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**Stirbl, Robert Clark**

**HYBRID OPTICAL-DIGITAL ENCODING FOR VIDEO BANDWIDTH  
REDUCTION**

*City University of New York*

**Ph.D. 1982**

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HYBRID OPTICAL-DIGITAL ENCODING FOR  
VIDEO BANDWIDTH REDUCTION

by

ROBERT CLARK STIRBL

A dissertation submitted to the Graduate Faculty  
in Engineering in partial fulfillment of the  
requirements for the degree of Doctor of Philosophy  
in Electrical Engineering  
The City University of New York

1982

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This manuscript has been read and accepted for the Graduate Faculty in Engineering in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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## Abstract

### HYBRID OPTICAL-DIGITAL ENCODING FOR VIDEO BANDWIDTH COMPRESSION

by

Robert Clark Stirbl

Advisor: Professor George Eichmann

A hybrid optical-digital encoder incorporating a new optical preprocessing method for reducing visible error instability noise in the reconstructed video display of adaptive delta modulation (ADM) encoded signals is presented. The method employs the edge contrast dependent phase gradients, produced by the localized transition surface reliefs of the input image absorption transparency. Phase gradients add a local angular carrier to the input illumination angle, causing the position of the Fourier transformed spatial spectra of the light from high contrast, instability producing transitions to be displaced from the axially centered and close lying transformed spectra. The close lying spectra of slowly varying and low contrast transitions do not cause highly visible disturbing error instabilities.

In the transform domain, directional and differential weighting of the composite transformed spatial spectra is implemented using an asymmetric linearly transmitting absorption spatial filter. The filter is produced photographically

on Kodak 649F photographic emulsion by an analog exposure technique. The effect of the filtering on the retransformed output image distribution is essentially to superimpose a visualized image of the high contrast transition phase gradients on the retransformed real amplitude input image.

The resulting superposition modifies the slope of the original edge detail. Thus error instability usually seen at high contrast transitions in the video reconstruction of ADM encoded scenes sampled at low rates is reduced.

The method of optical preprocessing used modifies the input spatial spectrum distribution in a way not possible by either simple binary symmetric low pass filtering or image defocusing--optical methods used to reduce image resolution-bandwidth requirements.

The method is explored for three illumination image class cases: Temporally and spatially coherent illumination of monochrome still and moving scenes, temporally incoherent partially spatially coherent polychromatic illumination of monochrome still and moving scenes, and temporally incoherent partially spatially coherent polychromatic illumination of still and moving color scenes.

In each case optical preprocessing reduces the subjective image noise when encoder rates fall below 10 Mbit/sec. The increase in image stability in each case results in the compression of the bandwidth needed to produce a given quality of the transmitted scene.

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I would like to dedicate this thesis to my father, Fredrick I. Stirbl who was an engineer and showed me the joy and wonder of science, technology and life, and my son Aren I. Stirbl, who I hope will see these things as well.

Many thanks to my Committee, Family and Friends for their support and assistance during the course of this undertaking.

R.C.S.

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## CHAPTER I

### INTRODUCTION AND BACKGROUND

#### The Need for Bandwidth Reduction of Digitally Encoded Video Images

The transmission of images has applications in many diverse areas, such as man-man, man-computer, computer-computer and many remote sensing applications. Most of today's image sensors generate video information far in excess of what usual digital channels can handle. For the observer who has the time to wait for the images to be transmitted, the digital bandwidth limitation is not a problem. However, in real-time digital video applications, bandwidth compression is a necessity. The mechanism of bandwidth compression is called source encoding. The purpose of this work is to develop source encoding techniques for real-time video transmission application.

Real time video systems for information processing are receiving a great deal of attention [1-5]. Applications where real time processing is a must include satellite surveillance, teleconferencing and control. Here the video observer or photo interpreter is the ultimate receiver of the information. Any design of source encoders must include some measure of how the video image is perceived [6-9].

The bandwidth compression ratios that we discuss are thus based on the relative reduction of image noise by subjective quality judgments assessed by viewers at a standard viewing distance and under standard ambient viewing conditions.

The method which we demonstrate to be effective at low sampling rates is motivated and based on known psychovisual perception studies related to the characteristics of each of the three types of images in each application and is based on subjective data taken under standardized conditions.

Chapter I of this thesis contains material of an introductory nature on coding for bandwidth compression. In Chapter II, contemporary methods of predictive digital encoding as well as optical-hybrid bandwidth compression are covered in connection with encoder noise problems. These optical methods are highly sensitive to coherent image noise. In addition, an unnecessary loss of information is due to these systems' failure to discriminate between high intensity error causing and low intensity non-error causing spatial frequencies.

In Chapter III, the characteristics of the edge noise are studied at different orientations and under different sampling rate conditions to determine visibility characteristics. A new method of optical hybrid bandwidth compression to reduce video image instability and improve image quality at low sampling rate is presented. The method

discriminates between edge image content. This then allows the reconstructed instability to be reduced by determining what amount of image predistortion is needed to stabilize the image at low transmission rate. Standards for image evaluation are also covered.

In Chapter IV, the production and analysis of the filter, preprocessing of still temporally and spatially coherent illuminated objects in a Fourier lens transform preprocessor are given in detail.

In Chapter V, time sequential input stage systems were built to investigate and simulate real-time operation of "moving" images for monochrome scenes. Through the use of a single element reflective transform optical arrangement the reconstructed noise is further reduced and the accompanying image quality is improved. Temporally incoherent and spatially partially coherent illumination for the preprocessing of still and moving monochrome inputs is also presented.

In Chapter VI, a polychromatic hybrid encoder that permits encoding of color still and moving images at low transmission rates is covered. This low rate for color moving images finds immediate application in the recent development of teleconferencing as well as remote probe and surveillance application in high noise environment.

In Chapter VII, we present future research, and suggestions for improvement of the system are made for further application of hybrid optical-digital encoders.

### 1.1 Background -- Three Major Source Encoding Categories:

#### Statistical, Predictive, and Transform Encoders [10]

Statistical encoders are mainly used on half-tone images where runs of black or white areas have high statistical probabilities. For full-tone images, either predictive or transform encoders are applicable. We are concerned with predictive encoding for the transmission of full-tone still and moving monochrome and color images. To convert analog digital images into digital format, some type of predictive encoder, either a differential pulse code modulation (DPCM) or a delta modulation (DM) video system is generally used. To compress the bandwidth of the digital image, these encoders must operate close to the Nyquist sampling rate. However, at this rate, unacceptable image distortions occur.

Image quality is impaired by both encoder quantization noise as well as channel noise. To determine the effects of quantization noise introduced by the digital encoder, a noiseless channel is used. The effect of channel noise on image quality is handled separately and is called the channel coding problem [ 6, 7 ] and lies outside the scope of this thesis.

In order to understand the source coding problem, let us take a look at a practical block diagram for an image transmission system [ 6 ] depicted in Fig. 1.1-1.

The image is first introduced into an optical

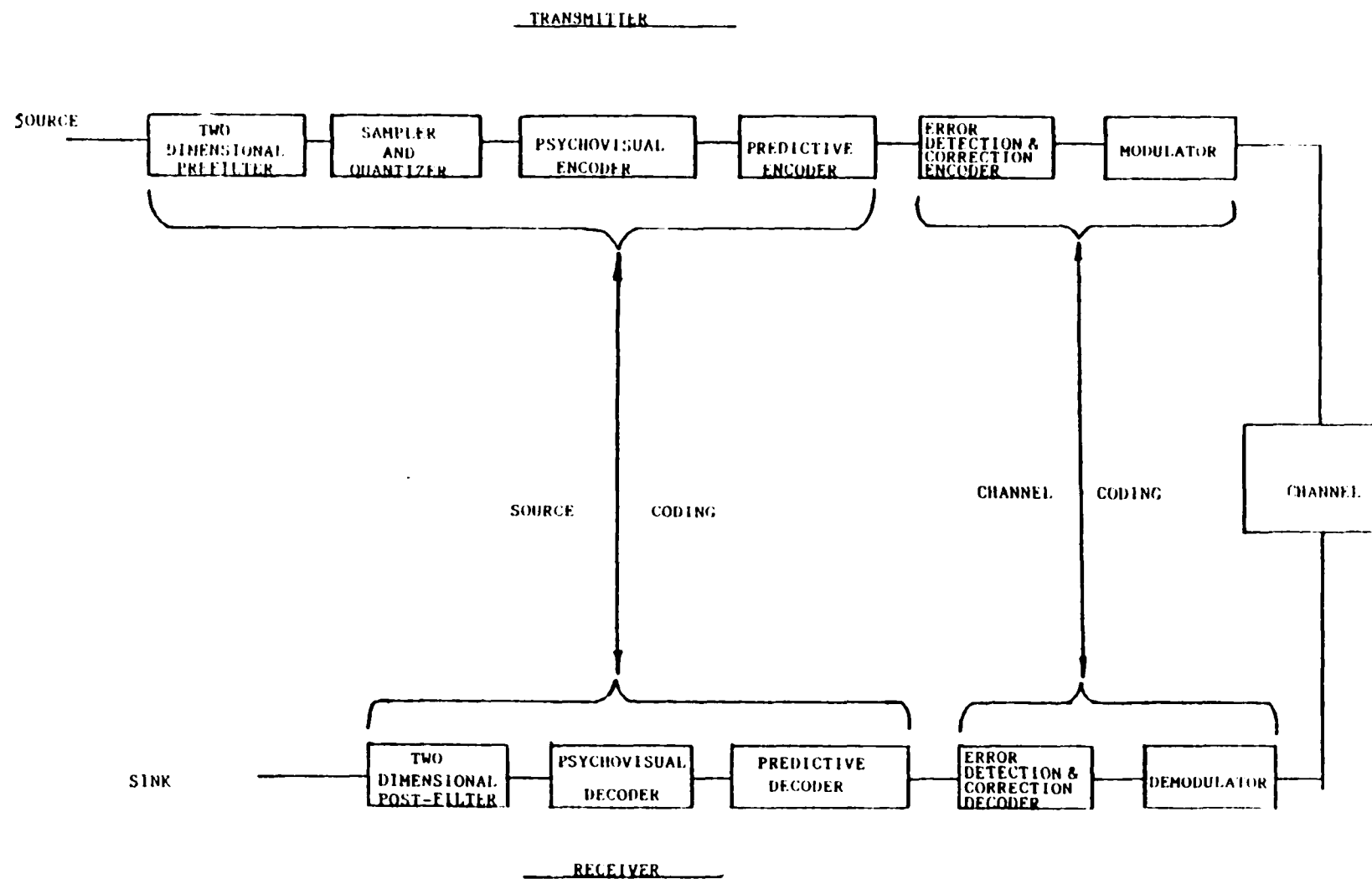


Figure 1.1-1. Typical block diagram for an image transmission system

preprocessing system shown here as a two-dimensional prefilter. It is then scan sampled, quantized, and enters the predictive encoder which removed redundancy. A psychovisual encoder block is shown in the diagram to take into account the design of the encoding system based upon the results of psycho-physical experimentation. The resulting signal is then prepared for the channel by the use of error detecting and error correcting codes that add redundancy for channel noise immunity. The bit stream is then modulated for transmission over the channel. At the receiver, the signal is demodulated and error corrected. The resulting bit stream then enters the predictive decoder where an algorithm that is matched to the encoder's is applied. The reconstructed digital image signal may then be passed through the psycho-visual decoder and a two-dimensional post-filter. The effects of viewing a CRT at a given distance, using phosphores of a certain beam spread, time response, and color are taken into account in these last two blocks.

We will first discuss the bandwidth compression methods presently used, then predictive encoders, and specifically how adaptive delta modulation (ADM) reduces the bit rate and examine the causes of edge busyness noise instability in ADM. We then discuss how the analog Fourier optical processor operates and how it can be used as a real-time pre-filter in conjunction with



digital encoders.

We will then cover image evaluation techniques used to determine the amount of compression that can be achieved by various encoding methods.

### 1.2 Bandwidth Reduction Methods

To overcome the large bandwidth requirements of PCM, researchers have designed encoders that use the statistical property of still pictures and time sequential images as well as the psycho-visual properties of the human perceptual channels, to reduce the bandwidth requirements of digital channels.

### 1.3 Statistical Coding

In order to perform statistical encoding of images one assumes each picture or image is a finite collection of picture elements (pels) in a square array, each element having a finite number of brightness levels.

Commercial analog video interlaced scanning contains 525 horizontal lines per frame and for commercial bandwidth approximately 485 pels on each line. In digital systems, powers of two facilitate ease of hardware implementation so that a 512 x 512 square array of pels is assumed to be the spatial resolution of the original picture. Each pel is also assumed to have 64 different quantized brightness levels. Then the total number of

possible pictures that can be represented is:

$$(64)^{(512)^2} = 2^{1,572,864} = 10^{500,000} \quad (1.3-1)$$

Most of these  $10^{500,000}$  digital picture possibilities have a very low probability of being sent and would appear as random noise or dots. This is because real image data contains significant structure, and structure is a departure from randomness.

If an encoder is assumed to store a unique code word for each of the  $10^{500,000}$  images, we could assign short length code words for the more likely pictures and long code words to the less likely pictures. We could then have a system where the average number of bits required per picture would be close to the entropy

$$\sum_{i=1}^{10^{500,000}} p_i \log p_i \quad (1.3-2)$$

where  $p_i$  is the probability of the  $i^{\text{th}}$  picture.

In terms of rate distortion theory where a  $4^\circ \times 4^\circ$  visual field with  $512 \times 512$  samples is generally assumed, one can associate a vector  $U$  for each code word or code vector. If we assume a random signal or picture vector  $U$  the distribution of which we may typically be able to describe only partially, we can speak of a reconstruction process at the output given by  $\bar{U}$ . A quality measure

based on the original image  $U$  and its reproduction  $\bar{U}$  is given by  $d(U, \bar{U})$  that represents the distortion between  $U$  and  $\bar{U}$ . Therefore, given a random source  $\bar{U}$ , the source-coding problem is to design an encoder that operates at a given rate which minimizes the average distortion where  $u$  represents a particular sample value.

$$d^* = E[d(U, \bar{U})] \quad (1.3-3)$$

Based on this average measure, Shannon's rate distortion theorem sets a lower limit on the average minimum distortion  $d^*$ . If  $f(u)$  denotes the source probability density, with  $f(\bar{u}/u)$ , an arbitrary transition density (which might for example correspond to a particular method of encoding and decoding) and  $I(\bar{U}, \bar{U}^*)$  is the average mutual information under the joint density  $f(\bar{U}^*/\bar{U})/f(\bar{U})$  the rate distortion function is then

$$R(d^*) = \min_{f(\bar{u}/u): E[d(U, \bar{U})] \leq d^*} I(U, \bar{U}) \quad (1.3-4)$$

i.e. the average mutual information depends on  $f(\bar{u}/u)$ , and  $R(d^*)$  is the minimum value of this information over all transition distributions yielding an average distortion  $d^*$ .

The significance of Shannon's coding theorem which states that no encoder, regardless of form or complexity, can yield an average distortion less than  $d^*$  at a transmission rate  $R(d^*)$ , but it is possible to design an

encoder (of sufficient complexity) to yield an average distortion  $d^*$  at a rate arbitrarily close to  $R(d^*)$ .

The mutual information  $I(\bar{U}, \bar{U}^*)$  can be expressed

$$I(U, \bar{U}) = H(\bar{U}) - H(U/\bar{U}) \quad (1.3-5)$$

in which  $H(\bar{U})$  is the average entropy of the source  $\bar{U}$

$$H(U) = -E\{\log f(U)\} = -\int \dots \int du f(u) \log f(u) \quad (1.3-6)$$

and  $H(\bar{U}/\bar{U}^*)$  is the average entropy of  $\bar{U}$  knowing  $\bar{U}^*$  so that the Rate Distortion relation in terms of entropy can be expressed as

$$R(d^*) \geq H(U) - \max_{E\{d(U-\bar{U})\} \leq d^*} H(U-\bar{U}) \triangleq R_L(d^*) \quad (1.3-7)$$



source distribution



distortion measure

So the optimal selection of the code vectors or digital encoder depends upon knowing both the source characteristics and the distortion measure [11].

W.F. Schreiber [12] suggests that the entropy of pictures is about 1 bit per pel. Using pure statistical encoding, we can reduce the bandwidth of digital TV from 48 MHz for PCM to 8 MHz for statistical encoders. Unfortunately, the complexity of such an encoder with  $10^{500,000}$  words of memory is excessive and cannot be built. One possible approach might be to break up the picture

into subpictures of only 4 x 4 pels, but this would still require  $10^{28}$  words of memory for a statistical encoder.

#### 1.4 Psychovisual Coding

Psychovisual coding achieves bandwidth reduction by removing that information that will not be missed or is disturbing to the human observer.

By removing information from a picture, the picture is changed, i.e. distorted, but some types of distortion cannot be perceived or are preferred over other types of distortion by a human observer. This type of coding is deemed irreversible coding when the information is discarded and cannot be reconstructed based on the remaining data.

##### 1.4-1 Psychophysical Parameters Effecting Coding for Bandwidth Compression

There has been much research and many models put forward to describe the complicated, non-linear, content-depending mechanisms that operate during visual perception. References [3,6-11,13-38] are only a partial listing of work done on human perception but give a representative sample of how perceptual mechanisms are related to the source coding communication problem and what assumptions are made for different classes of input images.

#### 1.4-2 Hierarchy in Recognition

Since the purpose in many applications of video transmission is the recognition of information by the human observer, the proper starting point in evaluating which distortions, encountered when a particular compression scheme is implemented, affect the efficient detection of information, is the hierarchy of visual data in the image. Figure 1.4-1, adapted from R. Benjcsy and D. Rosenthal [39] shows the most important perceptual mechanism toward the top of the diagram, i.e. those quantities that are perceived first at a pre-conscious level and then brought into awareness. These properties are reflectivity or luminous energy, motion, boundaries, color and texture. These key perceptual components are then used together to organize the perceptions into recognizable and identifiable object types in sectors of the scene being viewed (i.e. their fields, natural vegetation, man-made vegetation, etc.).

#### 1.4-3 Effects of White Noise Over Large Areas

When white noise is introduced into the video signal, this distortion is sensed as "salt and pepper" noise over large areas of the visual field.

The visual field is shown depicting in Fig. 1.4-2.

