracy is preserved after data compression. To be fair, we assume that the original image and the reconstructed image are clustered separately, but by the same process. Call the first space of undistorted (precompression) measurements X, and the distorted (compressed and reconstructed) measurements Y. For the classification accuracy to be preserved, the two partitions should be such that if y is a distorted value corresponding with x, then the category to which y belongs should be the same as the category from which x came. From Figure 5, it is seen that class 1 and class 2 can be distinguished equally well in the space X and the space Y with the appropriate partitions. Under certain distortions D, however, it may not be possible to preserve classification accuracy. The percentage of picture elements classified differently in the original image and the reconstructed image is used as the classification inaccuracy for the particular bandwidth compression method.

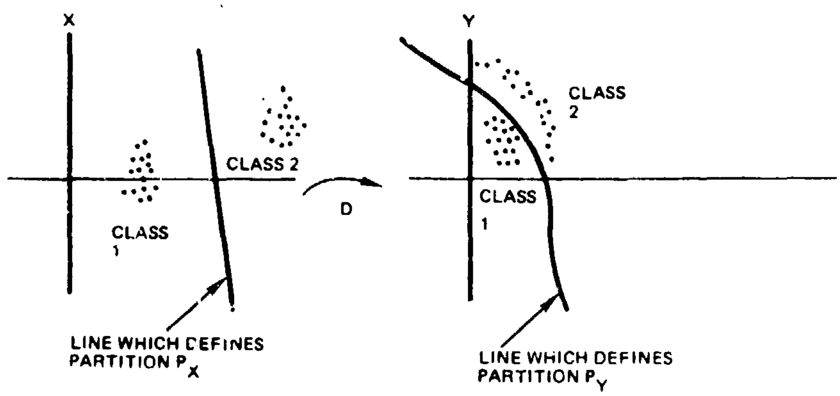


Figure 5. Partitioning Data in Two Classes Before and After Distorting the Data

Implementation Complexity

Once it is shown that several compression techniques can signficantly reduce the required data rate without introducing unacceptable distortion, it is necessary to compare their implementation complexity. Compressor complexity is a particularly significant factor for spacecraft applications. Reconstruction complexity on the ground has less effect on overall system costs. From a strictly algorithmic level, complexity may be measured by the number of computations per pixel. However, a breakdown by arithmetic operations, such as add/subtract, multiply/divide, and memory operations, is required for closer comparison of compression techniques. Data storage requirements are often the significant complexity factor. It should be noted that both memory and computation rates are sensitive to the particular multispectral scanner assumed.

Sensitivity to Sensor Effects

Certain properties of the detectors used in multispectral sensors affect the data structure and thus in turn interact with compression performance. The specific distortion introduced varies with the compression technique. As a typical imaging sensor to be used in the next decade, consider the thematic mapper projected for NASA's Earth Observatory Satellite (EOS) program. It is a multispectral scanner using photodiodes as transducers and a moving mirror to scan lines perpendicular to the satellite's track. The properties that cause distortion during data compression are nonuniformity and nonlinearity of the photodiodes' gain response and spectral misregistration due to the optics and scanning patterns. In this study, these variations are modeled statistically and then related to increased mean square error.

4.3 BANDWIDTH COMPRESSION METHODS FOR MULTISPECTRAL IMAGERY

Many techniques exist for compressing monochrome images and they are richly described in the literature. Since a multispectral image can be thought of as N monochrome images (for N spectral bands), one approach is to compress each monochrome image separately by any one of the standard techniques. This tends, however, to ignore any redundancy existing in the spectral domain. Suppose that the brightnesses recorded in different bands were correlated. Then the distribution of vectors would lie primarily in some hyperplane in the multispectral space, S. This, in turn, would imply that the data has structure which can be taken advantage of for data compression, since the hyperplane has a lower dimension than the original space. Transformation to a new basis vector set is often used for this purpose. In its optimum form, the transformation finds an ordered set of basis vectors (called principal components) for S which have the property that the first basis vector points in the direction of the greatest data variance, the second basis vector points in that direction orthogonal to the first basis vector having the next greatest variance, and so on. This results in a new set of monochrome images in which most of the information is in only one or two bands and the other bands appear very nearly uniformly grey. Data compression is accomplished by quantizing most finely the data in the important bands and either discarding or coarsely quantizing the remainder.

Transform Coding

Typical mathematical transformations used for the above processes are the Fourier, Hadamard, and Karhunen-Loeve. Each has its advantages and disadvantages in terms of performance and complexity of implementation. The transform process can also be carried out one or two dimensionally in a monochrome image with compression taking place via quantization of the coefficients in the transform domain. The data compression literature shows this to be the preferred technique for compressed data rates less than 2 bits per pixel.

Differential Pulse Code Modulation (DPCM)

There are many variants of DPCM, but all utilize a predicted value $\hat{X}$ which is a function $P(\cdot)$ of past data, a subtractor, a quantizing function, and a coding function as shown in Figure 6. Reconstruction, in the absence of channel errors, is accomplished by decoding the channel symbol stream and reproducing $\hat{X}$ by duplicating the predictor function. The only distortion in DPCM is introduced by the quantizer which utilizes only m levels to represent the error signal ε, and thus establishes a bit rate of $\log_2 m$ bits per pixel.* In general, DPCM produces superior reconstructed images at rates greater than 2 bits per pixel and is preferred to transform coding in that range. An additional attraction is its simplicity of implementation favoring on-board applications.

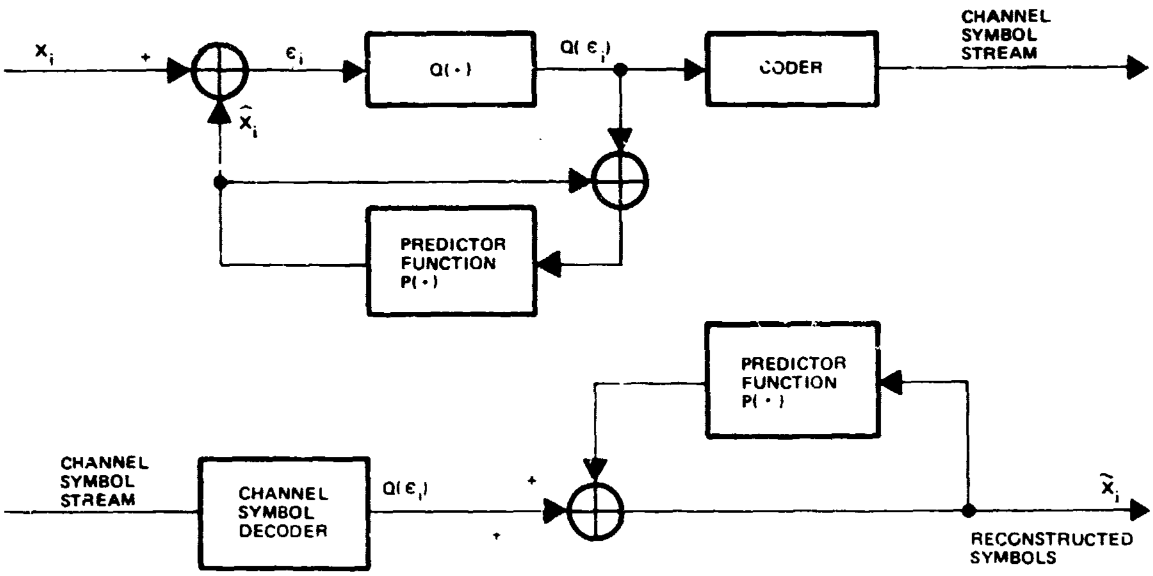


Figure 6. Generic DPCM Encoder and Receiver

Hybrid Transform/DPCM Techniques

In addition to DPCM and transform coding techniques, hybrids of the two have shown good performance for both intra- and inter-frame coding of television signals. These systems as applied to MSS data can be divided into three categories:

1) Systems that perform a two-dimensional transform in each band of the MSS data and use a bank of DPCM encoders to process the transformed coefficients across the individual bands

2) Systems that take a transform across the spectral bands and use different two-dimensional DPCM encoders to compress the data in each transformed band

*The well known delta modulators are defined as DPCM with m = 2; i.e., 1 bit per pixel.

3) Systems that follow a transformation across the spectral bands by a second transform in the horizontal direction (scan direction) and a DPCM encoder in the vertical direction separately for each transformed band.

Techniques 2) and 3) are shown in this report to hold good promise for earth resources data applications.

Cluster Coding of Multispectral Data

For many classification applications, multispectral data is first used to obtain a clustered image as described previously. This presents an alternate approach to compressing the bandwidth of multispectral imagery consisting of classifying the multispectral data on-board the space vehicle and transmitting only the clustered imagery. That is, at each pixel location, instead of transmitting the multidimensional vector, only the cluster number to which the pixel belongs is sent. Subjectively, the reconstructed multispectral images are very good but any single band image can be heavily degraded. Thus cluster coding is excellent for some users and not acceptable for others. Different approaches to this method of bandwidth compression have appeared in the re[illegible] literature.

5. STUDY RESULTS

5.1 LITERATURE SURVEY

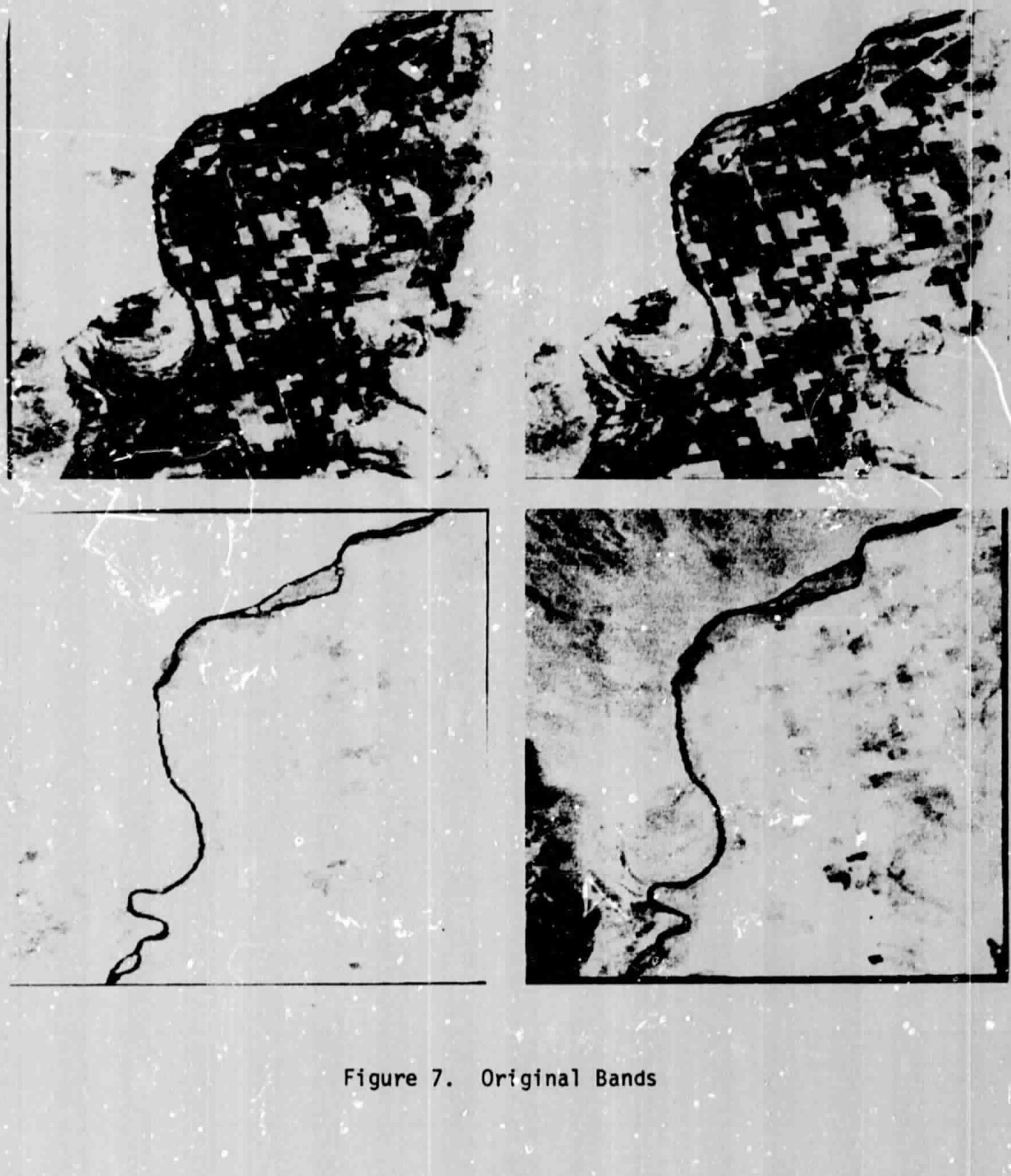
As a beginning point for the study, some 150 references relevant to d[illegible]pression of remotely sensed earth resources imagery were compiled. Each reference includes keywords and a brief description of its contents. This bibliography is included as an appendix of the Final Report. The literature survey is broken into three areas consisting of:

- Requirements, methods, and applications of remote sensing
- Data compression techniques relevant to imagery
- Techniques and applications of automatic classification to remotely sensed imagery.

Twenty-two generic classes of compression techniques were identified as relevant to the study. They fell into the four general categories of transform coding, predictive coding, entrophy coding, and cluster coding.