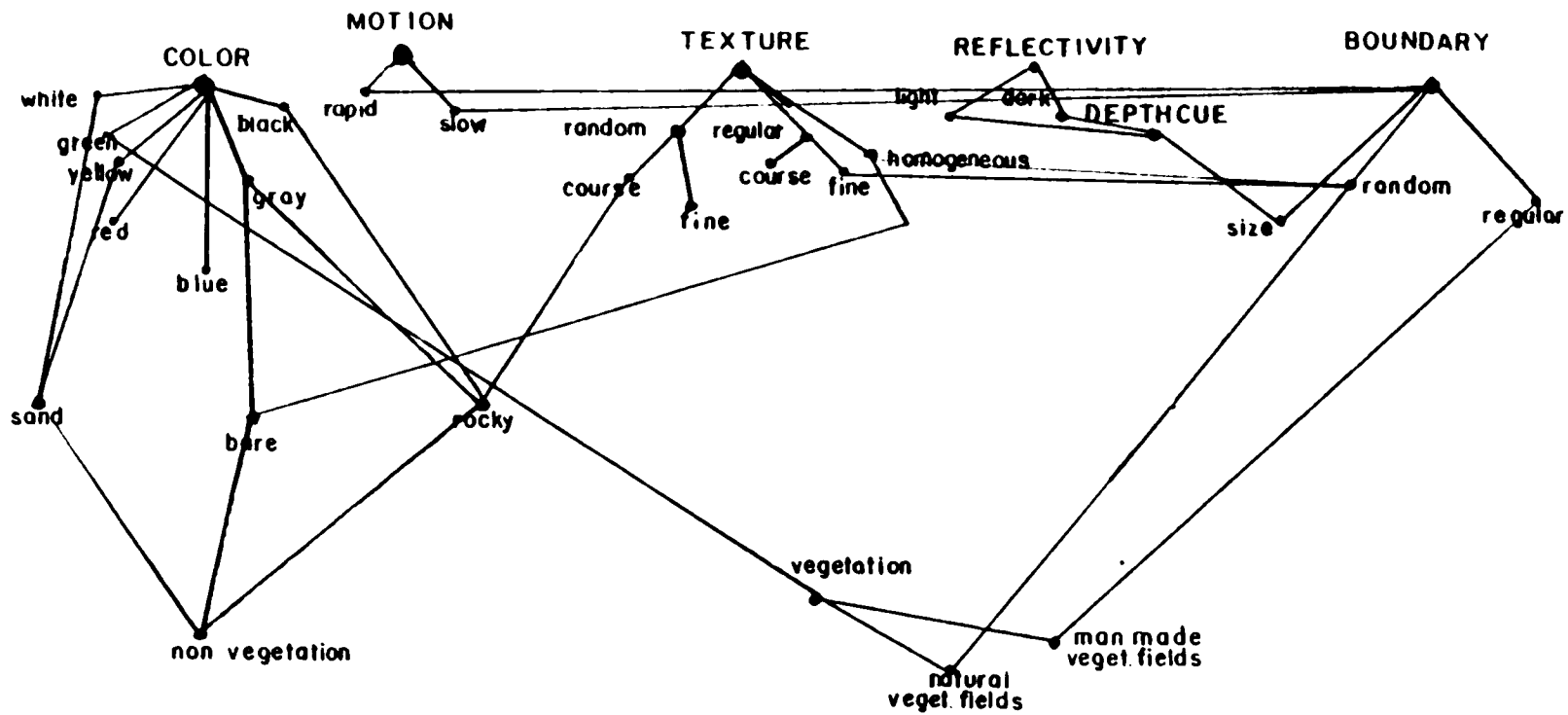


Figure 1.4 -1 Hierarchy in Visual Perception

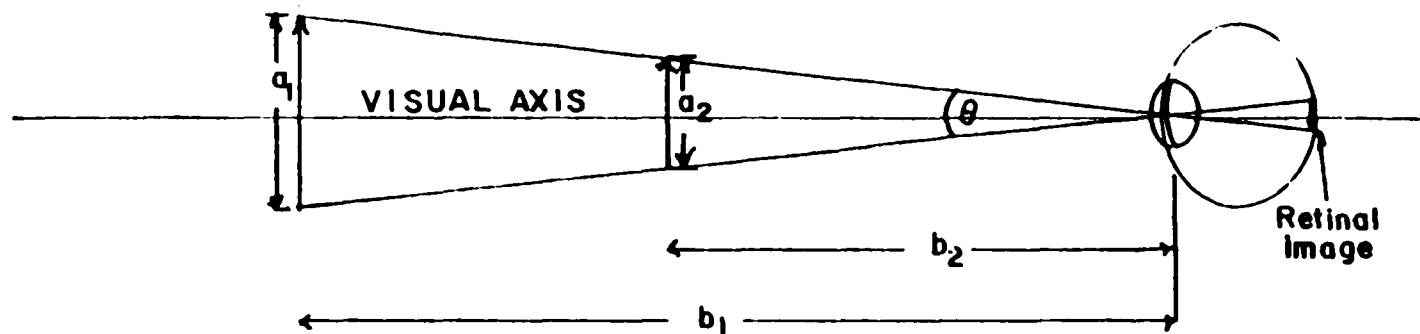


Fig. 1.4-2. The visual field angle subtended by a display at the eye  $\theta = 2 \arctan (a_1/2b_1) = 2 \arctan (a_2/2b_2)$  and determines the retinal image size



Table 1.4-1

Spatial Frequency per cyc/cm Converted to cyc/degree  
Subtended at the Eye

(Entries underlined are frequencies beyond the  
eye's cut-off frequency under average display  
viewing conditions)

| Spatial<br>Frequency (cyc/cm) | 0.5                              | 1         | 1.5        | 2          | 3          | 4          | 5          | 10         | 20         |
|-------------------------------|----------------------------------|-----------|------------|------------|------------|------------|------------|------------|------------|
|                               | Spatial Frequencies (cyc/degree) |           |            |            |            |            |            |            |            |
| 0.01                          | 0.01                             | 0.02      | 0.03       | 0.03       | 0.05       | 0.07       | 0.09       | 0.17       | 0.35       |
| 0.2                           | 0.17                             | 0.35      | 0.52       | 0.70       | 1.0        | 1.4        | 1.7        | 3.5        | 7.0        |
| 0.8                           | 0.70                             | 1.4       | 2.1        | 2.8        | 4.2        | 5.6        | 7.0        | 14         | 28         |
| 2                             | 1.7                              | 3.5       | 5.2        | 7.0        | 10         | 14         | 17         | 35         | <u>70</u>  |
| 6                             | 5.2                              | 10        | 16         | 21         | 31         | 24         | 52         | <u>105</u> | <u>209</u> |
| 10                            | 8.7                              | 17        | 26         | 35         | 52         | <u>70</u>  | <u>87</u>  | <u>175</u> | <u>394</u> |
| 40                            | 35                               | <u>70</u> | <u>105</u> | <u>140</u> | <u>209</u> | <u>279</u> | <u>349</u> | <u>698</u> | -          |

Texture and motion are stimulated at a higher level of pre-conscious perception than the information in the constant background, and therefore exist mechanisms that distract the viewer's attention as well as destroy image quality. Work on estimating the exponential model for the relationship between noise parameters relative to search object detail parameters has been investigated by Soviet researchers Alekseev, Veselova and Kushpil [40]. They showed that search time as a function of task errors depends upon the similarity of the noise luminance of a non-uniform background to the test object being searched for as well as noise instability as a function of the probability of occurrence of noise.

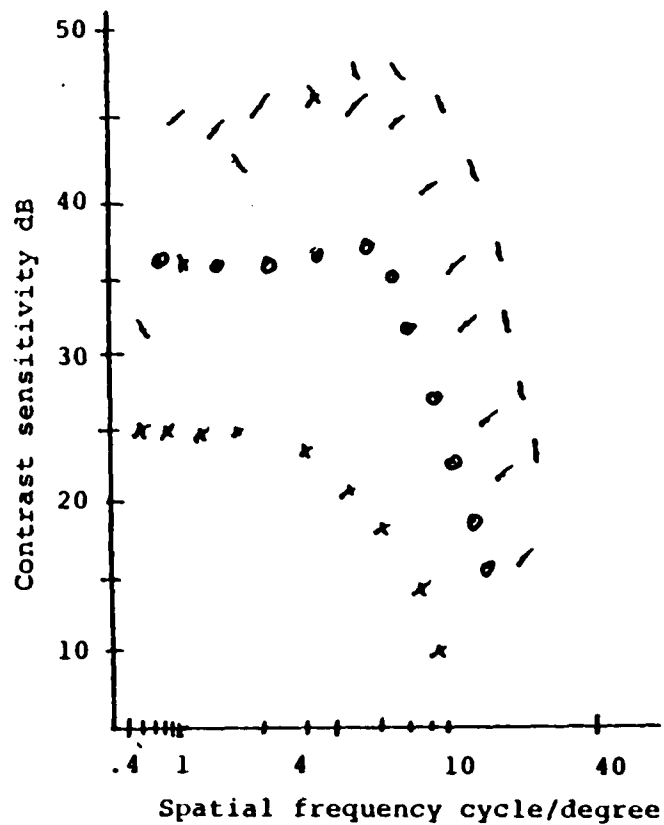
Visual accommodation and discomfort are also effected during a prolonged search task as a function of instability and the area of the noise [41]

Because of these effects of large area noise and the reduction of image quality, encoders are designed to avoid the propagation of this global two-dimensional large area noise by quantizing and companding the signal so that the noise is localized in small areas of the image at high contrast edges where it is relatively less visible due to spatial masking. Spatial masking hides the

noise due to an inhibition of neural firing of the surrounding neurons on the retina due to the response to a transition ( this is covered in the next section). The effect is that for noise that is below the visual level or at the just perceivable level--defined as obtaining 50% correct and 50% incorrect responses to the presence or absence of a stimulus--requires a larger brightness to be perceived near an edge than in a constant area of the picture.

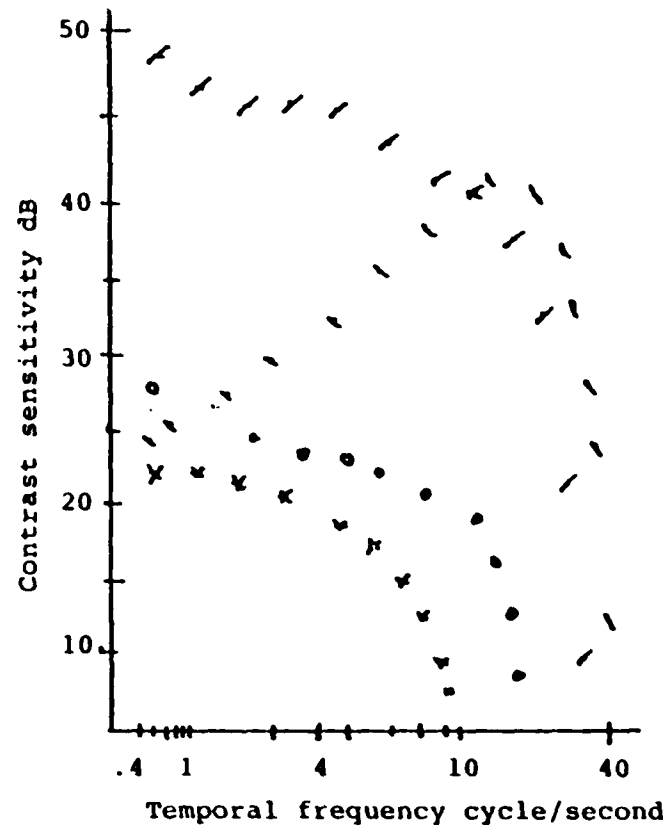
Psychovisual data obtained from subjective[42] testing by observers using sets of sinewave gratings of different spatial frequency as visual test objects, are shown in fig. 1.4-3 (a) and (b). These graphs show the reduced response of the observer to high spatial and temporal frequencies being tested below or at the just perceivable visual threshold. These curves have the vertical coordinate plotted in contrast sensitivity; the inverse of contrast threshold (the brightness level needed to obtain a just perceivable response).

Fig. 1.4-4 shows the contrast sensitivity (inverse threshold contrast) under different pupil size and viewing conditions. These spatio-temporal sensitivity curves to sinewave gratings support [43]



(a)

/ = Temporal frequency of 6 Hz  
 \ = Temporal frequency of 1 Hz  
 o = Temporal frequency of 16 Hz  
 x = Temporal frequency of 22 Hz



(b)

/ = Spatial frequency .5 cycle/deg.  
 \ = Spatial frequency 4.0 cycle/deg.  
 o = Spatial frequency 16 cycle/deg.  
 x = Spatial frequency 22 cycle/deg.

Figure 1.4-3 (a) and (b) Spatial and Temporal Frequency Response of the eye

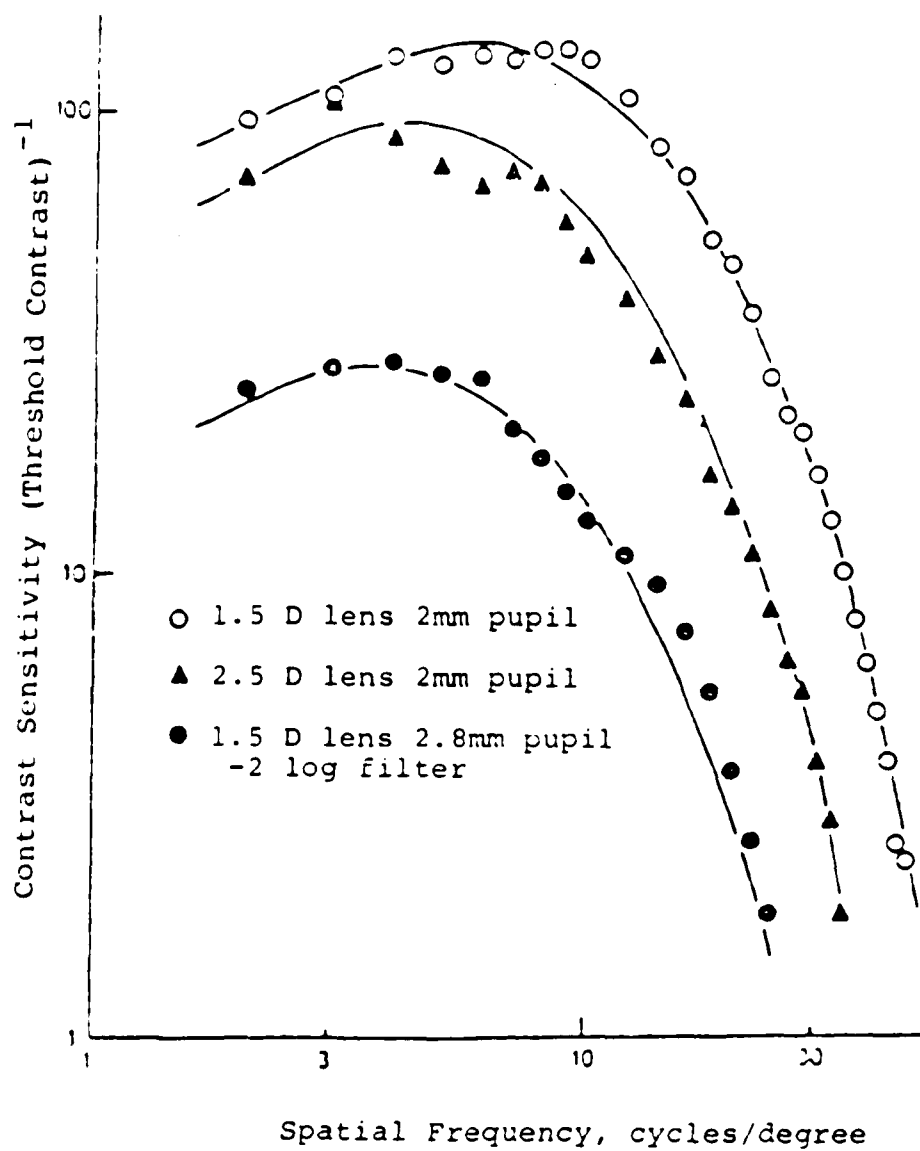


Figure 1.4-4 Contrast sensitivity under different pupil size and viewing conditions

the use of edge localized noise. Fig. 1.4-5 from Crawford [44] shows the threshold luminance of brief flashes presented at different time instances with respect to a .5 second 10 cd/ft<sup>2</sup> conditioning light pole on a dark adapted eye. Fig. 1.4-6 from the work of Limb [45] shows the threshold as a function of peak-to-peak signal of a line presented close to a dark-to-light boundary as a function of the separation between the line and the boundary.

In addition to the above simple test field research work on visual threshold at different spatial and temporal frequencies, the subjective quality of real monochrome and color image material i.e., crowds, head and shoulder scenes, for different types of noise, i.e. random, white and edge noise, has been carried out.

Studies on these subjective effects due to noise were made by Mounts [ 2 ], Candy and Bosworth [ 46 ], Barstow [ 47 ], and Brainard [ 48 ]. It was found in these studies that edge noise, i.e. noise placed at edges, was preferred over large area "white" noise at high sampling rates. When the size and frequency of the edge noise fell in the band that the viewer could clearly perceive, it was discovered that other measures of image

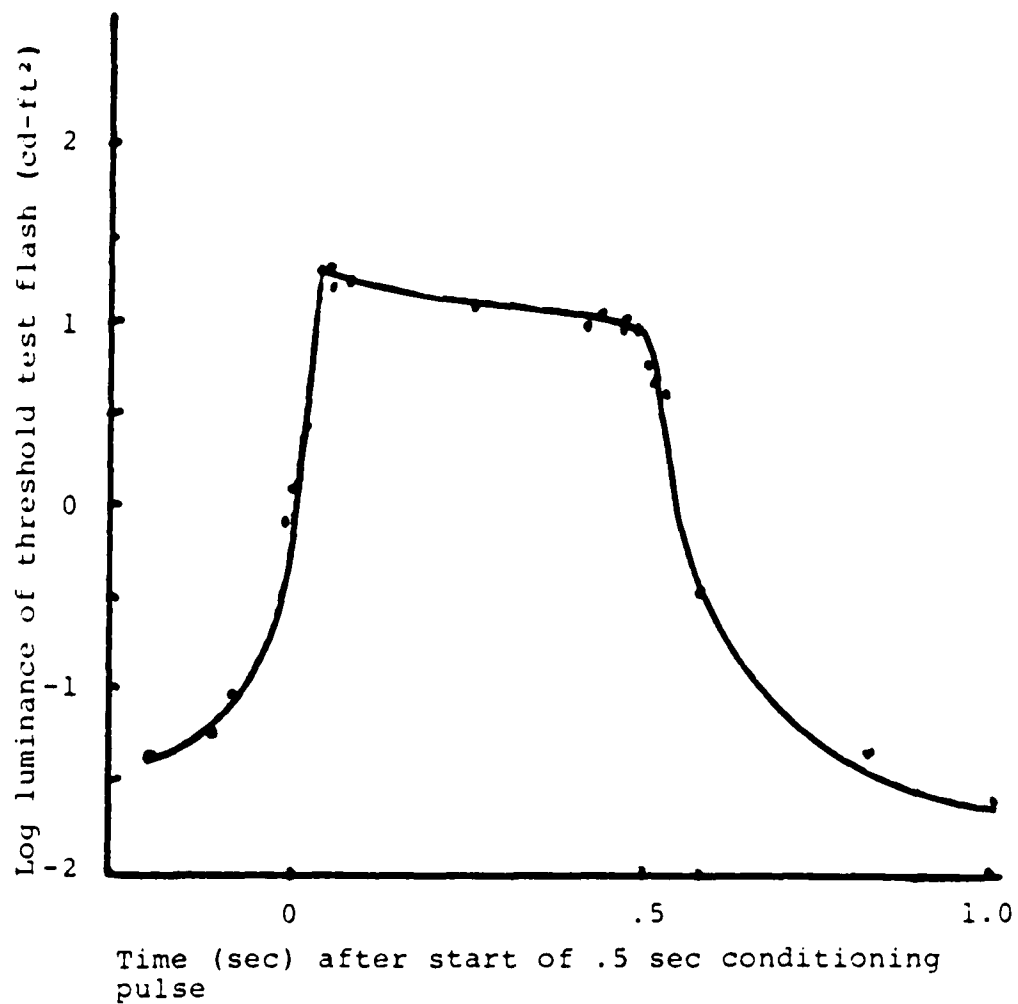


Figure 1.4-5 Threshold luminance of brief flashes  
presented at different time instances  
[44]