5.2 MULTISPECTRAL SCANNER DATA CHARACTERISTICS

The four bands of a typical LANDSAT MSS image are shown separately in Figure 7. This 256 x 256 pixel image was taken o[illegible] the Imperial Valley in California and includes agriculture, mountains, deser[illegible] d water. It is a good test image for data compression because it has both very high (field boundaries and river) and low (desert) spatial frequencies. Measurements reveal that the data in each band has an exponential



MSS-4
Green

MSS-5
Red

MSS-6
Infrared
No. 1

MSS-7
Infrared
No. 2

Figure 7. Original Bands

spatial correlation in both the horizontal (across track) and vertical (along track) directions. This indicates that one and two-dimensional DPCM should perform well. Furthermore, the spatial correlation remains exponential after application of any of the popular unitary transforms (KL, Fourier, Hadamard, Haar, or Slant). Figure 8 shows the spatial correlation in each band of the LANDSAT image after a Haar transform.

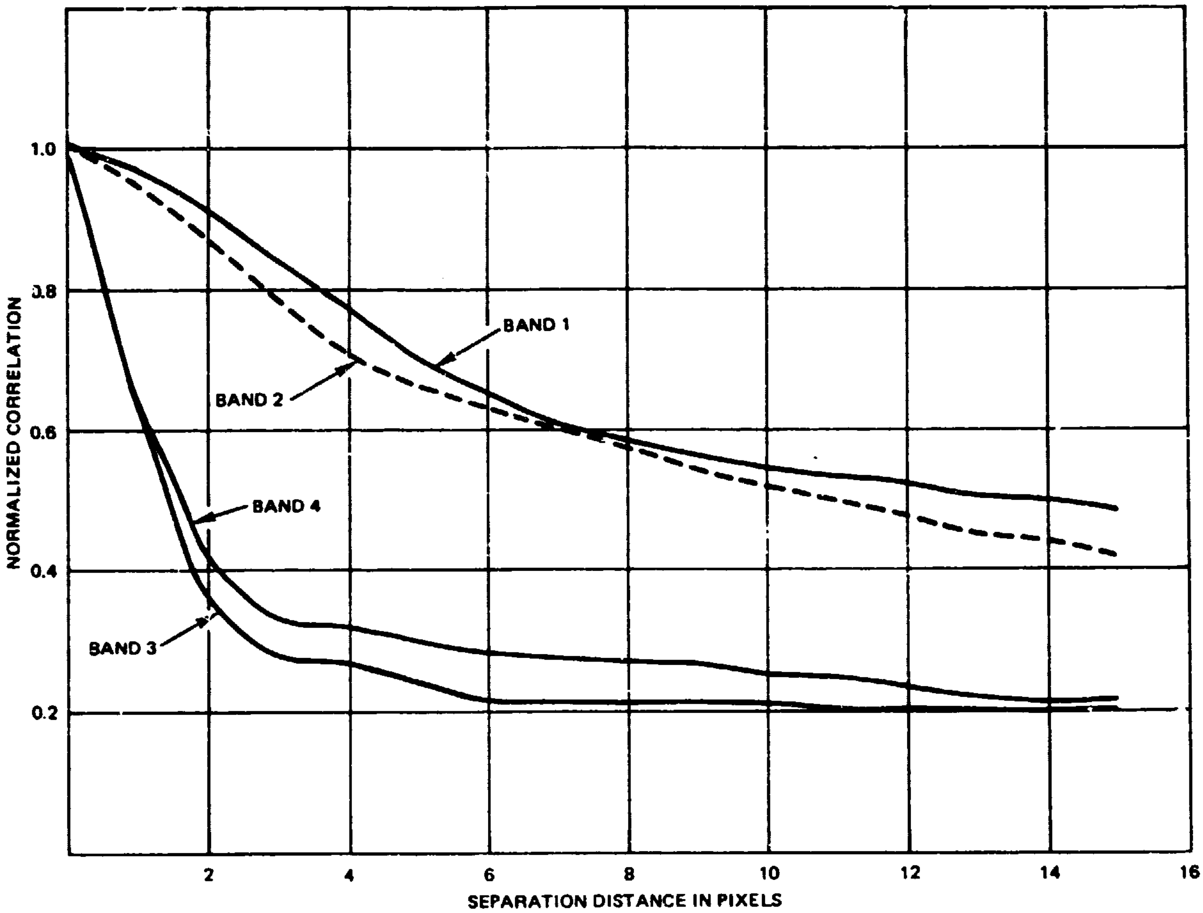


Figure 8. Spatial Correlation of Transformed Bands after Haar Transform of Multispectral Image

Spectral correlation, however, does not vary exponentially from band-to-band. Indeed the various bands show similarities and differences which are not usually found in other applications such as color television. Table 1 shows a typical spectral correlation measured for the LANDSAT image of Figure 7, and may be summarized as:

- Large positive correlation between the red (MSS-5) and green (MSS-4) boards
- Large positive correlation between the two infrared bands (MSS-6 and MSS-7)
- Small negative correlation between the red and the two infrared bands.

While these correlations apply on the average, they do not apply for many particular object classes - water being one counterexample.

Table 1. Spectral Correlation Matrix of the Representative MSS-LANDSAT Data

	RED	GREEN	IR#1	IR#2
RED	1.000	.866	.276	-.141
GREEN	.866	1.000	.288	-.177
IR#1	.276	.288	1.000	.654
IR#2	-.141	-.177	.654	1.000

5.3 SELECTION OF CANDIDATE TECHNIQUES

In order to arrive at a smaller list of specific compression techniques, the 22 generic classes from the literature survey were examined for their applicability to multispectral scanner generated data. Specific attention was paid to how each would perform on data with the spatial and spectral correlations just described. The following techniques were found to be viable candidates:

1) Three-dimensional transform coding with block quantization using either the Fourier, Hadamard, Slant, or Cosine transforms.

2) Mixed three-dimensional transforms using the optimal Karhunen-Loeve (K-L) transform across the spectral bands and either the Fourier, Hadamard, or Cosine transform two dimensionally in each transformed band.

3) Two-dimensional spatial transform (either Fourier, Cosine, or Hadamard) followed by DPCM from band-to-band, separately for each transform coefficient.

4) Optimal K-L transform across the spectral bands and two-dimensional DPCM in each transformed band.

5) Optimal K-L transform across bands and hybrid coding (Cosine/DPCM) in each transformed band.

6) Cluster coding algorithms.