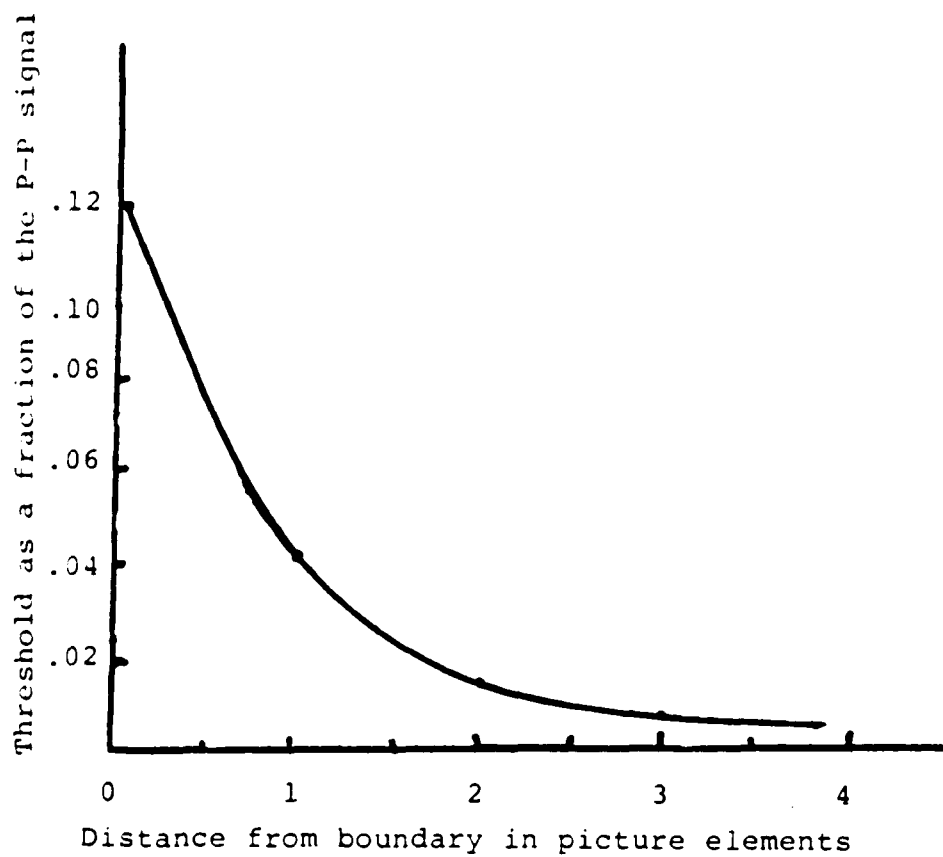


Figure 1.4-6 Threshold as a fraction of the P-P Signal vs.  
Distance from boundary in picture elements [45]



quality had to be developed to take into account the superthreshold , i.e. not just perceivable but clearly and always perceivable noise in the image portion of the scene. Sharma and Netrovali [30] devised several quantization noise weighting functions that took the superthreshold effects into account when designing DPCM encoders. For picture signals, input data from subjective quality evaluation testing, was used to compare the new measures with the usual mean square error criteria. The measures that were judged were

- 1) The mean square quantization error (MSE):

$$MSE = \sum_{i=1}^N \int_{X_i}^{X_{i+1}} (x - Y_i)^2 P(x) dx \quad (1.4-1)$$

- 2) Mean Square Superthreshold Quantization Error (MSTE)

$$MSTE = \sum_{i=1}^N \int_{X_i}^{X_{i+1}} [(x - Y_i)^2 - T^2(x)] U(|x - Y_i| - T(x)) P(x) dx \quad (1.4-2)$$

- 3) Mean Square Subjective Quantization Error (MSEE)

$$MSEE = \sum_{i=1}^N \int_{X_i}^{X_{i+1}} (x - Y_i)^2 f(x) dx$$

4) Mean Square Subjective Superthreshold Quantization Error (MSSTE)

$$MSSTE = \sum_{i=1}^N \int_{X_i}^{X_{i+1}} [(x-Y_i)^2 - T^2(x)] \cdot U(x-Y_i) \cdot f(x) dx \quad (1.4-4)$$

$-T(x)f(x)dx$

where

$x$  is the slope of the picture signal (i.e. the difference of the luminance of the adjacent elements);

$X_i, Y_i, N$  are decisions, representations, and number of levels of a quantizer in which any input between  $X_i$  and  $X_{i+1}$  is represented as  $Y_i$ ;

$P(x)$  is the probability density of the element difference  $x$ ;

$T(\cdot)$  is the visual threshold level function;

$U(z)$  is the input stepfunction (i.e.  $U(z) = 0$  for  $z < 0$  and  $= 1$  otherwise);

$f(x)$  is the visibility function of the noise at slope  $x$ .

Their findings indicate that MSSTE provides the smoothest relationship between picture quality and the distortion measure out of the four measures tested. The MSSTE weighs only that portion of the quantization noise which is above the

visual threshold, i.e. superthreshold.

We see then that though one still does better at low sampling rates by placing the noise near the edges instead of spreading it over the entire picture, one can no longer assume that the edge noise is negligible due to masking and the distracting effects must be countered if image quality and thus compression at low sampling rate is to be achieved.

#### 1.4-4 Neurophysiological and Psychovisual Data Affecting the Superthreshold Edge Noise Component and Video Compression

When low sampling rates are used, the size of the spatial sampling period and thus the pixel element error size increases in the visual field of the observer and noise at edges of high contrast is above the visual threshold. The psycho-visual data obtained from the eye scan experiments of the Russian researcher Yarbus [49] support the importance of boundaries where edge noise occurs in the distraction of attention. Fig.1.4-7 shows the eye scans of a human observer when looking at a photograph of a sculpted head. In addition to the above work, neurophysical data on mammalian striate visual cortex, shows that there exist receptor fields that form feature detectors sensitive to



Fig. 1.4-7 Eye tracks while looking at a photograph of the sculptured head [49]

to detecting edge excursions at specific orientations [50].

#### 1.4-5 Receptive Fields and Feature Detectors

Kuffler [51] showed that the receptive fields (the visual space to which neurons respond) in the retina of the cat are of two types: "on-center" and "off-center." The firing rate, determined by inserting an electrode into the neuron, increases in the "on-center" neuron if a small spark of light, placed in the center of the receptive field, was turned on. Some cells that maintain discharge in the absence of stimulation increase their firing rate of discharge temporarily when a small spot of light, placed at the center of the receptive field, is turned off. These are the "off-center" neurons. Small spots of light turned on in the surround of "on-center" neurons were turned off for the "off-center" neurons reduces their characteristic response. This is called lateral inhibition.

Feature detectors are composed of receptive fields that are uniquely selective to disks, edges, and edge excursions (tongues) in that they respond maximally when a perfect match between the receptive field and light incident on the retina (stimulus) with a particular geometrical shape

occurs. In other words, the presence of an edge or an edge excursion is signal because a receptive field of the correct size and position with respect to the visual field has been excited.

Fig. 1.4-8 shows the work of Hubel and Wiesel [50] on non-striate visual cortex of the cat and where the electrode was placed for different receptor size and orientation responses. Fig. 1.4-9 shows the electrode probe traces as an object moves over different receptor fields due to excitation and inhibition.

Distraction and discrimination in human perception [53] has also been shown to exhibit orientation and size dependent characteristics similar to those obtained in testing the striate cortex of the monkey [57]. In these studies very narrow tuning in both orientation and spatial frequency were found.

Therefore, above visual threshold (super-threshold) these receptors to small edge excursions are turned on and heighten distraction [52-56].

In the context of the above research, compression of adaptively encoded image signals must address this real problem of superthreshold edge noise if bandwidth reduction at low rates is to be achieved.

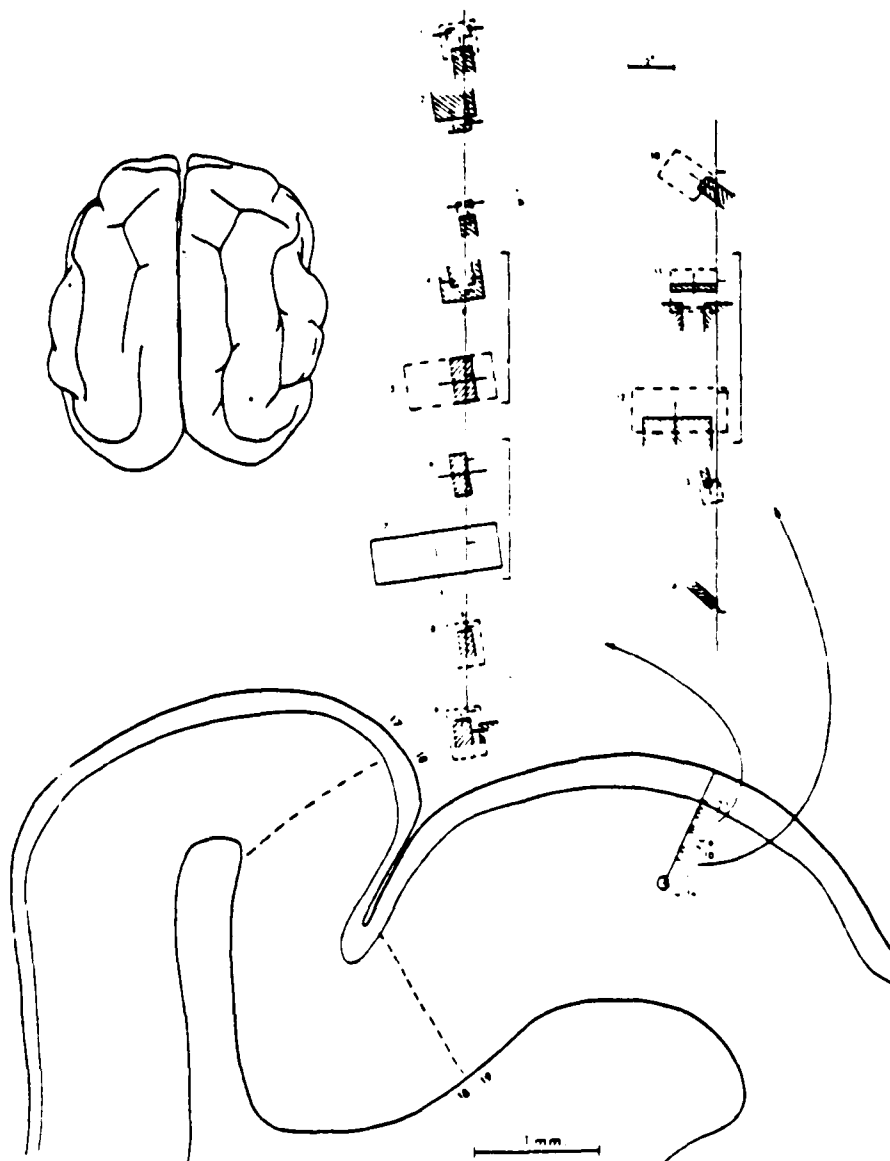


Figure 1.4-8 Electrode positions for different receptor field sizes and orientation responses [50]

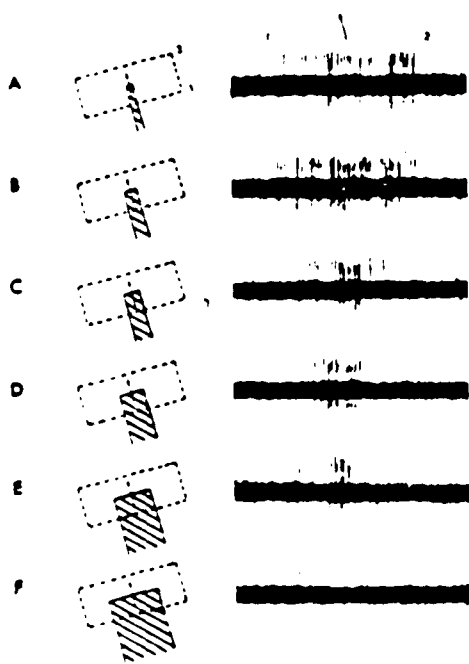
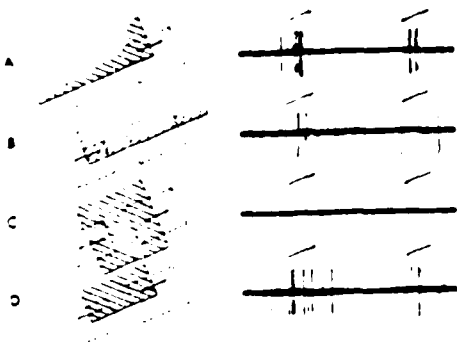
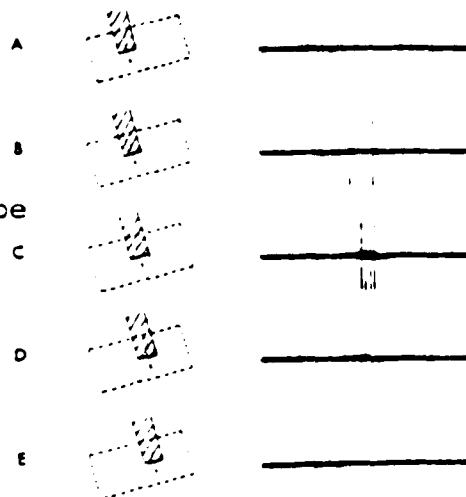


Fig. 1.4-9 Electrode probe traces as object moves over different receptor fields [50]





Several authors have commented on the importance of this edge noise and the following are excerpts from two experts in the field: As noted by Cutler [58], "the transient fluctuations at sharp edges in the encoder [output display] without...[compensation] are localized and infrequent, so they do not show strongly in the measured signal S/N. They are however eye-catching and very bothersome." Steele [59] comments: "...this objectionable twinkle effect should be removed...."

In the next section the effects of color and movement related to subjective image noise and bandwidth compression are discussed.

#### 1.4-6 Color and Motion in Bandwidth Compression

The psychovisual coding [13-15,24,32,33,56,60,61] of images for compression is aided by the reduced sensitivity of the observer to noise and images where motion and color are present. The limitation of the human eye to color detail forms the basis of current practical picture coding, such as the standard for color television systems [62-64]. Also, the inclusion of color in picture transmission adds greatly to the information content often providing valuable clues for recognition and makes the illusion more complete.

Valensi [65] and Groneman [66] have shown that effective coding schemes for transmission of color pictures requires only a fractional increase over that required by monochrome transmission.

Bhushan's work [24] explores the effects of color using PCM or DM encoded video scenes for various sampling rates. The results of subjective quality testing are shown in Fig. 1.4-10 for PCM and Fig. 1.4-11 for DM. Table 1.4-1 shows the comparison of PCM and DM. Note that the subjective perception of blue images encoded with less bits (levels PCM or at a lower sampling rate DM) have a high subjective quality than either a red or green channel image. This property can be used to advantage to reduce the sampling rate of the blue and red image components relative to the green image component.

Several other digital systems [32,33] for imaging coding have also shown compression within the framework of the human visual model or Perceptual Space for the luminance and chrominance channels of NTSC color video.

Motion in image coding has been studied by Seyler and Budrikis [15], where it was shown that after a scene change in the image detail perception was reduced and it required approximately

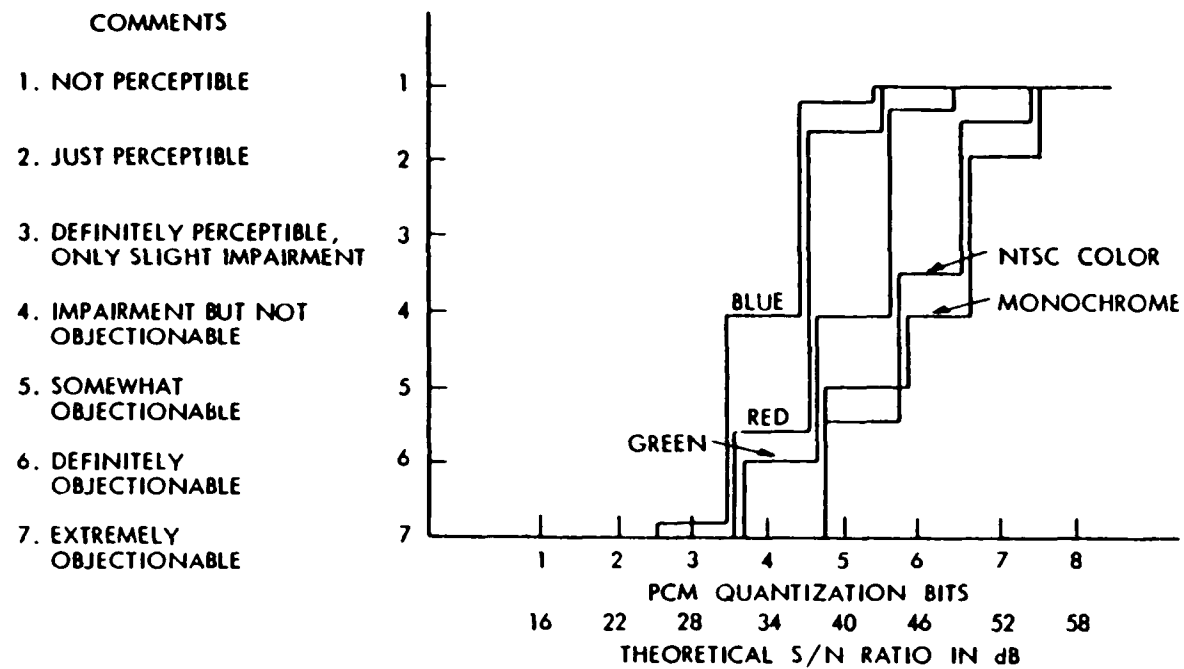


Figure 1.4-10 Subjective effects of PCM quantization noise in color signals [24]

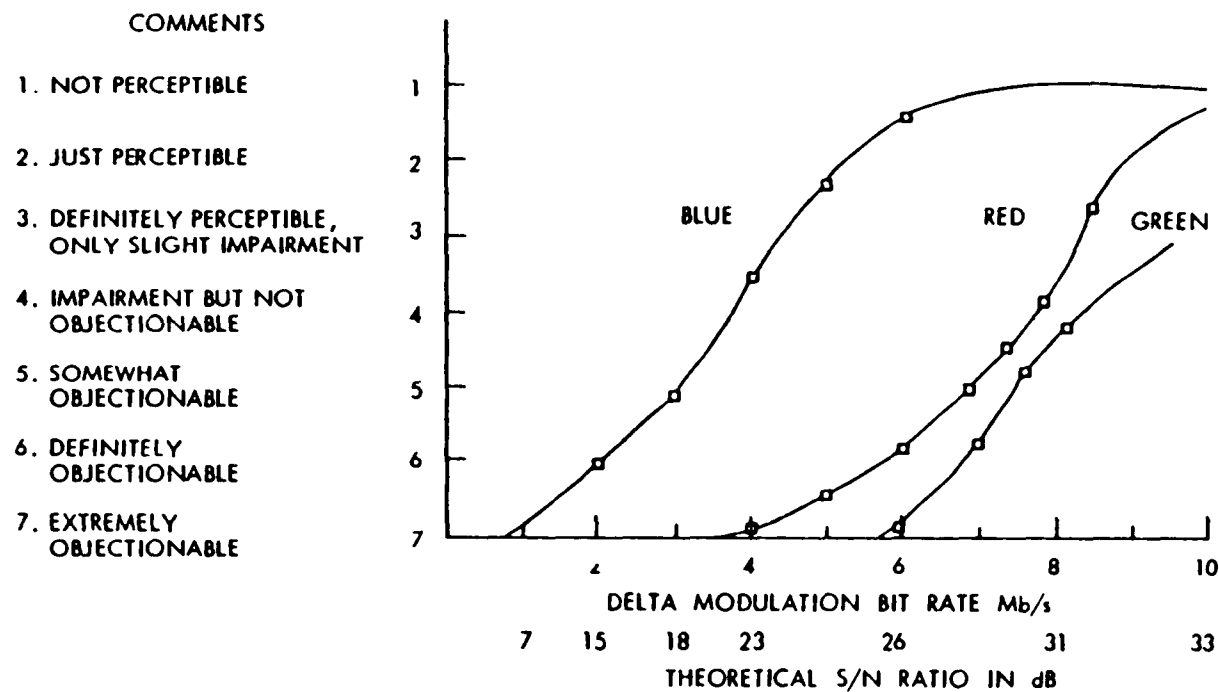


Figure 1.4-11 Subjective effects of  $\Delta M$  noise in color channels.  
[24]

Table 1.4-2  
Comparison of Standard PCM and Delta Modulation  
[24]

| Trans-<br>mission<br>Objective | Delta Modulation |     |      |                      | Bit Rates Required (Mb/sec) |       |       |       |       |       |       |       |       |                      |
|--------------------------------|------------------|-----|------|----------------------|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|----------------------|
|                                |                  |     |      |                      | Standard PCM                |       |       |       |       |       |       |       |       | Total<br>Bit<br>Rate |
|                                |                  |     |      |                      | Green                       |       |       | Red   |       |       | Blue  |       |       |                      |
|                                | Green            | Red | Blue | Total<br>Bit<br>Rate | S. R.                       | Q. B. | B. R. | S. R. | Q. B. | B. R. | S. R. | Q. B. | B. R. |                      |
| 1-2                            | 16               | 10  | 6    | 32                   | 3                           | 6     | 18    | 2.5   | 5     | 12.5  | 1.5   | 5     | 7.5   | 36                   |
| 2-3                            | 12               | 8.5 | 5    | 25.5                 | 2.5                         | 6     | 15    | 2.35  | 5     | 11.75 | 1.25  | 5     | 6.25  | 33                   |
| 3-4                            | 9                | 8   | 4    | 21                   | 2.4                         | 6     | 14.4  | 2.30  | 5     | 11.50 | 1.2   | 5     | 6     | 31.9                 |
| 4-5                            | 8                | 7   | 3    | 18                   | 2.3                         | 5     | 11.5  | 2.25  | 5     | 11.25 | 1.1   | 4     | 4.4   | 27.2                 |
| 5-6                            | 7                | 6   | 2.5  | 15.5                 | 2.25                        | 5     | 11.25 | 2.0   | 4     | 8     | 1     | 4     | 4     | 23.3                 |

S. R. - Sampling rate in MHz

Q. B. - Quantization bits

B. R. - Bit rate in Mb/sec

.6 seconds for the eye to adjust to a complete scene change.

Work by Beddoes, Meier and Chu [25,26] has shown how this reduced sensitivity to scene change in presentations can be used to reduce the scan rate of images that were alternately preprocessed, using binary symmetric lowpass filtering.

#### 1.4-7 Summary

In this section on psychovisual coding we have shown the importance of countering superthreshold edge noise for compression and how reduced sensitivity to color and motion may be exploited for bandwidth reduction.

#### 1.5 Transform Coding

Transform coding is a method for accomplishing some aspects of both statistical and psychovisual coding. The first step in transform coding is to map the image from time-space into spatial frequency-space. This can be done through optical or digital means. The transform is then operated upon to weight, phase shift, or filter out components in the transform domain. The filtered elements can be transmitted and then retransformed. The resulting operations allow for source encoding of the image not otherwise available to reduce the bandwidth. Digital transform coding requires that the picture to be sampled

and digitized be at least 6 bits. The samples (pels) are then arranged in a matrix such that the location of the pel in the picture corresponds to its location in the matrix (see Fig. 1.5-1).

The picture represented by  $N \times N$  matrix  $[X]$ , is then transformed into a new  $N \times N$  matrix  $[Y]$ . If the transformation is properly chosen, some of the elements of  $[Y]$  can be discarded and others quantized coarsely. The resulting  $[Y]^*$  matrix can then be transmitted to the receiver using fewer bits than would have been necessary if  $[X]$ , the original picture, were sent. At the receiver  $[Y]^*$  matrix is inverse transformed back into a picture  $[X]^*$ . If the transform was chosen properly and if no important elements of  $[Y]$  were discarded, then  $[X]^*$ , the received picture, should look nearly the same as  $[X]$  the original picture.

To illustrate how transformed coding works on pictures, we begin with the familiar one-dimensional discrete Fourier transform (DFT). The basis vector for this transform are harmonically related sinusoids. To perform the transform we correlate our signal  $X(n)$ ,  $n = 0, 1, 2, \dots, N-1$ , with each sinusoid. The result of each correlation is a number or coefficient  $Y(K)$ . Mathematically we may write the correlation as

$$Y(K) = \frac{1}{N} \sum_{n=0}^{N-1} e^{-j2\pi K n/N} X(n), \quad K = 0, 1, 2, \dots, N-1 \quad (1.5-1)$$



Figure 1.5-1 Numerical printout of picture



So,  $e^{-j2\pi k n/N}$  has frequency  $K$ , and  $X(0), X(1) \dots X(N-1)$  are the amplitudes of the first, second, and last sample of the signal to be transformed.

We may rewrite equation (1.5-1) in matrix notation as

$$\bar{Y} = \frac{1}{N} [F] \bar{X} \quad (1.5-2)$$

where  $\bar{X}$  is a vector whose elements could be the brightness or phase of the pels in a line of the picture. The vector  $\bar{Y}$  is the transform of  $\bar{X}$ , and  $[F]$  is an  $N \times N$  matrix the elements of which are given by:

$$F_{ij} = e^{-j2\pi i j / N} \quad i, j = 0, 1, 2, \dots, N-1 \quad (1.5-3)$$

The amplitude of the elements of equation (1.5-2) are depicted in Fig. 1.5-2.

$\bar{X}$  may be recovered from  $\bar{Y}$  by simply multiplying each coefficient of  $\bar{Y}, Y(K)$ ,  $K = 0, 1, 2, \dots, N-1$ , by its corresponding sinusoid (basis vector) and summing up the result.

In matrix notation we would write it as

$$[F]^T \bar{Y} = \bar{X} \quad (1.5-4)$$

(Here  $[F]^T = [F]^{-1}$  for this matrix.)

At this point we have not saved any bandwidth since there are as many coefficients in the transform  $\bar{Y}$ , as there were samples in the original line  $\bar{X}$ . Only when

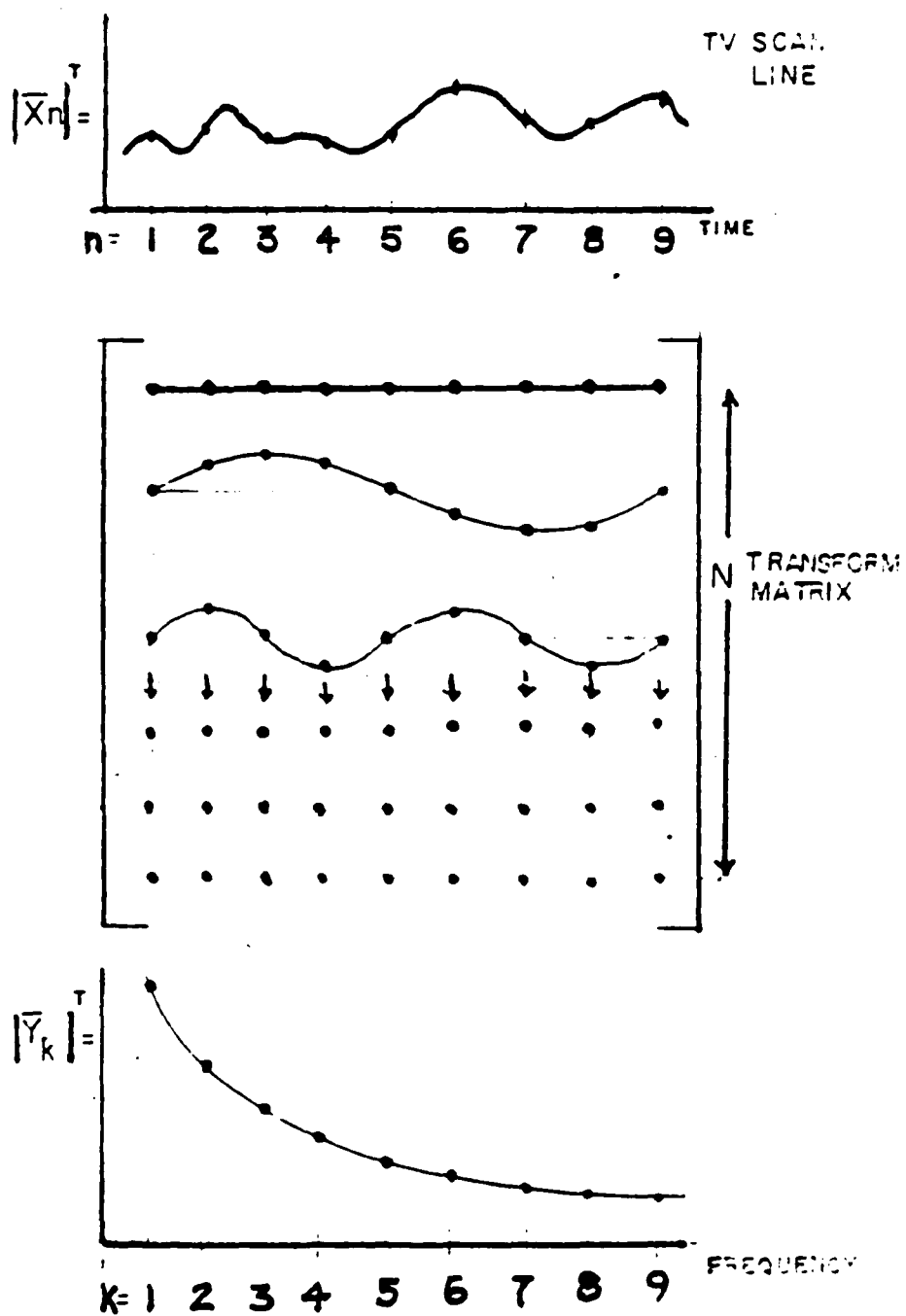


Figure 1.5-2 Amplitude of the elements of equation 1.5-2

some of the elements are discarded and others quantized coarsely in  $\bar{Y}$ , can we save bandwidth.

#### 1.5-1 Zonal Transform Coding

In a zonal transform coding system, a set of zones is established in each transform block. Transform samples in each zone are then quantized with the same number of quantization levels. The quantization levels are generally set proportional to the expected variance of the transform coefficients. For a constant word length code,  $N_B(u,v)$  code bits are assigned to each coefficient ( $u,v$  are the spatial frequency coordinates). This results in

$$L(u,v) = 2^{N_B(u,v)} \quad (1.5-5)$$

quantization levels. A total number of  $N_B$  bits

$$N_B = \sum_u \sum_v N_B(u,v) \quad (1.5-6)$$

are required to code the picture. The bit assignment  $N_B(u,v)$  for each coefficient is set according to the log-variance relation

$$N_B(u,v) = \frac{N_B}{N^2} + 2 \log_{10} \left[ V_f(u,v) - \frac{2}{N^2} \sum_{a=1}^N \sum_{b=1}^N \log_{10}(V_f(a,b)) \right] \quad (1.5-7)$$

This is based on the vector quantization suggested by Ready and Wintz [67] for minimizing the mean square error quantization

$$E_r = \sum_{j=0}^{J-1} \int_{\text{Decision Region}} \text{tr} \left[ (\bar{f} - \bar{r}_j)(\bar{f} - \bar{r}_j)^T \right] p(\bar{f}) d\bar{f} \quad (1.5-8)$$

which applies to the Max quantization (optimal decision and reconstruction for a Gaussian signal density). Here the independent Gaussian variables are

$$b_i = \frac{B}{N} + 2 \log_{10}[\sigma^2(i)] - \frac{2}{N} \sum_{j=1}^N \log_{10}[\sigma^2(j)] \quad (1.5-9)$$

where  $\sigma^2(i)$  denotes the variance of the  $i^{\text{th}}$  sample.

Therefore we see in eq. (1.5-7) that  $V_f(u,v)$  is the two-dimensional variance of a transformed coefficient. If  $N_B$ , the number of bits, is set low, some coefficients will be assigned no quantization level and discarded.

In effect, the mean square error for zonal coding is equal to the mean square error of the discarded coefficients. Thus the mean error per pixel can be expressed as:

$$E_r = \frac{1}{N^2} \sum_u \sum_v E^{-2}(u,v) [1 - \epsilon(u,v)] \quad (1.5-10)$$

where  $\epsilon(u,v)$  is unity for kept components and zero for discarded components. Hence the mean square error performance of a unitary transform is determined by its degree of cumulative energy packing.

It is generally assumed that the statistics of natural scenes are such that many of the coefficients are very small. These are generally assumed to be those of high spatial frequency and many of them can be discarded with little effect on the picture at sampling rates above 16 Mbits/sec. From the psycho-physics of vision we have seen that high spatial frequency components may be quantized more coarsely when the noise is below threshold, since the eye at these pel sizes is incapable of discriminating fine shades of grey on high spatial frequency details. We have also seen that we may quantize blue and red signal components more coarsely than green channel components. The net effect is that some coefficients will require 8 bits to transmit, others fewer bits, and some can be discarded altogether, thus effecting a savings in bandwidth.

When the coefficients to be discarded are determined in advance (non-adaptive), the system is called zonal sampling. Fig. 1.5-3 shows a typical bit assignment in the transform domain for zonal coding in a 16x16 pixel block size.

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 8 | 8 | 7 | 7 | 7 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 8 | 8 | 7 | 6 | 5 | 5 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 |
| 8 | 7 | 6 | 4 | 4 | 4 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 7 | 6 | 4 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| 7 | 5 | 4 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 7 | 5 | 4 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 3 | 3 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 3 | 3 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 3 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 3 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 1.5-3. Typical bit assignment for a 16x16 transform domain zonal coding scheme.

If the coefficients to be sent are adaptively changed to optimize each picture, then the system is called adaptive transform coding.

One can extend the concept of a one-dimensional transform, which operates on a line of the picture, to a two-dimensional transform which transforms the picture in both the horizontal and vertical dimensions. The motivation for doing this lies in the fact that elements in the picture are correlated in every direction to the elements around them. If we assume the picture to be transformed is represented by an  $N \times N$  matrix  $[X]$ , a two-dimensional transform can be carried out by correlating  $[X]$  with  $N^2$  orthogonal vectors, each  $N$  elements by  $N$  elements. These orthogonal vectors  $[F]_{K,L}$ ,  $K, L = 0, 1, 2, \dots, N-1$ , comprise the basis pictures of the digital transform. The result of each correlation is a coefficient,  $Y_{K,L}$ . Mathematically we may write the correlation as

$$Y_{K,L} = \frac{1}{N^2} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} F_{KLij} X_{ij} \quad (1.5-11)$$

where  $F_{KLij}$  is the  $i, j^{\text{th}}$  term of the  $K, L$  vector, and  $x_{ij}$  is an element of the input matrix  $[X]$  as shown in Fig. 1.5-4.

$$[F]_{K,L} = \begin{bmatrix} f_{K,L}^{0,0} & f_{K,L}^{0,1} \dots f_{K,L}^{0,N-1} \\ f_{K,L}^{1,0} & f_{K,L}^{1,1} \dots \vdots \\ \vdots & \vdots \vdots \vdots \\ f_{K,L}^{N-1,0} & \vdots f_{K,L}^{N-1,N-1} \end{bmatrix}$$

(a)

$$[x] = \begin{bmatrix} x_{0,0} & x_{0,1} \dots x_{0,N-1} \\ x_{1,0} & x_{1,1} \vdots \\ \vdots & \vdots \vdots \vdots \\ x_{N-1,0} & \vdots x_{N-1,N-1} \end{bmatrix}$$

(b)

Figure 1.5-4(a) The K,L the basis picture shown as an NxN vector

(b) The digital picture to be transformed represented as an NxN matrix



We may visualize equation 1.5-11 as a mapping which places the  $[X]$  matrix over one of the  $[F]_{K,L}$  vectors (basis pictures). The elements that touch each other are then multiplied together and the result of the multiplication is summed up for each spatial frequency. This yields coefficient  $Y_{K,L}$ .

The next coefficient is found by changing the index of  $L$  or  $K$  in the  $[F]_{KL}$  vector. As in the one-dimensional transform, we may recover the picture  $[X]$  from the coefficients  $Y_{K,L}$  by multiplying each coefficient by its corresponding basis picture  $[F]_{L,K}$  and summing up the result:

$$X_{ij} = \sum_{L=0}^{N-1} \sum_{K=0}^{N-1} F_{ijKL} Y_{KL} \quad (1.5-12)$$

In general, two-dimensional transforms of an  $N \times N$  picture given by eq. (1.5-11) would require  $N^4$  Multiplications and Additions, dubbed MAs. Since the  $N^4$  multiplication process  $N^2$  picture elements, and the sampling rate of the picture elements for standard television is 125 ns/pel, we must then perform  $N^2$  MAs every 125 ns to transform real time TV signals digitally. If the transform technique is to be implemented in digital

hardware,  $N$  must be small, and the exponential growth of MAs with  $N$  must be avoided.

Wintz [68] and others have approached this problem of large  $N$  by dividing up the picture into subpictures, each  $n \times n$ , then transforming each  $n \times n$  subpicture separately. A compromise between  $n$  small and bandwidth saving must be made since when  $n$  is made too small, the ability of the transform to save bandwidth will suffer. This is because all possible  $N \times N$  sub-pictures will become equally likely; being equally likely, they will correlate equally on the average with all the basis pictures, and all the coefficients of eq. (1.5-11) will become equally important. Both Wintz [68] and Pratt [69] conducted computer simulations with several different types of transforms and the results are shown in Figs. 1.5-5 and 1.5-6, respectively. These figures suggest that  $n$  should be at least 8 and that with small  $n = 16$ , Wintz showed good results could be obtained.

The MSE coding area goes down only slightly for  $n = 8$  and goes up sharply for  $n = 16$ . Although it is generally acknowledged that the MSE error is not a good indicator of image quality, it does provide some measure of a relative noise content [70]. With  $N = n = 8$ , 64 MAs would still be required in

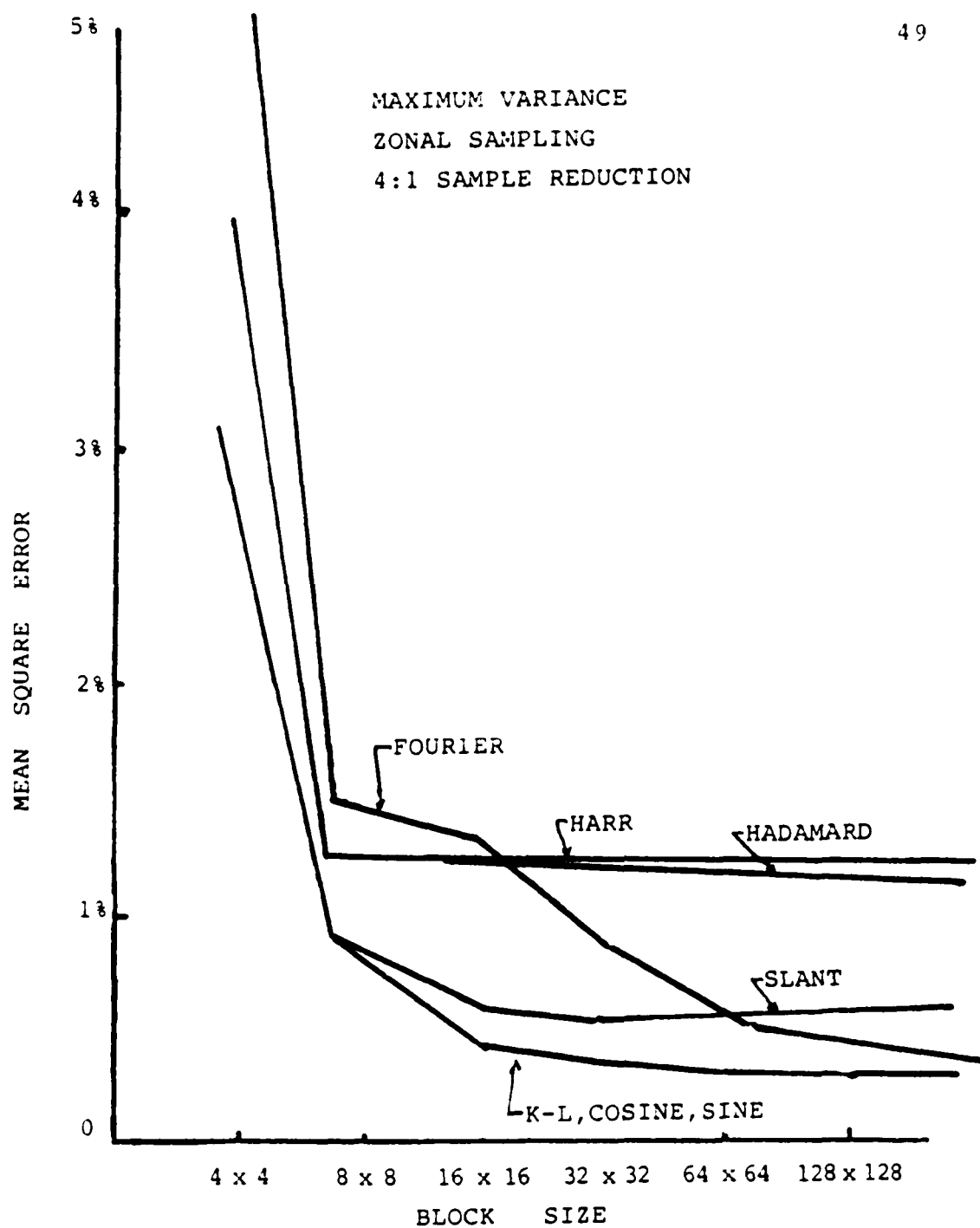


Figure 1.5-5 Zonal sampling mean square performance of image transforms as a function of block size