5.4 EXPERIMENTAL RESULTS

The above candidate methods were then subjected to both theoretical and experimental analysis in the data rate ranges of 1/2 to 2 bits per pixel. A very complete comparison of computational complexity was performed and sensitivity to sensor effects estimated. The criteria of optimality discussed in Section 4 were used. Based on these evaluations and simulations, a set of three recommended techniques was derived:

1) K-L transform across the spectral bands followed by two-dimensional DPCM in each transformed band (denoted KL-2D DPCM)

2) K-L transform across the spectral bands followed by the hybrid Cosine transform (across track or horizontally) and DPCM on the transform coefficients (along track or vertically)

3) The cluster coding technique.

Although future sensors may exhibit different data statistics, this selection will, with high probability, not change. Only specific parameters of each technique need be optimized.

The KL transform requires extensive computation because it is data dependent. For the spectral transform it may, however, be replaced with the deterministic Haar transform with little loss in fidelity. Similarly, in 2), the much simpler Hadamard or Slant transforms can replace the Cosine spatial transform. It was found that eliminating the spectral transformation altogether in 1) and 2) increases the MSE by a factor of about 1.4.

5.4 COMPARISON OF THE RECOMMENDED TECHNIQUES

In the following the three recommended techniques are compared under various criteria of optimality such as MSE, recognition accuracy, and computational complexity. The performance of methods 1) and 2) is also evaluated in the presence of channel noise.

5.4.1 Comparison of MSE and Signal-to-Noise Ratio Performance

Figure 9 shows the performance (i.e., bit rate vs distortion) of the three techniques. Signal-to-noise ratio is used as a criterion of distortion. It is directly related to MSE as given. It is seen that the KL-2D DPCM encoder performs significantly worse than the KL-Cosine-DPCM at low bit rates but their performance is similar at higher bit rates (about 2 bits per sample per band). The performance of cluster coding is just the opposite. It is superior to the others at low bit rates and inferior at high rates. Figure 9 also shows the performance of the KL-Cosine-DPCM and KL-2D DPCM encoders in concatenation with a variable rate (entropy) encoder. The optimal zero-order Huffman code is used which reduces the output bit rate by assigning short code words to the more probable quantizer output levels and longer words to the less probable. The effect is more dramatic (average 25% improvement) on the KL-2D DPCM than on the KL-Cosine-DPCM (10% improvement). Being an information preserving code, this technique lowers the rate while adding no distortion at a modest cost in complexity.

5.4.2 Comparison Based on Recognition Accuracy

Figure 10 shows the performance of the three recommended bandwidth compression methods in preserving the classification accuracy of the reconstructed multispectral imagery. Using the criterion defined in Section 4.2, the comparative performance of

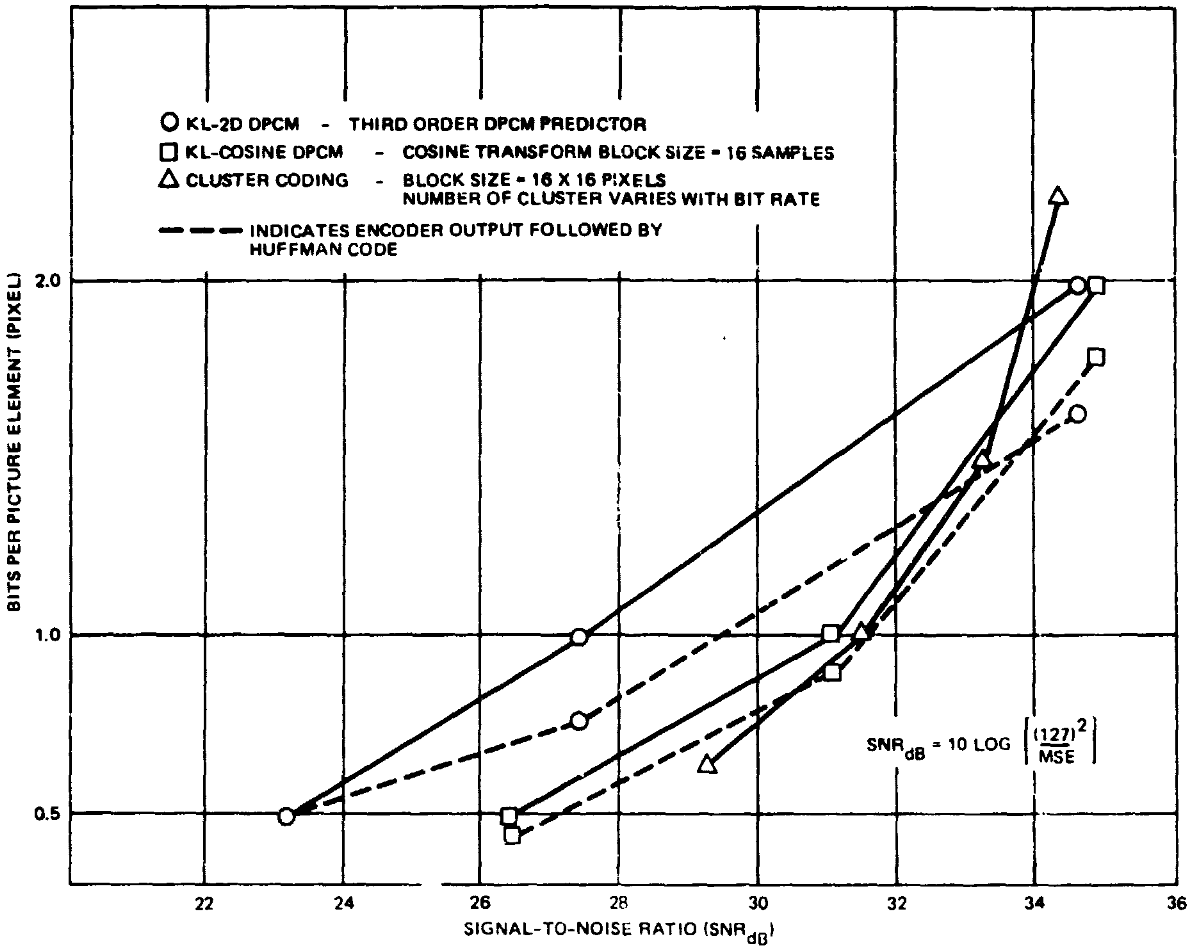


Figure 9. Bit Rate vs Signal-to-Noise Ratio

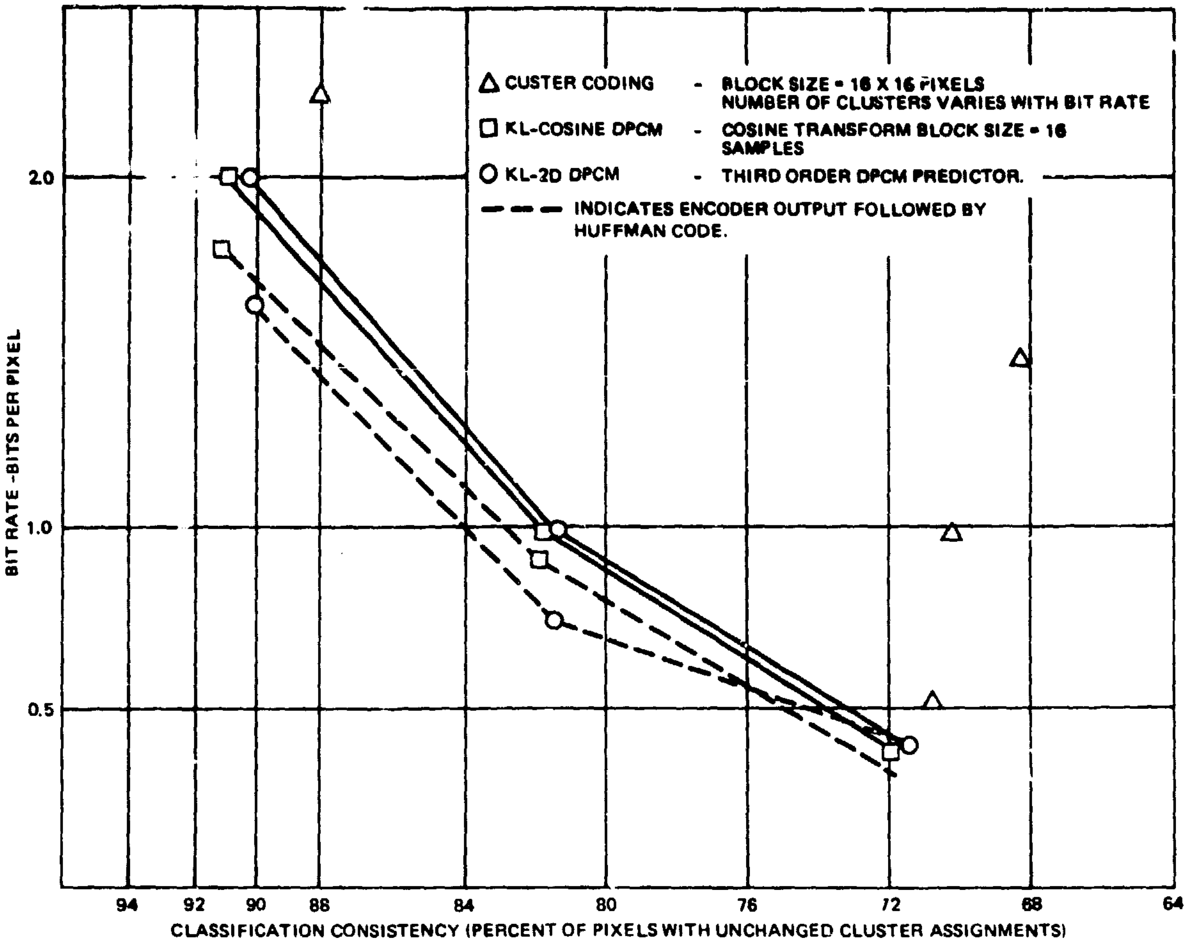


Figure 10. Bit Rate vs Classification Consistency

the KL-2D DPCM and KL-Cosine-DPCM is basically the same as when using signal-to-noise ratio. This suggests a strong correlation between MSE and classification accuracy, as performance criteria for selecting compression techniques.

Surprisingly, the classification accuracy of cluster coding decreases with increasing rate over a large range of rates. This behavior is due to the cluster coding procedure using a fixed size block (16 x 16 pixels) and varying the number of clusters per block while classification accuracy is measured with a 256 by 256 pixel block. 100% classification accuracy would result if the block sizes were the same. The use of large block sizes in multispectral image classification depends very much on the user and application. Large block sizes are likely to be used where one is only interested in a limited number of objects in a large segment of imagery, as in hydrology and urban planning. The results shown here for cluster coding are thus largely a result of the technique chosen for comparison and may be better or worse in a specific application.

5.4.3 Comparison of System Complexity

The computational complexity of the three recommended techniques is summarized parametrically in Table 2. The results are in terms of the number of computations and required memory per pixel. This table also shows typical numbers for four-channel (e.g., LANDSAT) data and the block sizes used in the simulations. An analysis of the complexity of the cluster coding method was not performed. However, based on the computer time required for cluster coding the LANDSAT data (Figure 7) and comparing it with the computer time required for the KL-2D DPCM, it was concluded that the cluster coding algorithm is about one order of magnitude more complex.

Table 2. Computational Complexity of the Three Recommended Techniques

Compression Technique	Computational Requirements (Number of Operations per Pixel)		Storage Requirements	
	Adds (or subtracts)/ Pixel	Multiplies/ Pixel	Record Storage	Memory
3-Dimensional Hadamard Transform and Block Quantization	$Log_2B^2S + T$ (Typically 11)	1 (Typically 1)	16BSW (Typically 3,300,000 bits)	$44B^2S + 8000$ (Typically 54,000 bits)
KL-2D DPCM	S + T + 3 (Typically 8)	S + 4 (Typically 8)	16SW (Typically 200,000 bits)	$16S^2 + 148S + 8000$ (Typically 9000 bits)
KL-Hadamard DPCM	$Log_2B + S + T + 1$ (Typically 8)	S + 2 (Typically 6)	32SW (Typically 400,000 bits)	84BS + 32B + 32S(S + 1) + 8000 (Typically 15,000 bits)

PARAMETER	TYPICAL VALUES
B = Block size	16
T = Bits/pixel	1
S = Spectral Bands	4
W = Sample in each scan	3200

5.4.4 Comparison of Channel Noise Effects

Both signal-to-noise ratio and classification accuracy are degraded by intoduction of a noisy transmission channel between the compressor and reconstructor. The results shown in Figure 11 refer to a binary symmetric channel with bit error rates ranging from 10^{-2} to 10^{-4} and a compressed data rate of 1 bit per pixel. Both algorithms degrade significantly at higher bit error rates ($\geq 10^{-3}$) with the Haar-2D DPCM somewhat worse. Figure 12 shows the reconstructed infrared band (MSS-6) at BER's = 10^{-3} and 10^{-4} after compression to 1 bit per pixel by the Haar-2D DPCM. At this rate, only a few errors are expected at 10^{-4} but propagation of channel error effects is clearly visible at