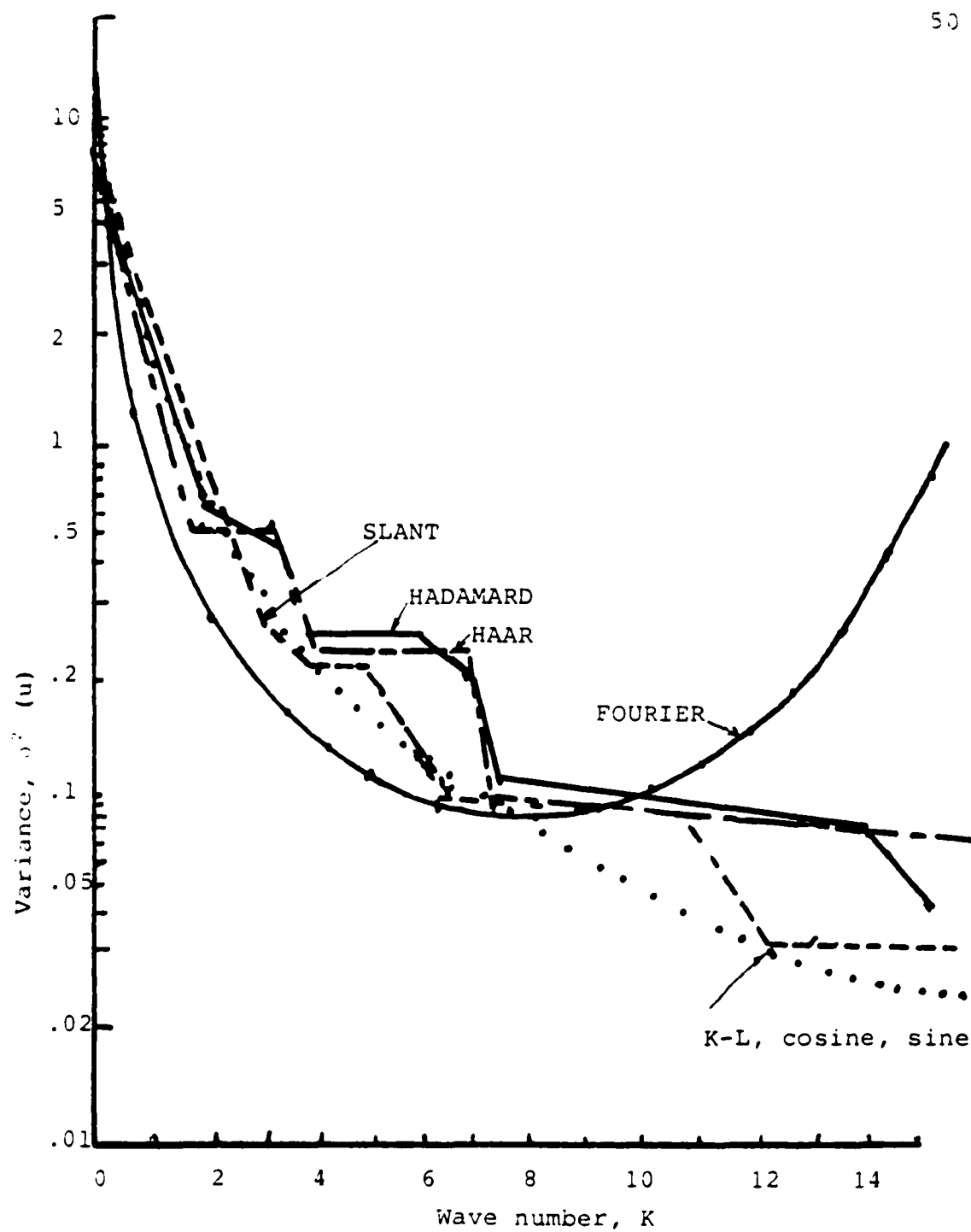


Figure 1.5-6 Variances of unitary transform coefficients,  
 $N = 16$

125 ns, which would not be feasible for digital implementation.

Other measures of two-dimensional picture quality (that include the effect of edge noise as well as superthreshold perception of monochrome video images corrupted by Gaussian white noise added to the video image) covered in the previous sections are better indicators of video quality.

The  $N^2$  growth rate in MAs can be reduced to  $2N$  when the proper transform basis set is chosen. In these transforms the basis pictures can be derived from  $N$  orthogonal vectors each of length  $N$ . If, as before,  $\bar{F}_K$   $\bar{F}_L$  are the orthogonal basis pictures, then  $[F]_{K,L}$  is formed from these vectors by the equation

$$[F]_{K,L} = \bar{F}_K \bar{F}_L^T \quad K, L = 0, 1, 2, \dots, N-1 \quad (1.5-13)$$

As an example consider the following:

$$\bar{F}_K = \begin{bmatrix} a \\ b \end{bmatrix} \quad \bar{F}_L = \begin{bmatrix} c \\ d \end{bmatrix} \quad [F]_{K,L} = \begin{bmatrix} a \\ b \end{bmatrix}^{[cd]} = \begin{bmatrix} ac & ad \\ bc & bd \end{bmatrix} \quad (1.5-14)$$

If the  $N$  orthogonal vectors used to form the basis

pictures via eq. (1.5-13) are arranged to form the rows of a matrix  $[F]$ , then the two dimensional transform of eq. (1.5-11) may be rewritten in matrix notation

$$[Y] = \frac{1}{N^2} [F][X][F]^T \quad (1.5-15)$$

As before,  $[X]$  is the picture and  $[Y]$  is the transform coefficient matrix.

The series representation for the transform and its inverse is given by

$$Y_{K,L} = \frac{1}{N^2} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} X_{ij} F_{KL} F_{jL} \quad (1.5-16)$$

$$X_{ij} = \sum_{K=0}^{N-1} \sum_{L=0}^{N-1} Y_{KL} F_{iK} F_{Lj} \quad (1.5-17)$$

This requires only  $2N^3$  MAs. Thus, a real time digital encoder using a transform implemented as in eq. (1.5-16) would require  $2N^3/N^2 = 2N$  MAs every 125 ns. With  $N = 8$ , such an encoder is possible but still very complicated.

There exist at present other fast computational algorithms one of which is due to Cooley-Tuckey [71] called the Fast Fourier Transform (FFT)

With this algorithm eq. (1.5-16) could be implemented in only  $2N^2 \log_2 N$  MAs. A real time encoder would thus require  $N \log_2 N$  multiplications every 125 ns. With  $N = 8$ , there would be only 6 MAs every 125 ns.

There exist six other transforms which also have fast computational algorithms that have been investigated. They are the discrete Fourier transform (DFT), the Haar transform, the Hadamard transform, the cosine transform, the sine transform, and the slant transform. The basis functions for these transforms are shown in Fig. 1.5-7 through 1.5-13. The slant transform performed better than the Haar, Hadamard, or Fourier transforms, though as the block size increases, the Fourier MSE improves and surpasses the slant transform and approaches the Karhunen-Loeve transform in performance. The KL-transform appears to be the best but is computationally slow and one must know the image statistics a priori. Ahmed [72] has shown that the discrete cosine transform which possesses a fast computational algorithm approaches the efficiency of the K-L transform for Markov-process image data.<sup>1</sup>

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<sup>1</sup>In a signal characterized as a Markov process, the present sample statistics are assumed to depend only upon the preceding sample value.

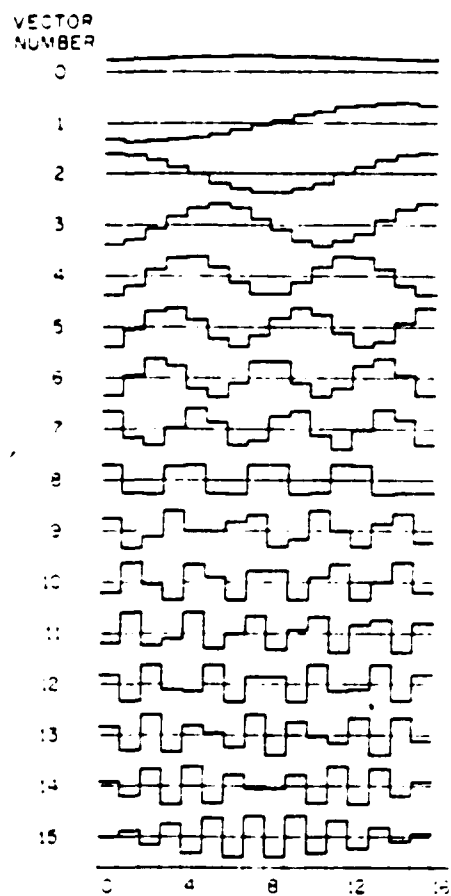


Figure 1.5-7 Karhunen-Loeve transform basis functions  
N = 16



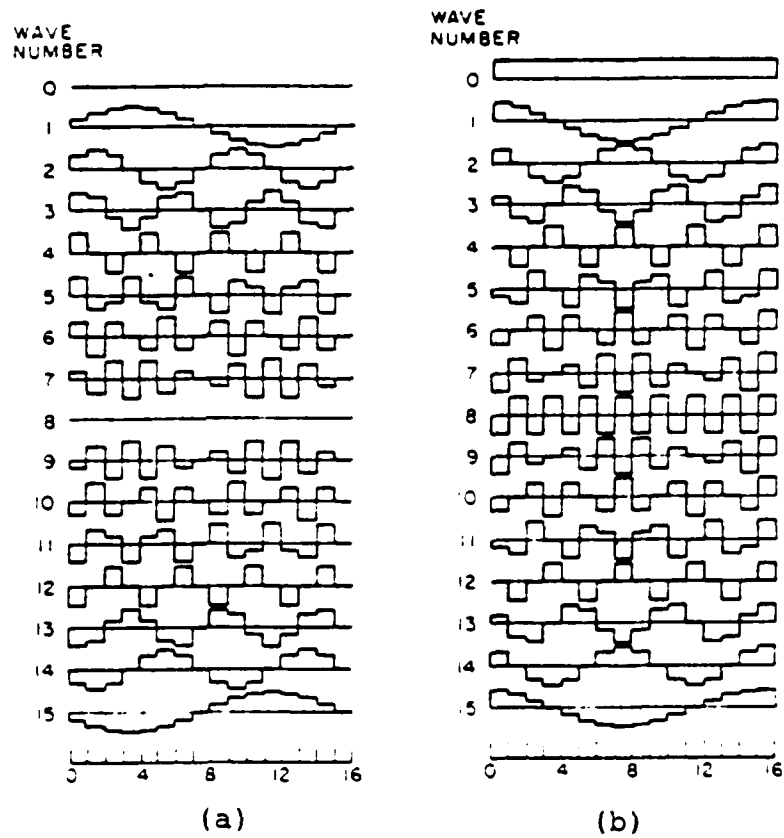


Figure 1.5-8 Fourier basis functions  
 (a) Sine component  
 (b) Cosine component

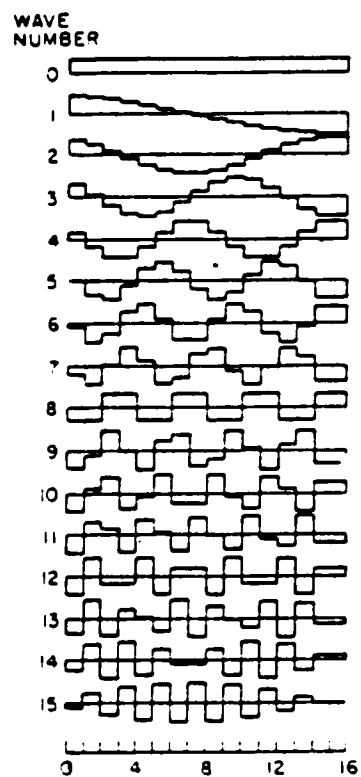


Figure 1.5-9 Cosine basis functions

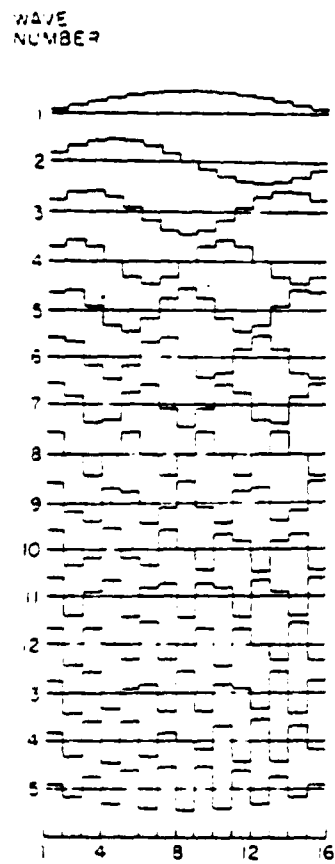


Figure 1.5-10 Sine transform basis functions,  
 $N = 15$

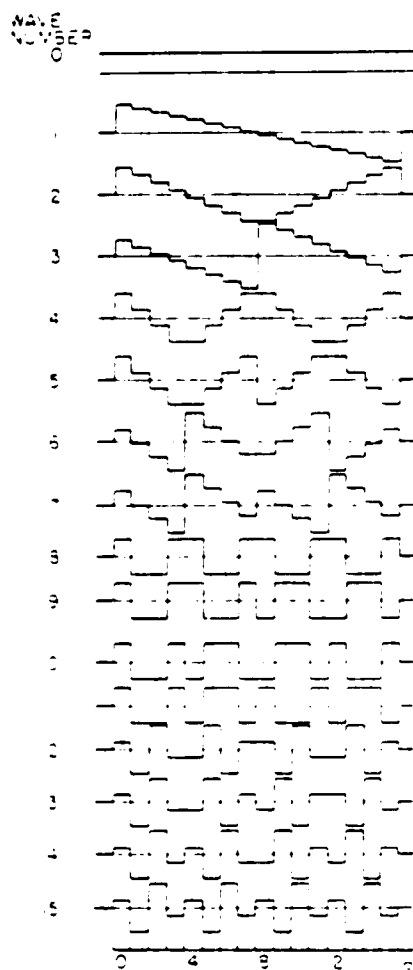


Figure 1.5-11 Slant transform basis functions,  
N=16

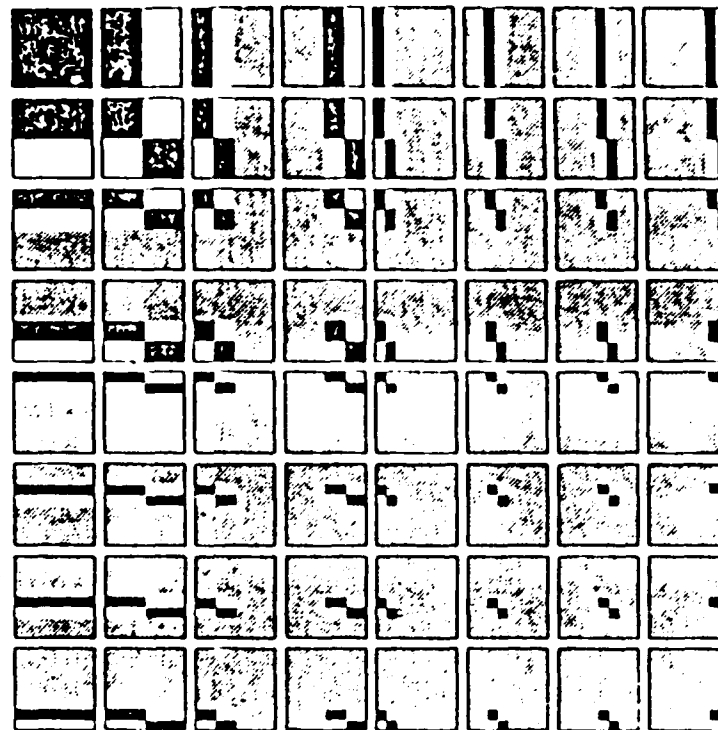
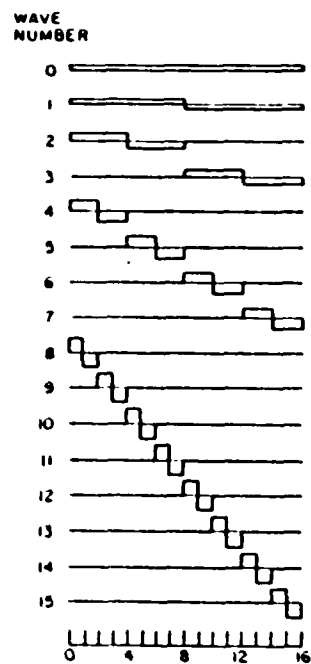


Figure 1.5-12 Haar transform basis functions,  $N=16$   
 Haar transform basis planes for  $N=8$ . Black = +1;  
 white = -1, cross-hatched = 0

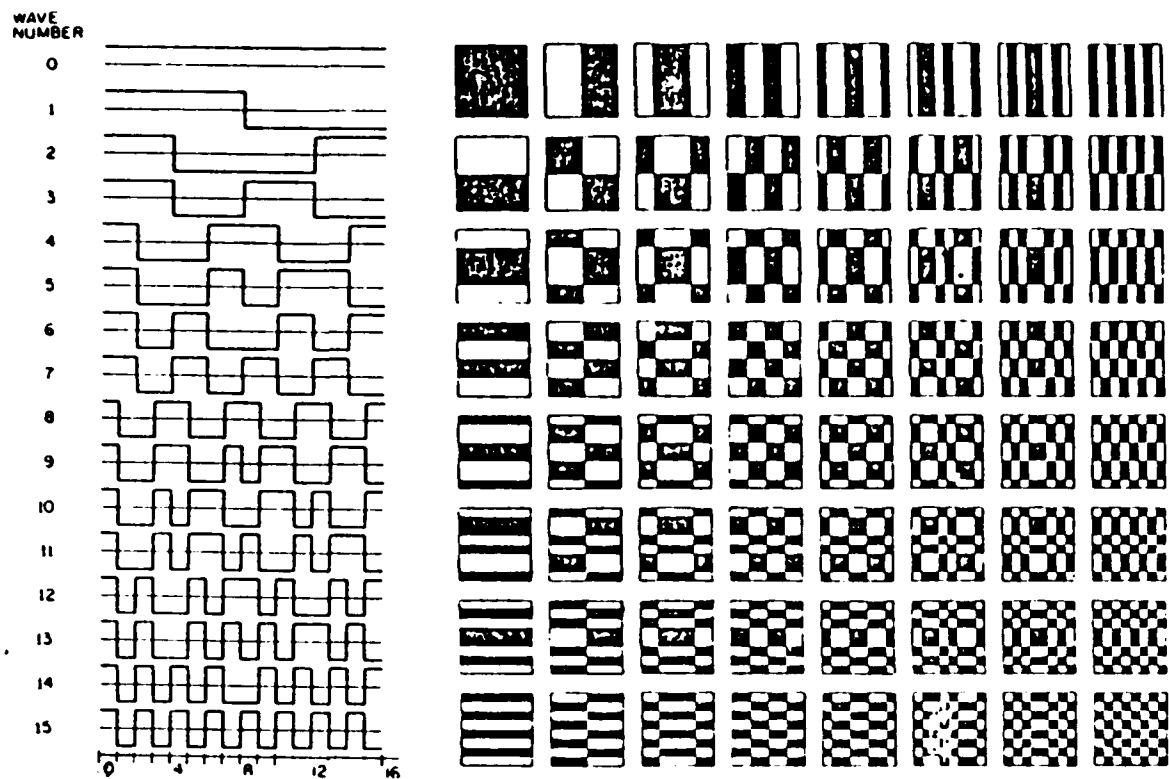


Figure 1.5-13 Hadamard transform basis functions,  $N = 16$   
Hadamard transform basis planes for  $N = 8$   
Black = +1; white = -1

Another fast transform is the sine transform, suggested by Jain [73] that has properties simulating those of cosine transform. When using the discrete cosine transform (DCT), the image must be uneven so that a 4-way folded image of the original is reproduced. The DCT coefficients are real. By adding an additional DC term to the transform coefficients, coefficients can be made positive and real. The DCT is related to the DFT and therefore can be computed using a fast Fourier transform algorithm.