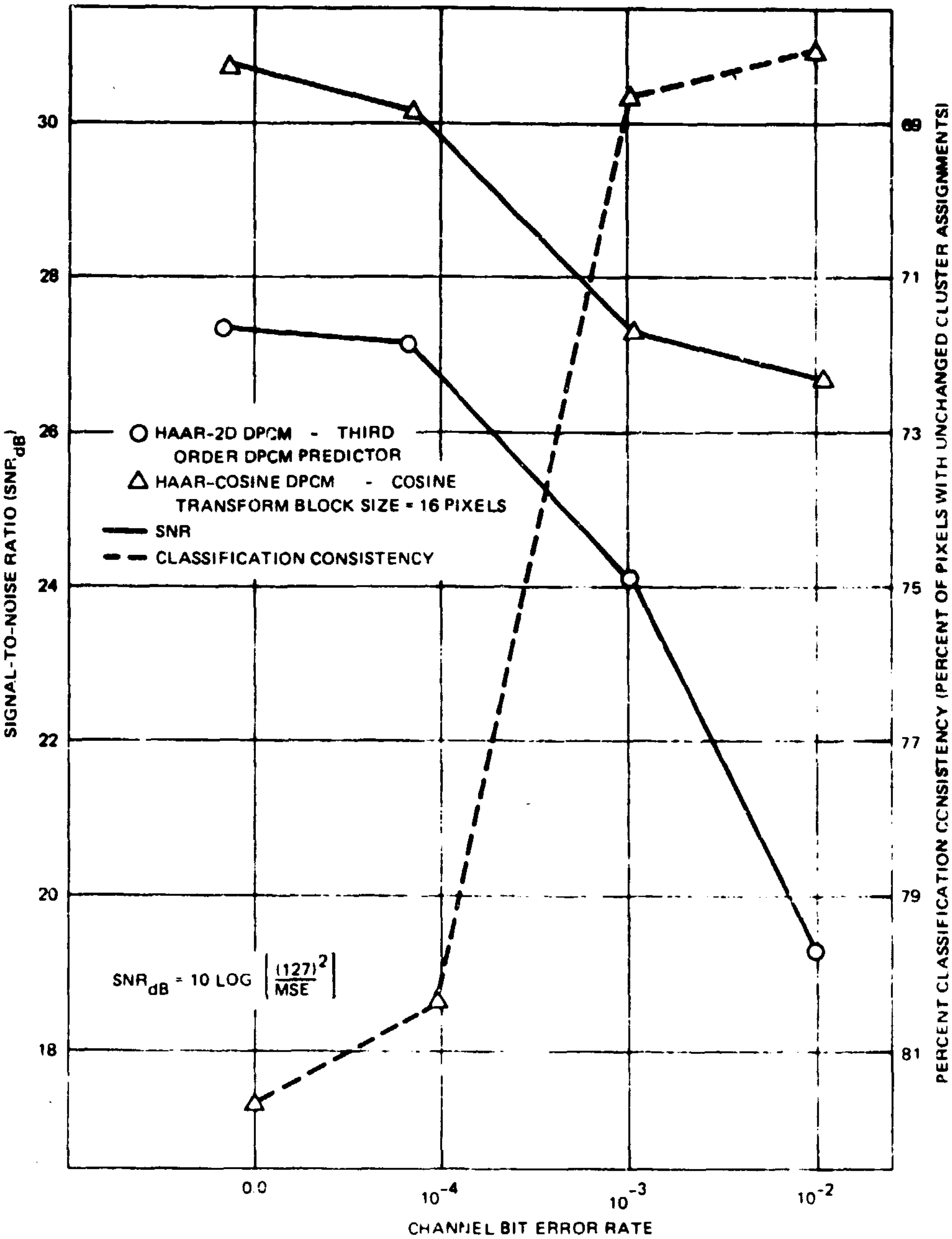


Figure 11. Signal-to-Noise Ratio and Classification Consistency vs Bit Error Rate

$P = 10^{-4}$ $P = 10^{-3}$

Figure 12. Band 3, 1-Bit Haar-2D DPCM

10^{-3}. This is still less significant than if simple two-dimensional DPCM were used because, with the Haar, an error occurring in one transformed band is redistributed amongst all spectral bands upon inverse transforming at the reconstructor. Although this leaves the total error unchanged, it distributes it amongst all spectral bands and makes both individual bands and the composite less objectionable.

5.4.5 Subjective Comparison of Reconstructed Imagery

Much of the user analysis of multispectral imagery is still performed using color composites. For this reason, a large number of techniques were compared at different data rates using reconstructed hard-copy images. Figures 13 through 15 show the individual reconstructed bands of KL-2D DPCM at 2 bits per pixel (1.5 bits per pixel with variable length encoding), the Haar-Cosine-DPCM at 1 bit per pixel, and cluster coding at 1 bit per pixel. The following observations are made here and expanded upon in the Final Report:

- Comparison with the originals shows very little degradation at 2 bits per pixel
- Subjectively, the individual bands from the cluster coding method are inferior to the Haar-Cosine-DPCM
- The subjective quality of the color composites for cluster coding is superior to the Haar-Cosine DPCM mainly because cluster coding does not inherently alter spatial frequencies.