It can be seen that digital transform coding of real time video has problems due to both speed and complexity constraints. Of the transform systems available the Hadamard transform with its +1 and -1 basis vector elements appears to be attractive for possible real-time application using small, block-size subpictures. This allows for computation of the transform to be computed with  $2N^2 \log_2$  additions and no multiplications.

The Hadamard transform matrix is shown in Fig. 1.5-13 for  $N=n=8$ . Here the +1 is represented by black, and the -1 is represented by white. The procedure that is followed is to break the original picture into subpictures and operate on each subpicture. In 1977, Merola et al. of the General

Electric Co. [74] implemented a hard-wired charge injection device (CID) focal plane Hadamard transform system. A matrix of  $4 \times 4$  arrays of microprocessor control Hadamard mass operated to transform a  $128 \times 128$  image. Moderate quality was reported for real time operation.

In this section we have shown the different digital transform coding schemes are limited by computational processing time constraints for real time application. In the next chapter we discuss another class of encoders that remove redundancy in a different fashion and lend themselves to optical-hybrid systems.



CHAPTER II

PREDICTIVE DIGITAL AND HYBRID ENCODING METHODS RELATED  
TO NOISE AND BANDWIDTH COMPRESSION

2.1 Predictive Encoding

Another class of encoders called predictive encoders has been studied for its bandwidth compression capabilities. Though it was originally used for audio signals, it has been studied for use with video signals as well.

A linear predictive encoder may be defined by the equation

$$X_0 = a_1 S_1 + a_2 S_2 + \dots + a_n S_n \quad (2.1-1)$$

$$E_0 = S_0 - X_0$$

where  $S_0, S_1, \dots, S_n$  are the successive samples of the signal.  $S_0$  is the current sample and  $X_0$  is the predictor estimate of  $S_0$  based upon the previous samples  $S_1, S_2, \dots, S_n$ .  $E_0$  is the error in the prediction and is what is transmitted.

The theory behind the compression capabilities of the predicted encoder lies with the assumption that if the prediction is close to the present sample value, the set of errors that is sent will have a smaller variance than the original signal. Thus, fewer bits are needed to send the  $E_0$  error stream than the  $S_0$  signal stream. At the receiver, the signal is reconstructed by computing

$$S_o = X_o + E_o \quad (2.1-2)$$

The constants  $a_1, a_2, \dots, a_n$  can be found from linear prediction theory by assuming a minimum mean square error between the original signal and the decoded signal. For picture material other measures for predictive encoding have been suggested [75-78].

The computational ease of evaluating the MSE for the predictive encoder ensues from the assumption that the image is (albeit to some degree inappropriate) a Gaussian process. Its form is:

$$E[S_o - X_o]^2 = E[S_o - (a_1 S_1 + a_2 S_2 + \dots + a_n S_n)]^2 \quad (2.1-3)$$

where  $E[\ ]$  denotes the expected value.

To find the minimum we take the partial derivatives of  $E[(S_o - X_o)^2]$  with respect to each one of the  $a$ 's and set them equal to zero:

$$0 = \frac{d}{da_i} E[(S_o - X_o)^2] = -2E[(S_o - (a_1 S_1 + a_2 S_2 + \dots + a_n S_n)) S_i] \quad (2.1-4)$$

where

$$E[S_o, S_i] = a_1 E[S_1, D_i] + a_2 E[S_2, S_i] + \dots + a_n E[S_n, S_i] \quad (2.1-5)$$

If we represent the covariance of  $S_i$  and  $S_j$  by:

$$R_{ij} = E[S_i, S_j] \quad (2.1-6)$$

We can then rewrite eq. (2.1-5) as:

$$R_{0i} = a_1 R_{1i} + a_2 R_{2i} + \dots + a_n R_{ni} \quad (2.1-7)$$

Eq. (2.1-7) defines a set of  $n$  simultaneous linear equations in the unknown  $a_i$ ,  $i = 1, 2, \dots, n$ . These can be found if the covariances are known. Graham [75] uses an autocorrelation that is very nearly Laplacean with

$$R_s(\tau) = e^{-(\alpha|\tau|)}$$

Equations (2.1-1) and (2.1-2) are implied by recursive relationship in the following equations:

$$X_K = a_1 X_{K-1} + a_2 X_{K-2} + \dots + a_n X_{K-n} + e_K \quad (2.1-8)$$

$$e_{K+1} = Q[S_{K+1} - X_K] \quad (2.1-9)$$

The function,  $Q[\cdot]$ , defines a non-linear quantizer. An implementation diagram for an  $n$  tap delay system predictive encoder is shown in Fig. 2.1-1 and uses  $n$  past results for creating the prediction of the present sample.

A number of investigators have carried out experiments to determine the optimal set of  $a_i$ 's for eq. (2.1-7) and optimal quantizer for eq. (2.1-9) [36].

O'Neal [76] determined that for minimum mean square

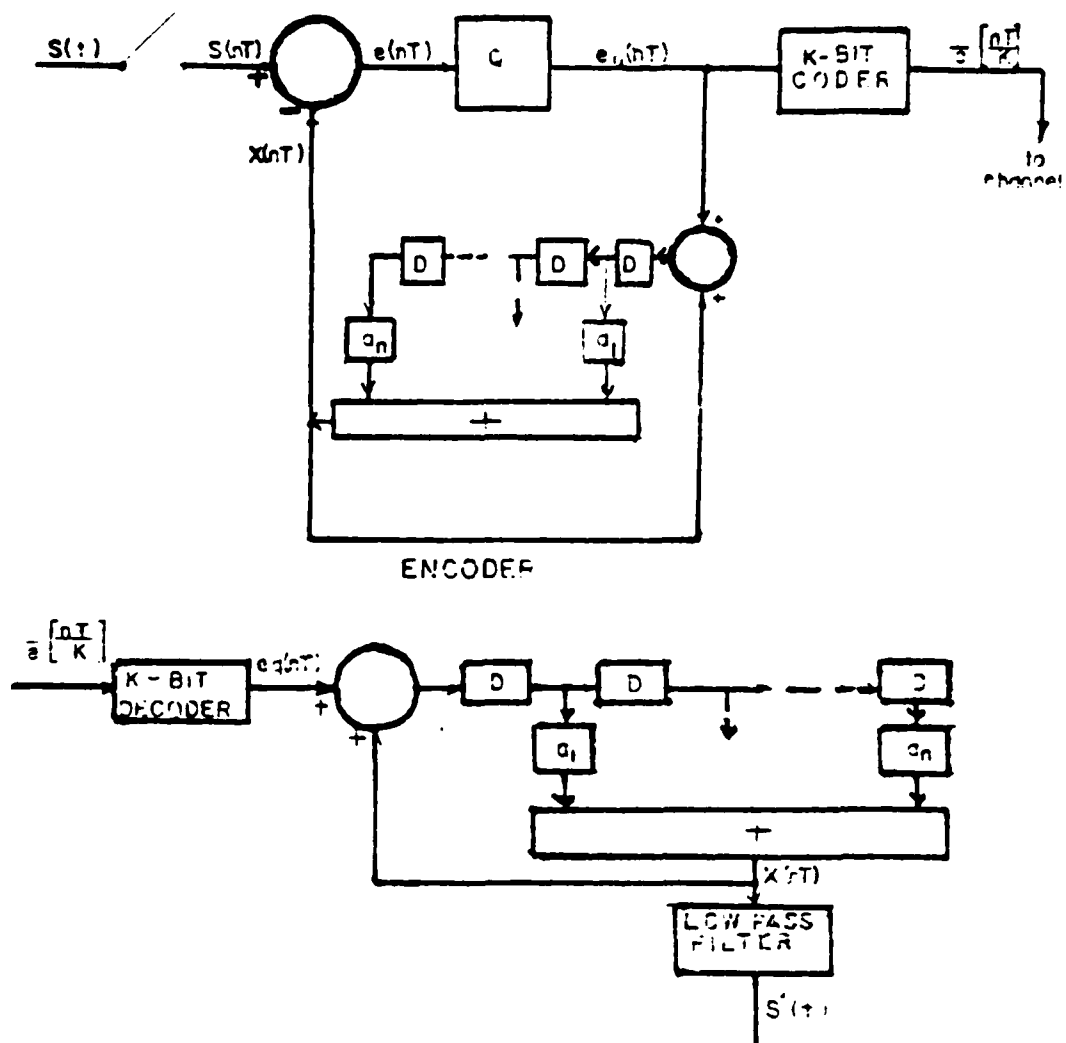


Figure 2.1-1 Block diagram for n-tap delay predictive encoder

error all of the  $a_i = 0$  except  $a_1$ . This means that only the previous sample is effective in decorrelating the signal. In terms of the scanned picture elements (pixels), Fig. 2.1-2 shows that for a causal linear prediction model [79] only the left, upper, and left diagonal elements need be considered. These pels are labeled 1, 2, and 3 in the diagram.

In practice, coefficients  $a_1, a_2, a_3$  that give the best subjective image results, are:

$$X_K = .75X_{K-1} + .75X_{K-L} - .5X_{K-L-1} \quad (2.1-10)$$

From O'Neal's work [76] it was determined that the optimum 8-level quantizer (3 bits/pel) for a picture requiring 128 brightness levels would act as a compander shown in Fig. 2.1-3. For a still picture the adjacent sample correlation coefficient was

$$\rho_s = \frac{E[S(t)S(t+T)]}{E[S^2(t)]} = .93 \quad (2.1-11)$$

After differential encoding with 3-bit PCM, the adjacent sample error correlation coefficient was measured from laboratory data to be

$$\rho_e = \frac{E[e(nT)e[(n-1)T]]}{E[e^2(nT)]} = .4407 \quad (2.1-12)$$

These results show that considerable redundancy has been

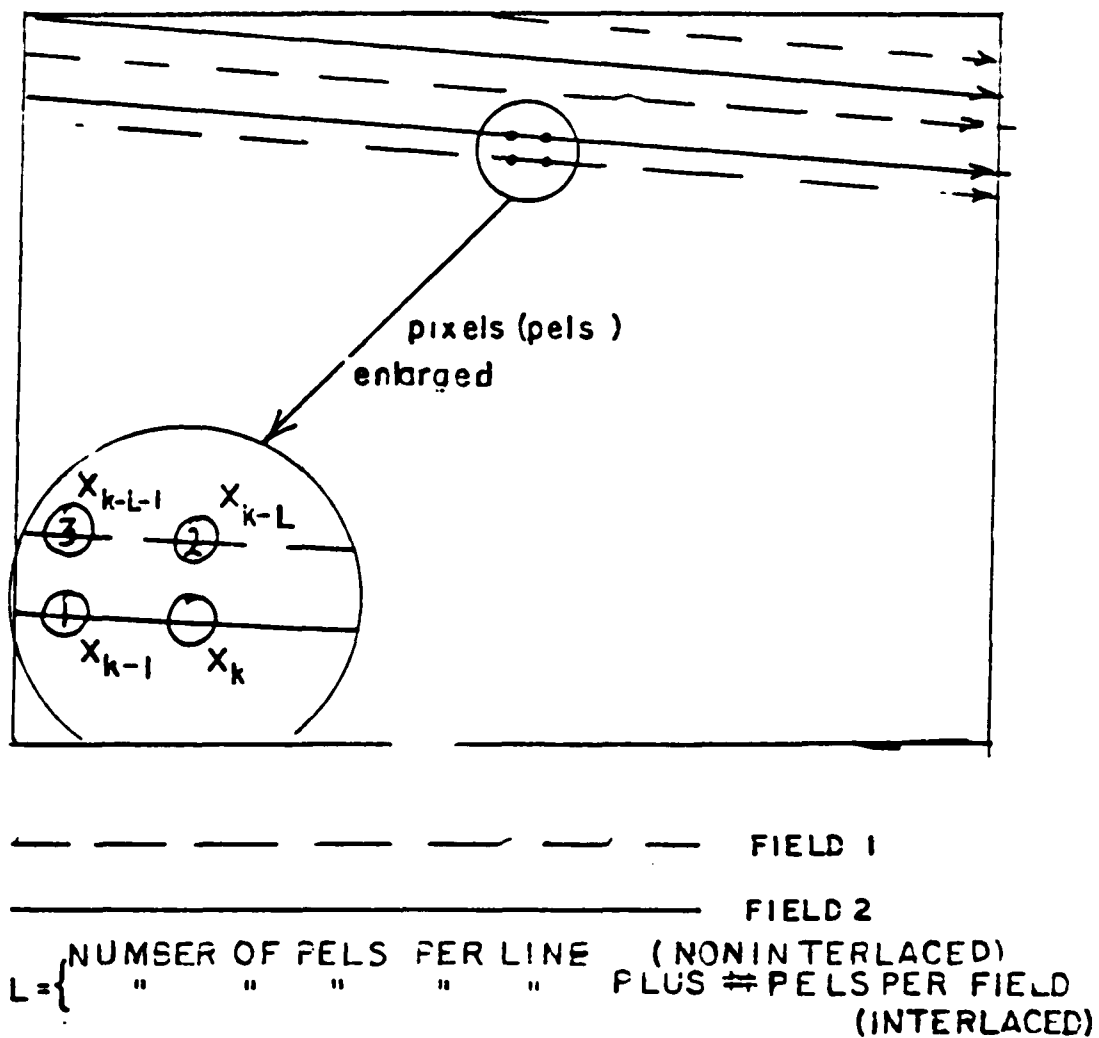


Figure 2.1-2 The two-dimensional array of picture elements (pels)

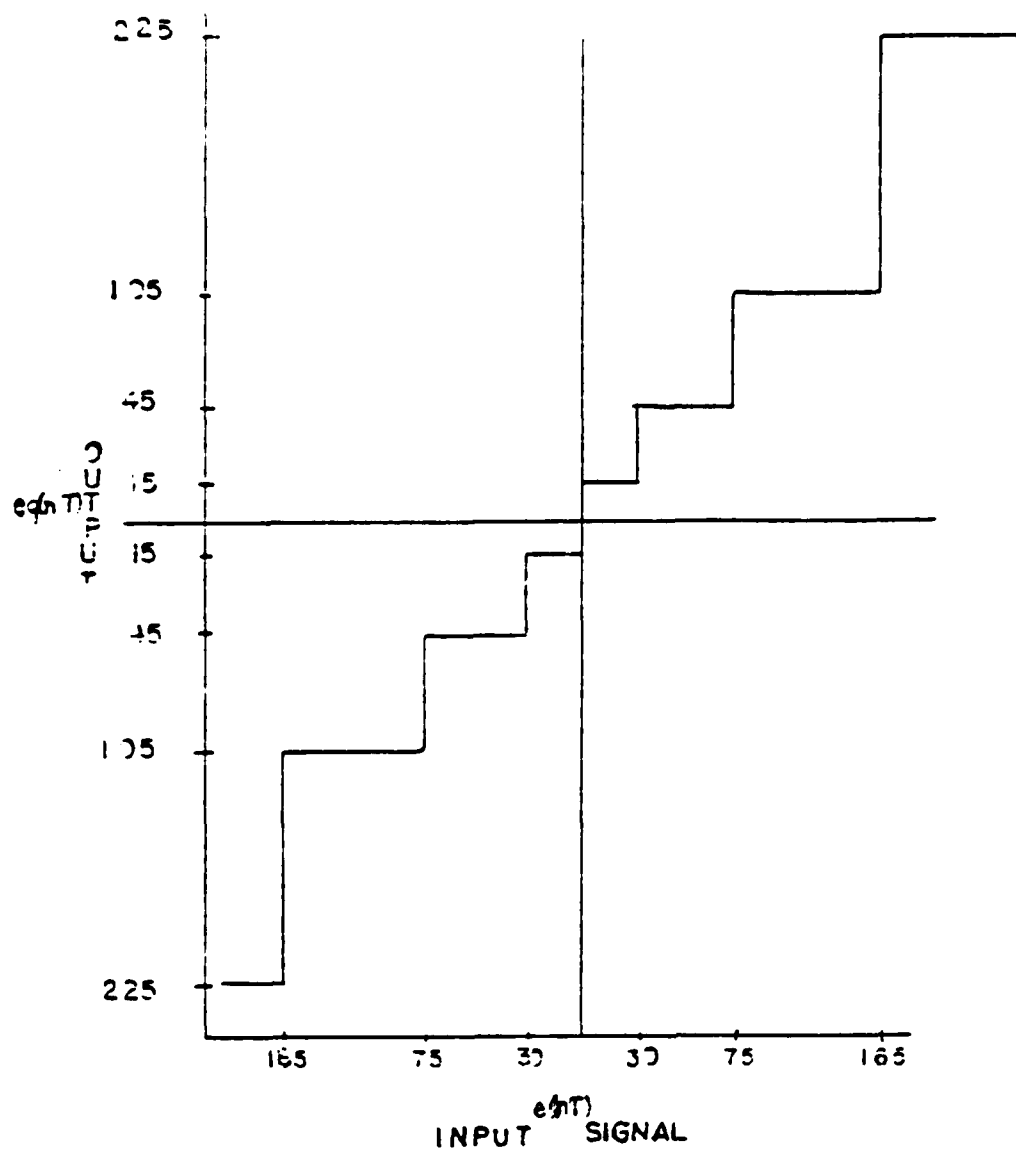


Figure 2.1-3 Three-bit DPCM Quantizer Characteristic

removed from the signal but that some sample-to-sample correlation still remains.

This fixed quantizer can be improved upon if the quantizer algorithm changes in the picture, i.e. made adaptive.

A comparison between predictive coding DPCM and two-dimensional digital encoding reveals that the DPCM encoder is less complex than the transforming decoder but that the DPCM encoder requires more bits per pel.

Wintz [68] reports that transform encoding at 2 bits per pel for an average results in quality similar to DPCM encoded pictures at 3 bits per pel. It has been estimated that it would require approximately one order of magnitude or more ICs to implement the digital transform encoder prepared with the DPCM encoder [80].

## 2.2 Interframe Encoding

The foregoing section represented processing for intra-frame encoding (i.e. within the same picture frame) and reduce redundancy between pixels or pels of one frame. Another form of encoding that takes advantage of a large degree of redundancy between frames is interframing coding.

Except for sudden changes of scene, successive frames of a TV picture are nearly identical. Studies done on broadcast TV signals reveal that on the average only 10% of the picture elements change by more than 2% between successive frames of a television signal [81].



Transform coding and predictive coding are adaptable to interframe coding by treating picture elements that are displaced in time as though they were displaced in a third dimension. This is shown in Fig. 2.2-1.  $x_K^{I-1}$  and its adjacent pels from the previous frame can now be considered one of its nearest neighboring pels. The picture elements along the time axis (the same pel position but in successive frames) are treated in the same way as pels displaced along the horizontal or vertical axis.

Another approach unique to interframe encoders uses the difference signal between frame elements as the basic element in the interframe scheme. In this system the previous frame stored in memory is compared sample by sample to the present frame. If a difference between samples from successive frames exceeds the given threshold, that sample value along with its position address, is replenished by transmitting it and updating the frame memory. The number of replenished samples transmitted to the receiver is a function of the amount of motion in the scene. A large buffer is required to average out the transmitted bit rate for picturephone application (low resolution and narrow band channel) this technique can reduce the bit rate to one bit per pel. Figure 2.2-2 shows that a broadcast quality television image would require at least two bits per pel.