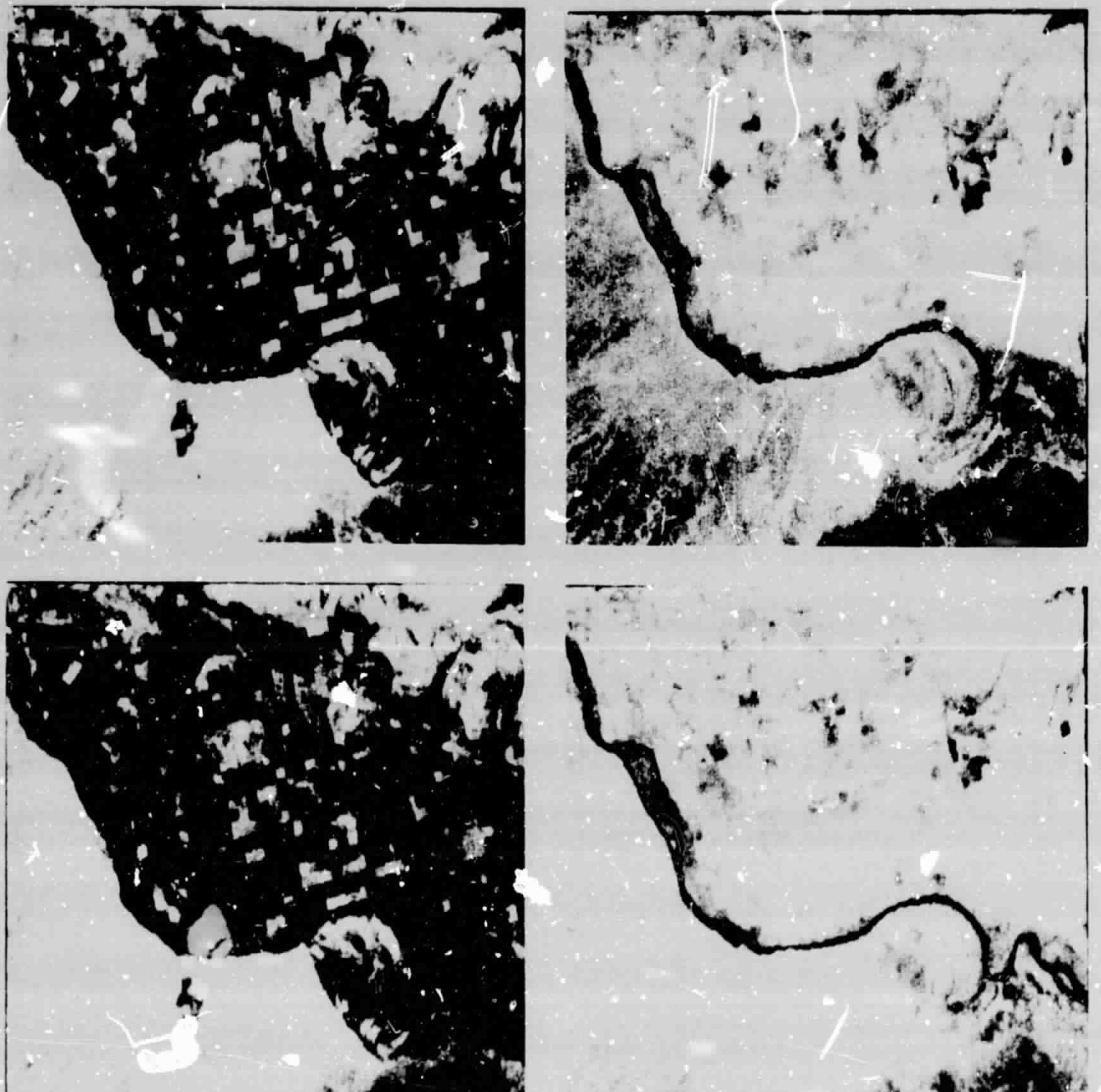


Figure 13. 2-Bit KL-2D DPCM

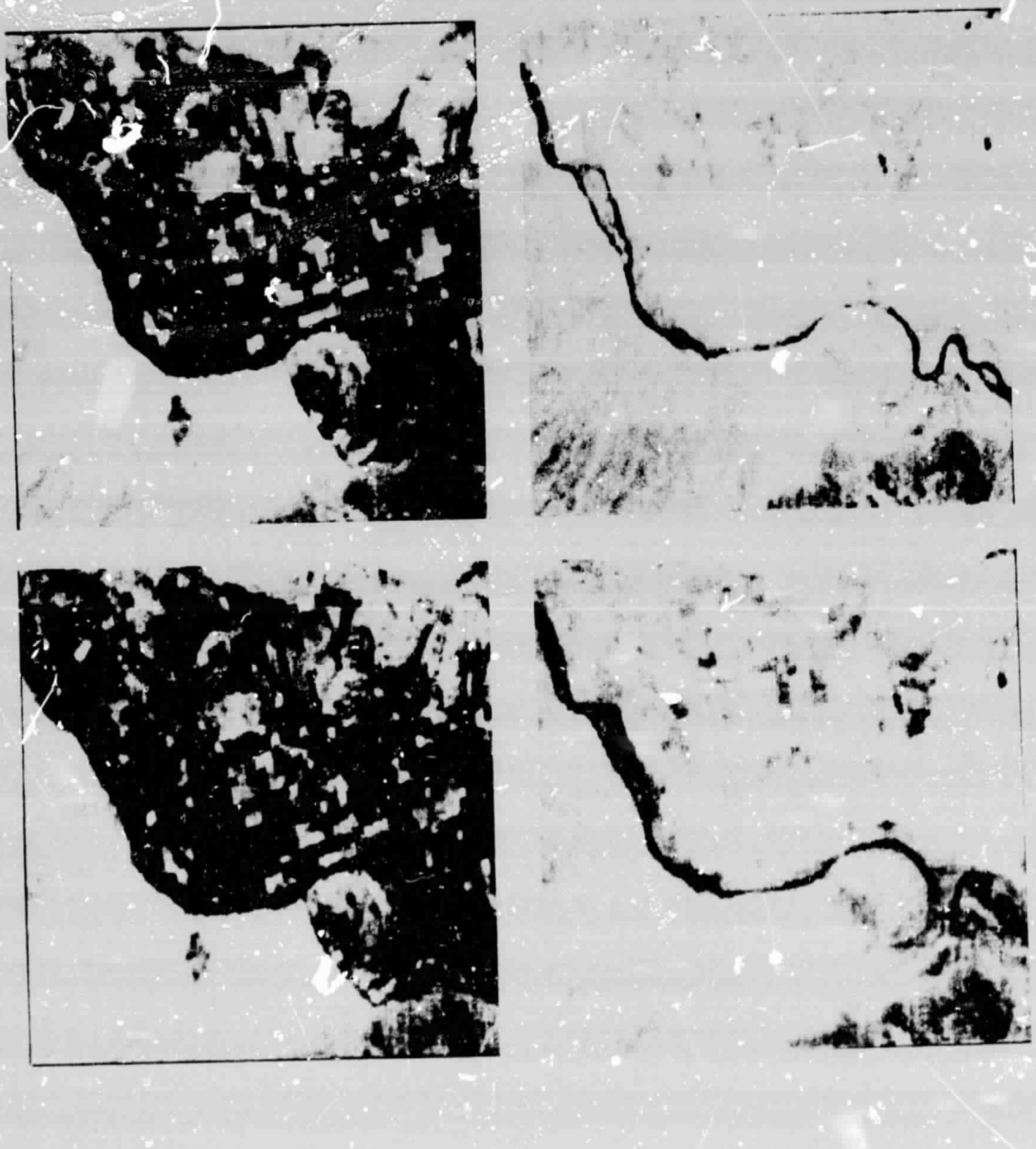


Figure 14. 1-Bit Haar-Cosine DPCM

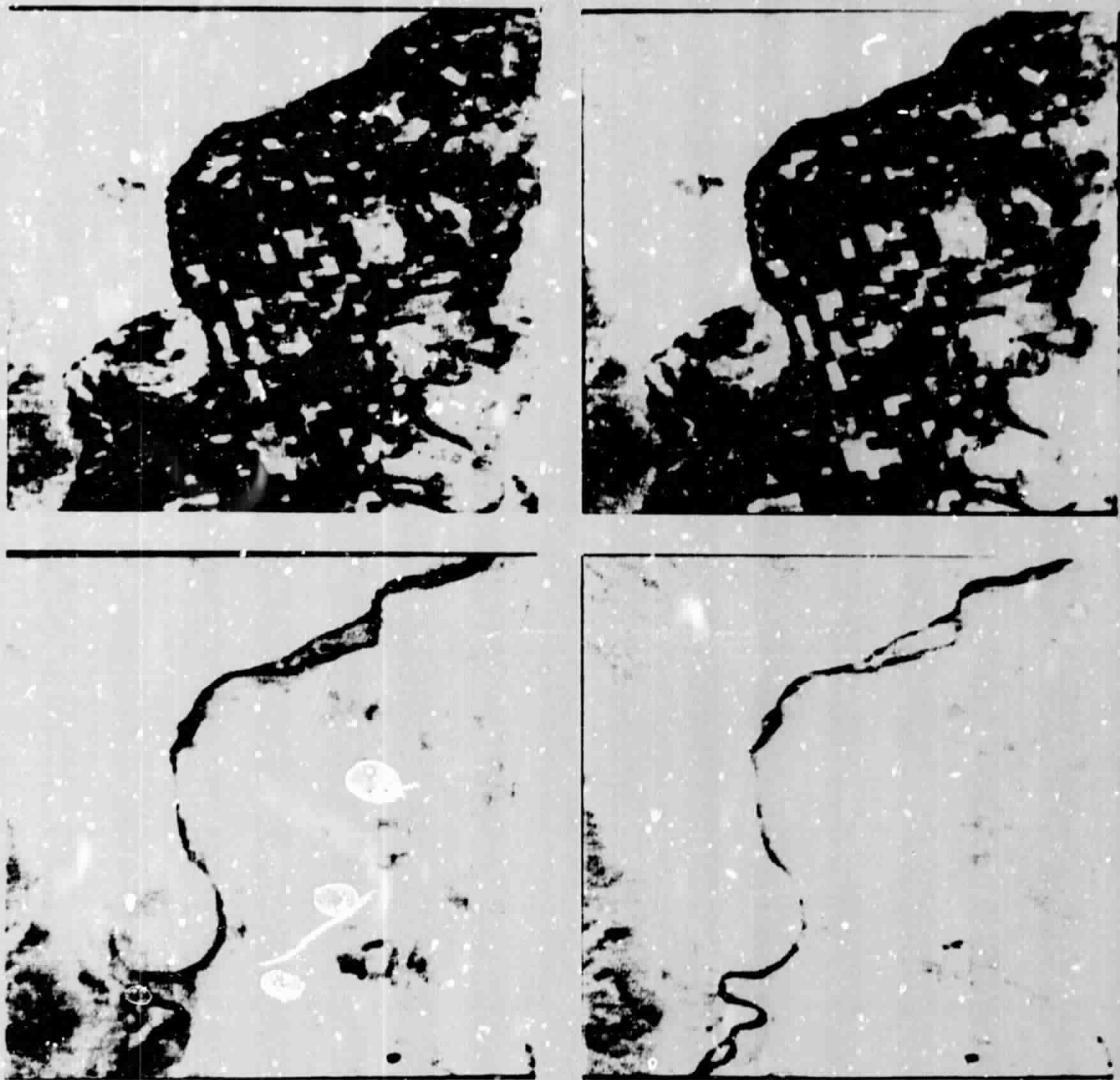


Figure 15. 1-Bit Cluster Coding

6. RESULTS AND CONCLUSIONS

The major study goal of providing tradeoff data for future NASA program planning was accomplished. Detailed results are provided in the Final Report with numerous charts and tables. An outstanding conclusion of the study is that compression ratios of 3-4 to 1 are achievable with very little distortion on multispectral earth resources imagery data. This is readily seen in Table 3 which shows negligible distortion for almost all conceivable applications at 2 bits per pixel data rates. The table also shows that by choosing the proper compression technique, a gradual degradation in complexity can be achieved at lower rates but at an increasing cost in complexity.

Table 3. Selection of Compression Techniques

Compression Ratio	Bit Rate	Recommended Technique	Typical SNR (MSE)	Typical Classification Consistency	Relative Computational Complexity
3.35 to 1	2 Bits/Pixel	Haar-2D DPCM	35dB (5)	90%	1
5 to 1	0.10 Bits/Pixel	Haar-Cosine DPCM	32.5dB (9)	86.5%	2
6.75 to 1	1 Bit/Pixel	Haar-Cosine DPCM with Huffman	31.5dB (11)	83%	4
11 to 1	0.625 Bit/Pixel	Cluster Coding	29dB (20)	71%	10*

*Estimated

Other important conclusions which may be drawn from Table 3 are:

1) Fixed rate encoders given excellent quality imagery at 3-4 to 1 compression ratios. This compression ratio may be increased to 5 to 1 by making the system operate at a variable rate with a Huffman encoder. Subjectively, reconstructed images are almost indistinguishable from the originals.

2) At a fixed bit rate and a compression ratio of almost 7 to 1, the Haar-Cosine-DPCM system gives acceptable results. Cluster coding techniques can be used to obtain a compression ratio of 11 to 1 with possibly acceptable performance. Compression ratios of 13 to 1 and higher correspond to noticeably degraded imagery which would probably be acceptable to only a few users.

3) The results obtained with LANDSAT imagery are corroborated by quite different 12-channel MSS aircraft gathered data. Thus the conclusions are felt to be quite general.

The cost and complexity of applying data compression will vary depending on the particular sensor and application. Nevertheless, the inescapable conclusion is that NASA should give serious consideration to data compression in future programs.

7. RECOMMENDATIONS

The fundamental conclusions of the study lead to the strong recommendation that NASA give serious consideration to on-board data compression for future earth resources missions. There is a high probability that its use will result in cost savings for major programs. Specific suggestions for future NASA activities in the data compression area are as follows:

1) A prototype of a data compression unit is recommended to both demonstrate the concept and provide a body of test data for evaluation by data users. A specific suggestion is to build a Haar-2D DPCM unit to be integrated with an operational multispectral scanner such as the thematic mapper now under development by NASA. Aircraft flight testing could then be performed to demonstrate a 4 or 6 to 1 compression of data either on tape or on a data link and compare the uncompressed data for user acceptability.

2) Perform system application studies to demonstrate cost savings by using representative earth resources projects such as LANDSAT or Earth Observatory Satellite (EOS). The benefits of data compression for EOS were stated in Section 1. Using the Haar-2D DPCM technique at a compression ratio of 6 to 1 will reduce the bit rate for this system from 120 Mbps to 20 Mbps. Extrapolating the LANDSAT results to the six-band thematic mapper, the bandwidth compression system gives a signal-to-noise ratio of about 32 dB with a classification consistency of over 35%.

3) Perform user acceptance studies. This is of major importance in the evaluation of bandwidth compression methods since at present it is not known just which reconstructed images are acceptable to which users. This can be performed by selecting current users of multispectral data and verifying the effects of compressed data on their standard processing.

4) Study the use of adaptive compression techniques for greater compression ratios.

5) Further study of the cluster coding method is recommended to determine its implementational feasibility and to optimize its performance.