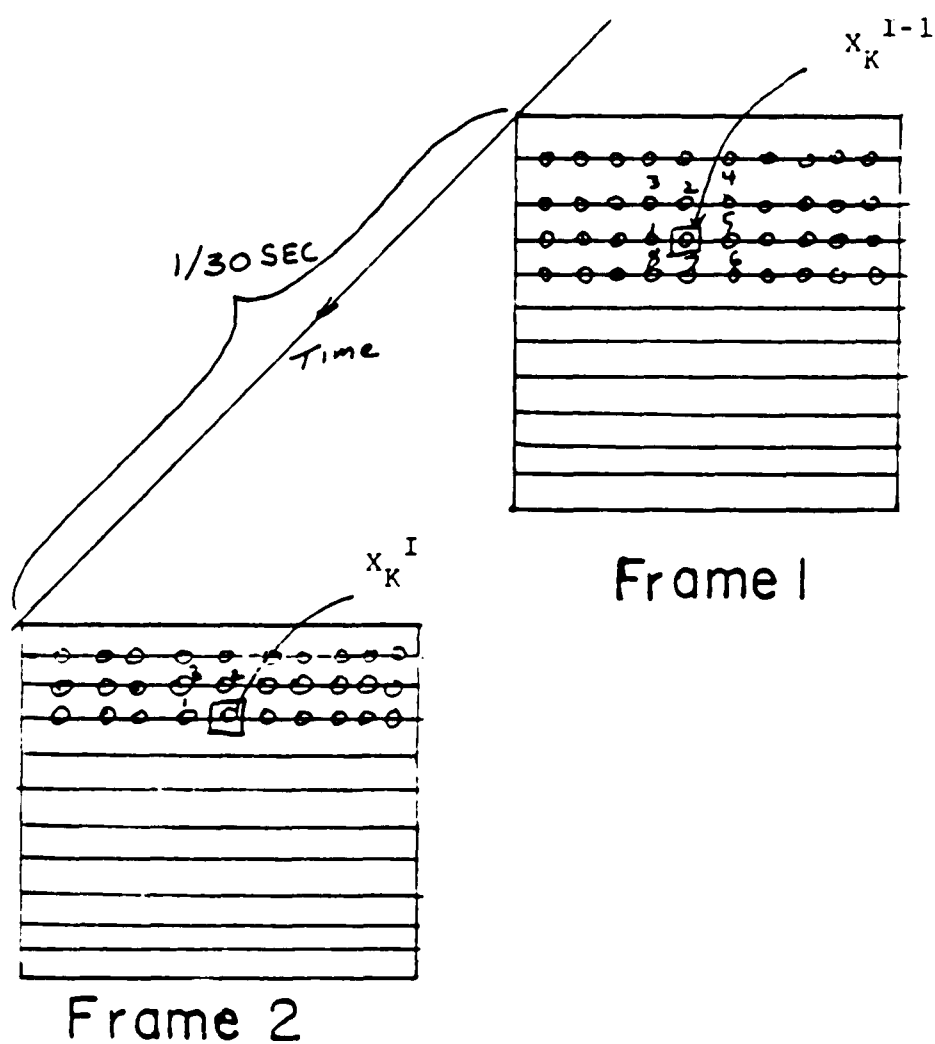


Figure 2.2-1 Interframe coding showing third dimension for nearest neighbor in time



### 2.3 Hybrid Processing

Hybrid processing marries the advantages of two or more of the foregoing types of encoding techniques in order to achieve greater bandwidth reduction. Huang et al. [28] Wintz [68], Andrews [83], and Pratt [84] discuss hybrid transform encoding where bandwidth reduction is achieved by digitally transforming the image and transmitting the coefficients using predictive and adaptive techniques for various block sizes. Fig. 2.3-1 shows their statistics and coding strategies. Fig. 2.3-2 shows the sampling rate in bits per pixel for various techniques. Fig. 2.3-3 shows the rate of compression in terms of normalized mean square error for different hybrid transform coding systems. Fig. 2.3-4 shows the percent mean square error for a given vector size for intraframe hybrid transform/DPCM coding as a function of block size. As can be seen, these hybrid coding systems have reduced the number of bits necessary to transmit the signal over purely transform or purely predictive new coding techniques.

There also exists another class of hybrid processors that marries the advantages of optical analog transform filtering (with its high space bandwidth product and real-time throughput) and digital processing (with its ability to manipulate and operate on samples point by point with high accuracy, and ease in algorithm modification).

The type of hybrid processor investigated in this

# CODING SYSTEM PARAMETERS

| System                              | Statistical Model              | Block Size   | Coding Strategy                       |
|-------------------------------------|--------------------------------|--------------|---------------------------------------|
| PCM                                 | Rayleigh                       | 1 × 1        | Constant length code                  |
| Linear predictive                   | Laplacian                      | 1 × 1        | Constant length code                  |
| Intraframe<br>transform             | d.c. Rayleigh<br>a.c. Gaussian | 16 × 16      | Zonal coding,<br>constant length code |
| Intraframe hybrid<br>DPCM/transform | Laplacian                      | 1 × 16       | Zonal coding,<br>constant length code |
| Interframe<br>transform             | d.c. Rayleigh<br>a.c. Gaussian | 16 × 16 × 16 | Zonal coding,<br>constant length code |
| Interframe hybrid<br>DPCM/transform | Laplacian                      | 16 × 16 × 1  | Zonal coding<br>constant length code  |

Figure 2.3-1 Coding System Statistics and Coding Strategy

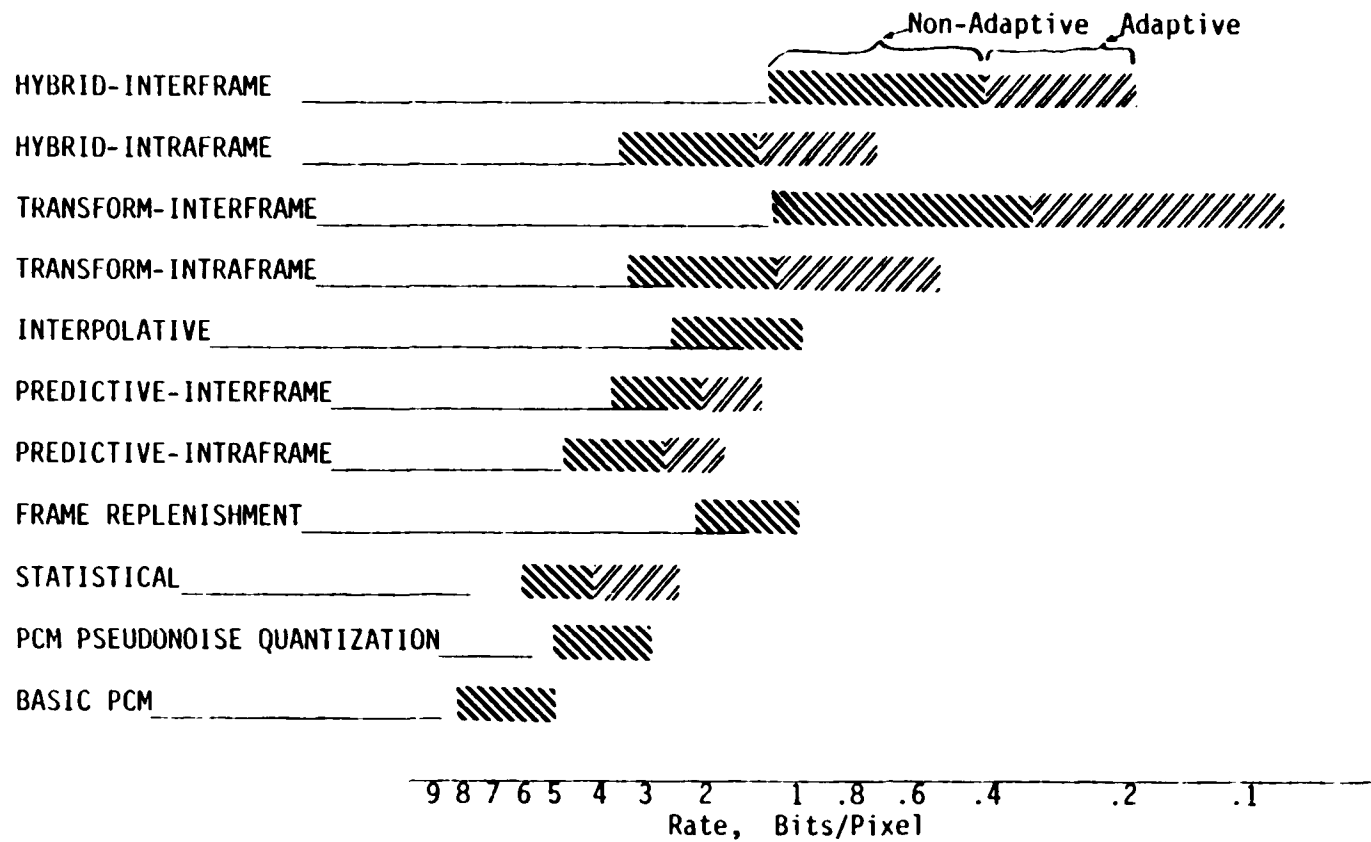


Figure 2.3-2 Coding rate of image coding systems

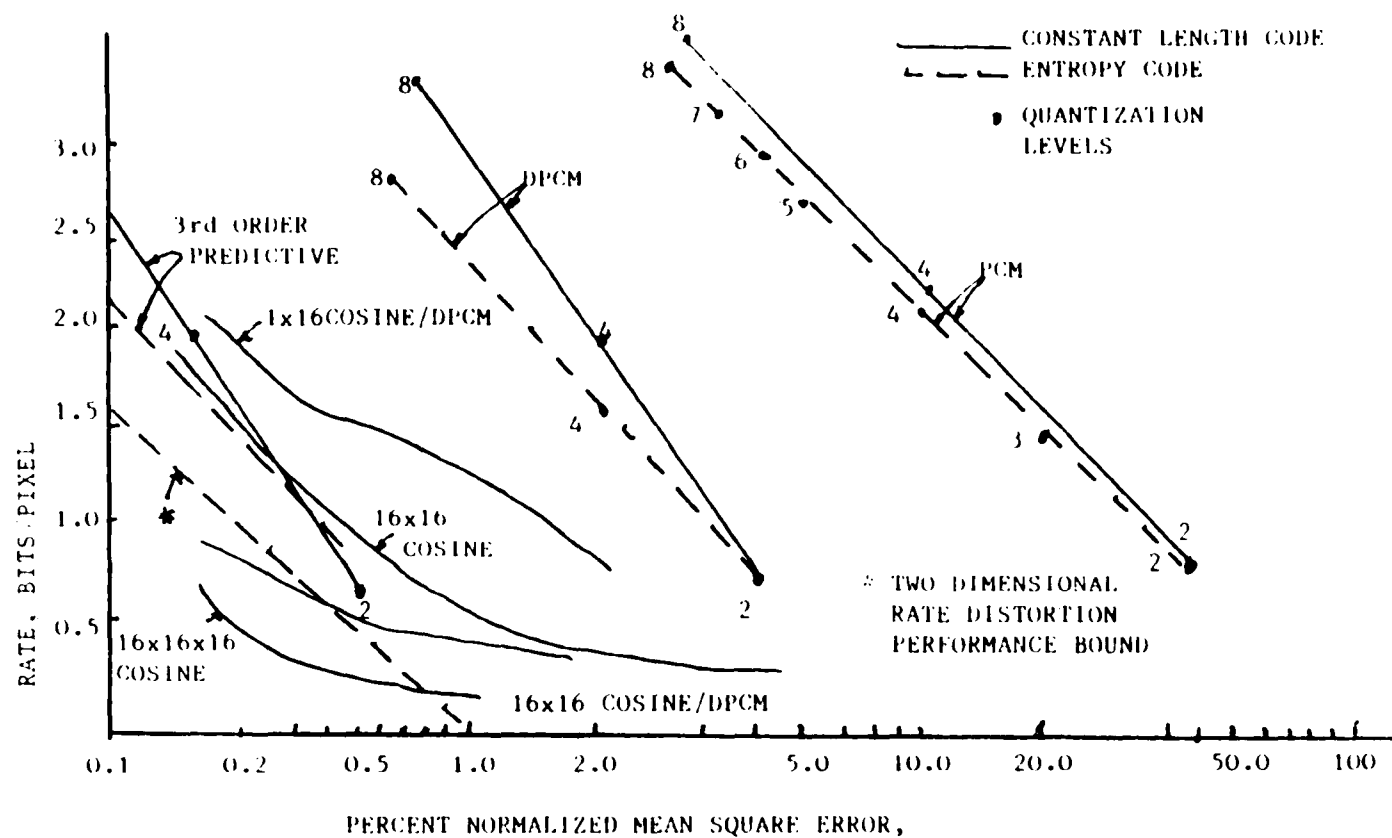


Figure 2.3-3 Rate versus mean-square error relations for image coding systems

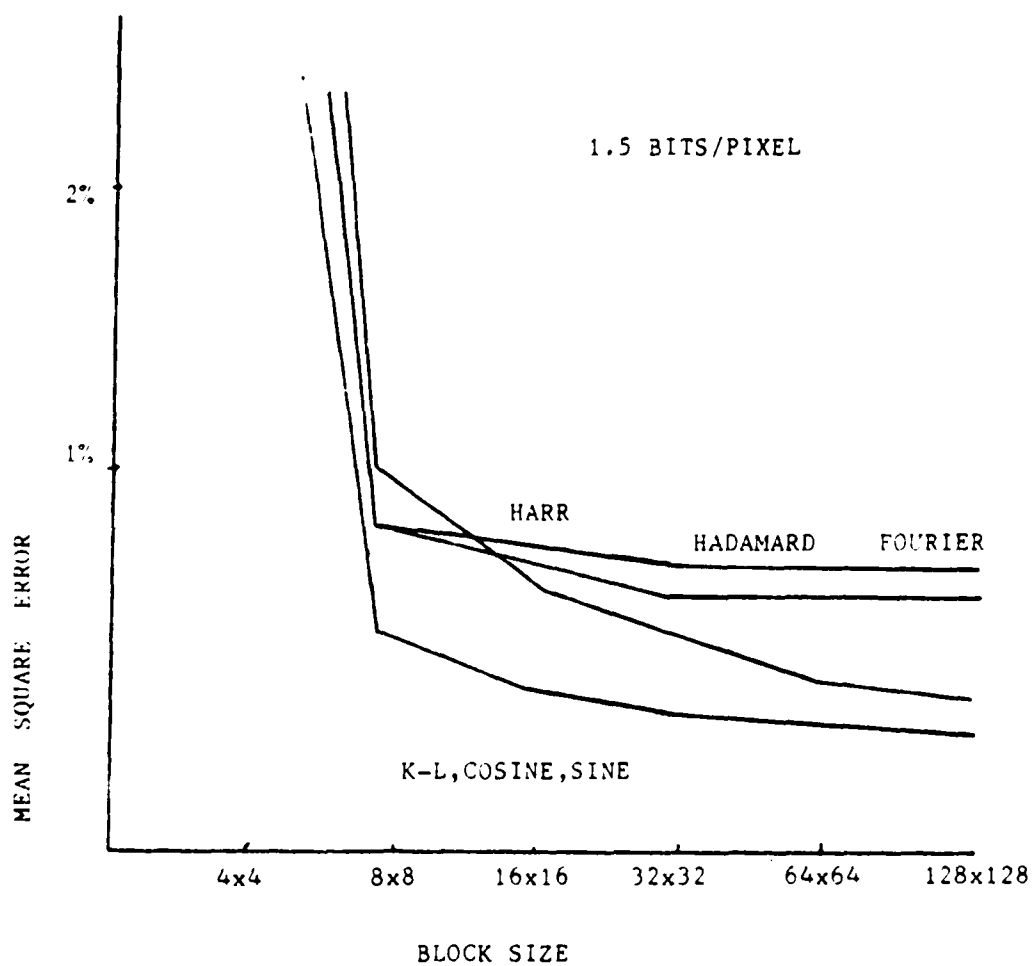


Figure 2.3-4 Intraframe hybrid transform DPCM mean-square error performance of image transforms as a function of block size



work utilizes adaptive predictive ADM encoder as the digital part of the optical digital hybrid to achieve bandwidth reduction.

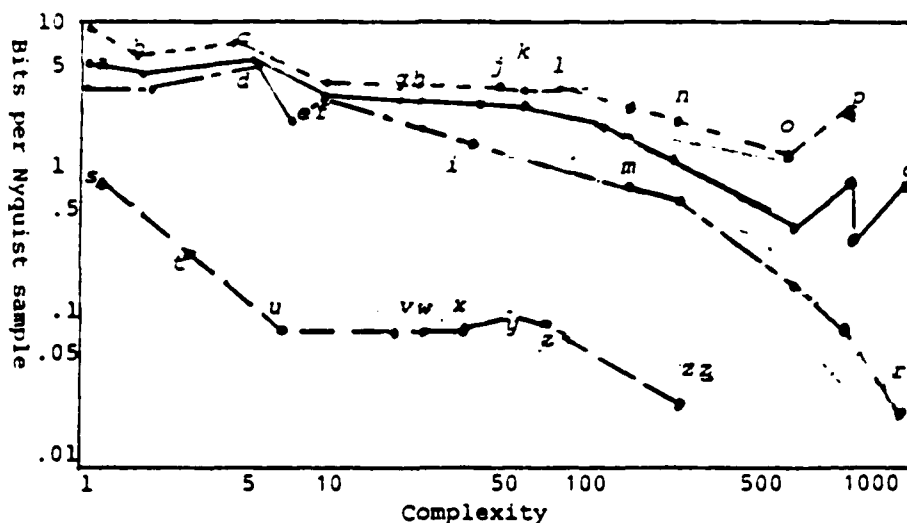
A review of some of these hybrid systems and their application to bandwidth compression follows. Source encoding using optical transform preprocessing is shown to decrease quantization noise inherent in low rate ADM as well as allow for an accompanying average bit rate reduction.

#### 2.4 Analog Optical Transform - Digital Predictive Encoding

The evolution of joint optical/digital hybrid processing [85,86] comes from the premise of marrying the advantages of two dimensional, real-time high bandwidth optical processing with the flexibility of adapted digital computation and transmission.

Comparisons of optical-digital vs. all digital techniques [87], and signal detection trade-off analysis of optical vs. digital Fourier transform computers [88] point to the advantages of the optical-digital approach in terms of speed and the optical transform advantage in terms of throughput over digital transform operations.

For video bit rate reduction encoders are usually judged with respect to speed, complexity and compression for a given image quality [88]. Fig. 2.4-1 from Haskell and Steele's paper [89] shows various codec systems (coder-decoder). As can be seen, as the complexity of the system increases, the bits per Nyquist sample decline. ADM is



Video bits per Nyquist sample  $n$  vs. Complexity for monochrome television and black/white graphics. The three picture qualities correspond roughly to peak-signal-to-rms-unweighted-noise ratios of 45 dB (excellent), 40 dB (good), 35 dB (fair). Codec abbreviations are:

|                 |                                                                    |
|-----------------|--------------------------------------------------------------------|
| a. ADM          | Adaptive delta modulation                                          |
| b. DPCM         | Element differential pulse code modulation                         |
| c. PCM          | Pulse code modulation                                              |
| d. PCM+D        | PCM plus dither                                                    |
| e. 1D:X         | One dimensional transform coding                                   |
| f. 2D:DPCM      | Two-dimensional DPCM                                               |
| g. 2D:DPCM+AQ   | 2D:DPCM plus adaptive quantizing                                   |
| h. DPCM+E       | DPCM+entropy coding                                                |
| i. 2D:HX+AQ     | Two dimensional hybrid transform coding plus adaptive quantization |
| j. 2D:X         | Two dimensional transform coding                                   |
| k. 2D:DPCM+E    | 2D:DPCM plus entropy coding                                        |
| l. 2D:DPCM+AQ+E | plus adaptive quantizing and entropy coding                        |
| m. CC           | Contour coding (two component model)                               |
| n. 2D:X+AQ      | 2D:X plus adaptive quantizing                                      |
| o. 3D:HX+AQ     | Interframe hybrid transform coding plus adaptive quantizing        |
| p. FRODEC       | Frame replenishment coder-decoder                                  |
| q. 3D:X+AQ      | Three dimensional transform coding plus adaptive quantizing        |
| r. FRODEC+TF    | Frodec plus temporal filtering                                     |
| s. PCM:1B       | PCM with one bit (two level) quantizing                            |
| t. 1D:WBS       | One-dimensional white block skipping                               |
| u. 1D:RLC       | One-dimensional run length coding                                  |
| v. 2D-PDQ       | Two-dimensional predictive differential quantizing                 |
| w. KDD          | Kokusai Denshin Denwa Ltd. coder                                   |
| x. KI           | Kalle Infotec U.K. Ltd. coder                                      |
| y. TUH          | Technische Universität Hannover coder                              |
| z. CC           | Contour coding                                                     |
| zz. OCR         | Optical character recognition                                      |

Figure 2.4-1 Various codec systems compression vs. complexity

as the system with the least complexity and highest speed in each category of image quality for monochrome television picture.

Based on the above advantages of speed and lack of complexity, we were motivated to investigate how hybrid optical-digital processing could be used to source encode pictures so that low sampling rates for a given quality picture could be achieved.

One method that was investigated [90] for improving the compression of video transmission was to reduce the average transmission rate by coarse-fine video encoding. This method was investigated by Beddoes and Chu [27].

Fig. 2.4-2 shows their coherent hybrid system used to produce the coarse-fine encoded images. The picture to be digitally encoded was first transilluminated with a collimated beam from a spatially filtered helium-neon laser source. The diffracted field was then transformed by a one-dimensional cylindrical lens and image to the transformed plane. In the transformed plane, binary filtering using a spinning wheel of variable rotational speed, alternately blocked or passed the high spatial frequency components of the image. The retransformed image produced by spherical and cylindrical lens was then scanned by a monochrome television camera and then digitally encoded with 3 bit DPCM. The encoder sampling rate (scan rate) of camera was lowered during the coarse field period and

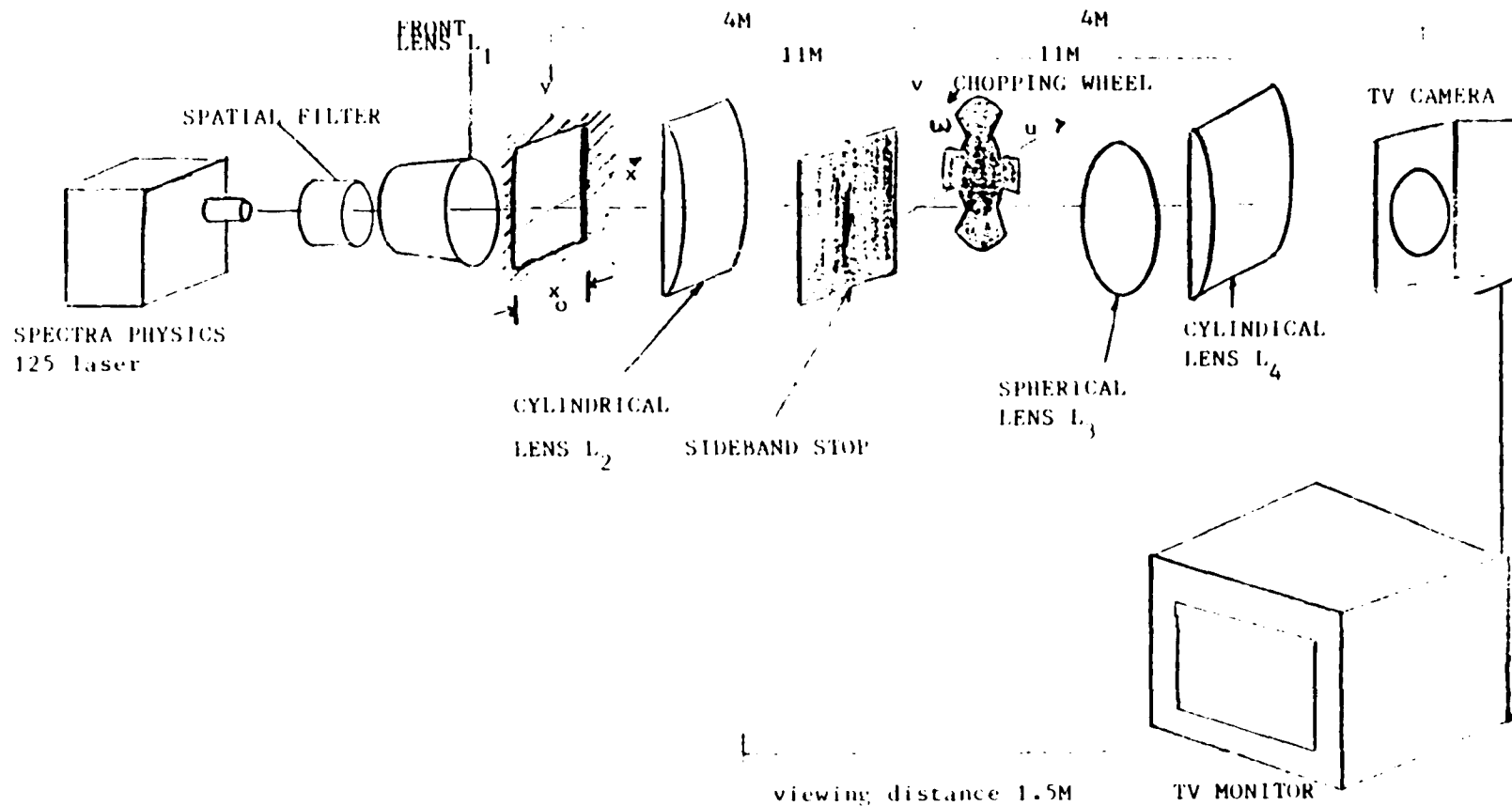


Figure 2.4-2 Coherent binary symmetric one-dimensional optical hybrid preprocessor for scan rate flicker reduction-compression [ ]

raised during the fine field. The relative length of time for the coarse vs. fine periods, based on objective quality judgments, needed to obtain a given image quality determined the rate of the spinning disk as well as the compression ratio. Since these periods at which the sampling rate was different had to be integrated over a constant rate channel, a large elastic buffer was needed. They reported an average compression of 1.5:1 for a given quality each. An additional compression was achieved by increasing the apparent image quality by the inclusion of a "high frequency electronic boost circuit."

For moving monochrome images the same system was applied. A resulting increase in compression reported due to the decreased sensitivity of the viewer to blur in moving images.

Their hybrid system was essentially a binary one dimensional coherent monochromatic optical preprocessor that sequentially reduced the picture resolution in the direction of the video scan.

The above work points to taking full advantage of the real time bandwidth compression capabilities of transform processes for color as well as black and white images for still and moving picture content to be encoded by using one bit adaptive ADM encoding.

In this chapter we have reviewed various digital and hybrid optical/digital alternatives for bandwidth compression that represent the state of the art. It was shown that the application of hybrid optical transform - digital adaptive ADM processing shows promise as a fruitful area of investigation for bandwidth compression in real time with less system complexity.

CHAPTER III  
ADAPTIVE PREDICTIVE ENCODERS EDGE NOISE CHARACTERISTICS  
AND OPTICAL PREPROCESSING

3.1 ADM: An Adaptive-Predictive Digital Encoder

For efficient bandwidth compression, both low sampling rate and a small number of quantizing levels per sample are required. For an ideal system with  $2 \times 10^6$  samples per square image, encoding with PCM at an 8 bit level (equivalent to 256 voltage levels) requires a digital channel capacity of 16 Mbits/sec. per square degree. A more practical system with sampling density of  $2.5 \times 10^5$  with 6 bit level for an efficient picture width of 50 degrees square needs a bit rate of 75 Mbit/sec. Actual PCM systems operate between 48-64 Mbit/sec. This data rate is still too high. Good quality video pictures have been encoded using ADM at 20 Mbit/sec. [10]. The analog video signal transmissions are broadcast with a 4.2 MHz bandwidth so we see that the digitally encoded signal requires several times the bandwidth of the generally allotted analog channel. Although digital systems usually offer better signal to noise ratios and the ability to employ sophisticated processing and encrypting techniques, the expensive trade-off with channel bandwidth limits its feasibility in many real-time applications.

Predictive digital encoders were shown in the previous chapter to compress bandwidth by coding the signal. The predictive encoder [59] was seen to form an estimate of the current signal from a combination of weighted past signal samples. The estimate or prediction is then subtracted from the next signal sample to form an error. The error is quantized and coded to form an N-bit word and fed back to the predictor as well as coded for transmission over the channel. At the receiver, the error signal was decoded and the signal is reconstructed by adding the error samples to the predictor estimates formed in the decoder with an algorithm that matches the encoder's predictive algorithm. The predictor uses the quantized error signals to form a new estimate that is closer to the correct value. In this way the variance of the error signal is less than the variance of the original signal sample to sample. The new prediction is generated by adding or subtracting some increment of the previous prediction.

At sampling rates close to the Nyquist rate, the sample-to-sample differences at high contrast transitions are large. The rate at which the encoder produces errors does not permit the predictor to track the transition accurately and, upon reconstruction, transition errors at these high contrast edges are apparent.

In the ADM predictive encoder, a form of DPCM, shown



in Fig. 3.1-1, the quantizer is a hard limiter which produces a 1 bit error signal:  $N = 1$ , with the two states being +1 or -1.

The advantages of ADM over other DPCM systems lies in its instrumental simplicity and ruggedness. All operations are performed by 1 bit register shifts and 1 bit comparator operations in addition, no elastic buffer is needed in order to achieve compression. The ADM also adjusts to local structural properties of the picture by adaptively varying the predictor estimate [59].

Since the early 1960s, many adaptive delta modulation methods have been developed, and ADM is gaining wide acceptance for narrow band speech communications because of its hardware simplicity and efficiency in bandwidth compression [91].

ADM is the system we used in conducting this optical-digital hybrid compression study. Monochrome as well as color ADM encoders and support equipment were made available to us by Professor Schilling [10].

The basic algorithm of the video adaptive DM used, the Schilling algorithm [10] and was first employed by Song [82]. Whereas in the linear or non-adaptive delta modulator a fixed step size is used, in this predictive algorithm the step size is dependent upon the previous bit transmitted and is given by:

$$E_{k+1} = \text{Sgn}[S_k - X_{k+1}] \quad (3.1-1)$$

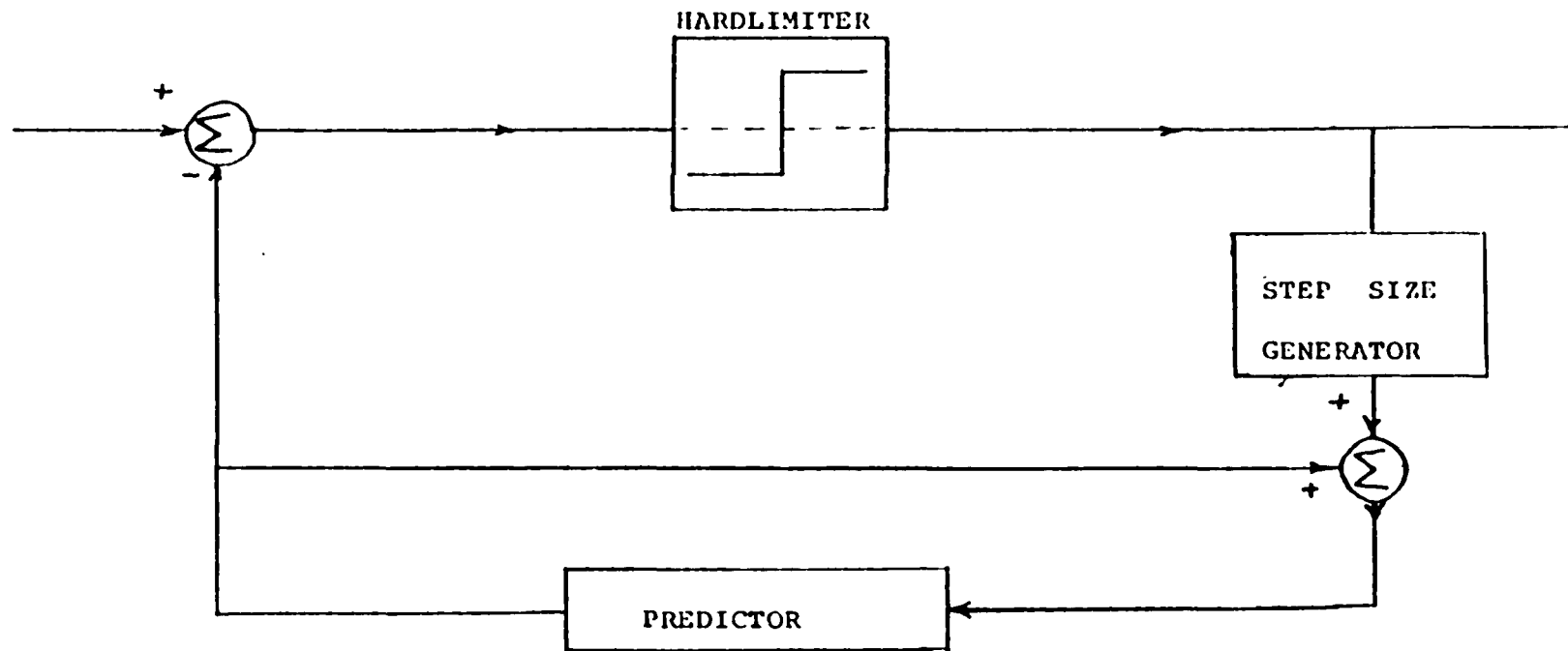


Figure 3.1-1 Block Diagram of the Adaptive Delta Modulator Predictive Encoder

$$Y_k = \begin{cases} |Y_{k-1}| (E_k + 0.5E_{k-1}) \\ 2 Y_{\min} E_k ; & |Y_{k-1}| < 2Y_{\min} \\ Y_{\max} & ; |Y_{k-1}| \geq Y_{\max} \end{cases} \quad (3.1-2)$$

$$X_k = X_{k-1} + Y_k \quad (3.1-3)$$

where  $E_{k+1}$  is the transmitted bit,  $S_{k+1}$  is the present sample of the input to the encoder,  $Y_{k+1}$  is the step-size of the delta modulator,  $Y_{\min}$  is the minimum allowable step-size,  $Y_{\max}$  is the maximum step-size, and  $X_{k+1}$  is the encoder estimate of the input sample.

At low clock rates the adapted algorithm exhibits "edge busyness" as depicted in Fig. 3.1-2. When a vertical edge is encountered transverse to the horizontal video scan, the signal being encoded by the ADM algorithm will catch up to this edge in a different amount of time for each horizontal scan. This depends on system noise and what values were transmitted before encountering the same high contrast edge. This affects the voltage history of the predictor line-to-line and causes the number of steps needed to reach the correct signal level to be different. Fig. 3.1-3 illustrates what occurs when the ADM encoder is attempting to track a signal derived from scanning a high contrast edge for two different initial predictor values. Here we see the dotted trace reaching the correct value in five steps as opposed to a previous or following scan line shown as a solid line, taken seven steps to reach

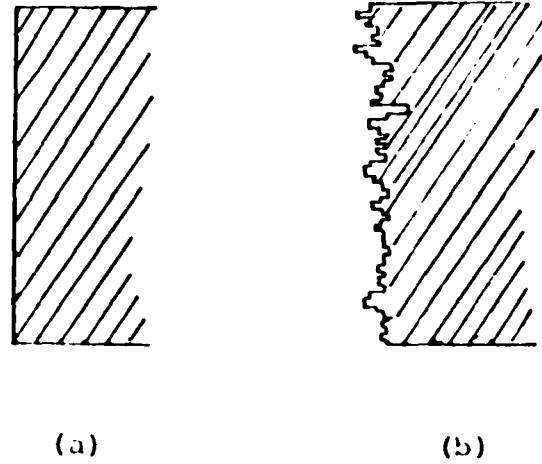


Figure 3.1-2 The effect of edge busyness on an edge  
(a) Edge before delta mod encoding  
(b) Edge after delta mod encoding

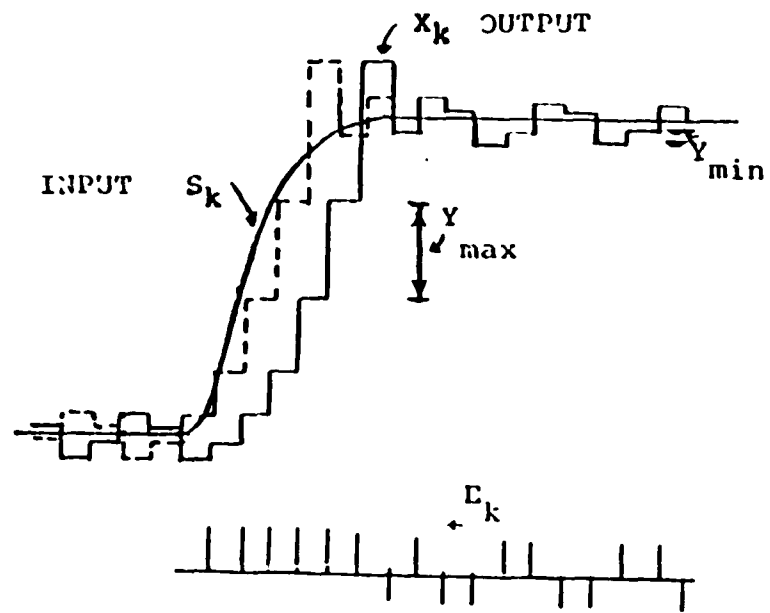


Figure 3.1-3 The response of the ADM to a step input with different initial conditions

the correct value. This difference is not highly visible when the sample rate is high, but as the rate is lowered, the visibility of the difference line-to-line increases. The combination of the one dimensional slope overload error, the resulting hunting to the correct signal level, and the two-dimensional line-to-line difference at the same high contrast boundaries causes this time-varying image degradation known as "edge busyness" [92-109]. This time-varying edge position instability or "dancing edge" is what we seek to reduce at low sampling rates using optical transform preprocessing.

### 3.2 Instability Characteristics in Adaptive Encoders

Instability in the reconstructed video image of adaptive delta modulation encoded vidicon irradiance signals, occurs when a jump in the input signal  $X(t)$  to the encoder exceeds a voltage gradient  $X'(t)$  in excess of what the encoder can track without producing non-linear, irreversible error instabilities due to overload.

If the voltage across the tracking capacitor is  $y(t)$  (as in the case of an adaptive encoder called exponential DM) and  $V$  is the charging aiming potential, then the threshold voltage that will cause overload is given as

$$E_s = E_{smax} = VH(j2\pi f) = V[1/(1 + (2\pi f_s T_{RC})^2)]^{1/2}$$

where  $T_{RC} = RC$ ,  $f_s$  is the sampling frequency Fig. 3.2-1

The maximum gradient  $X'(t)$  differs for different

adaptive delta modulator encoder structures and is a function of the sampling rate [59].

### 3.3 Adaptive 1-Bit Predictive Encoders

ADM is one of a class of adaptive predictive encoders and uses the assumption that the signal has a one-dimensional Markov distribution. This class of encoders all have the advantage of high channel noise immunity and the ability to achieve significant bandwidth compression. Their difference is in the structure and the way they create the prediction.

As noted by Hunt [110], this class of encoders is generally limited to "causal" predictions due to the video scan sequence that is based on the sample to the left of the current sample. This causality is not a general property of the images being coded and real time optical pre-processing of images can take place using "non-causal" data.

#### 3.3-1 Optical Bandwidth Compression and System Overload Noise

In an effort to further reduce the bandwidth of adaptively encoded video signals, one may attempt to decrease the sampling rate below 10 Mbit/sec. but as outlined in previous sections, this decrease is accompanied by distracting and disturbing superthreshold noise instabilities in the

decoded output image due to signal vs. sampling frequency dependent overload and pixel position size increase at low rates.

As stated by Steele [59], "Ideally the spectrum of the input signal [to be encoded] should have the same shape as the overload characteristic of the encoder thereby minimizing slope overload noise."

Fig. 3.3-1 gives the slope overload characteristic for exponential DM (one type of DM). This characteristic is a scaled plot of the feedback transfer function  $H(j2\pi f)$  and the maximum signal characteristic before overload occurs. This characteristic differs for different types of adaptive predictive encoders and is a function of the order of integration of the predictor, the maximum and minimum predictive step size, the sampling rate, and the degree of "leaky" integration used to stabilize streak errors.

Figures 3.3-2 through 3.3-5 compare the fixed step slow pulse response of the non-adaptive DM Fig. 3.3-2 to several types of adaptive predictive DM encoders.

Fig. 3.3-3 shows the pulse response for high information delta modulation (HIDM). Note, that the step size changes rapidly and the overshoot is



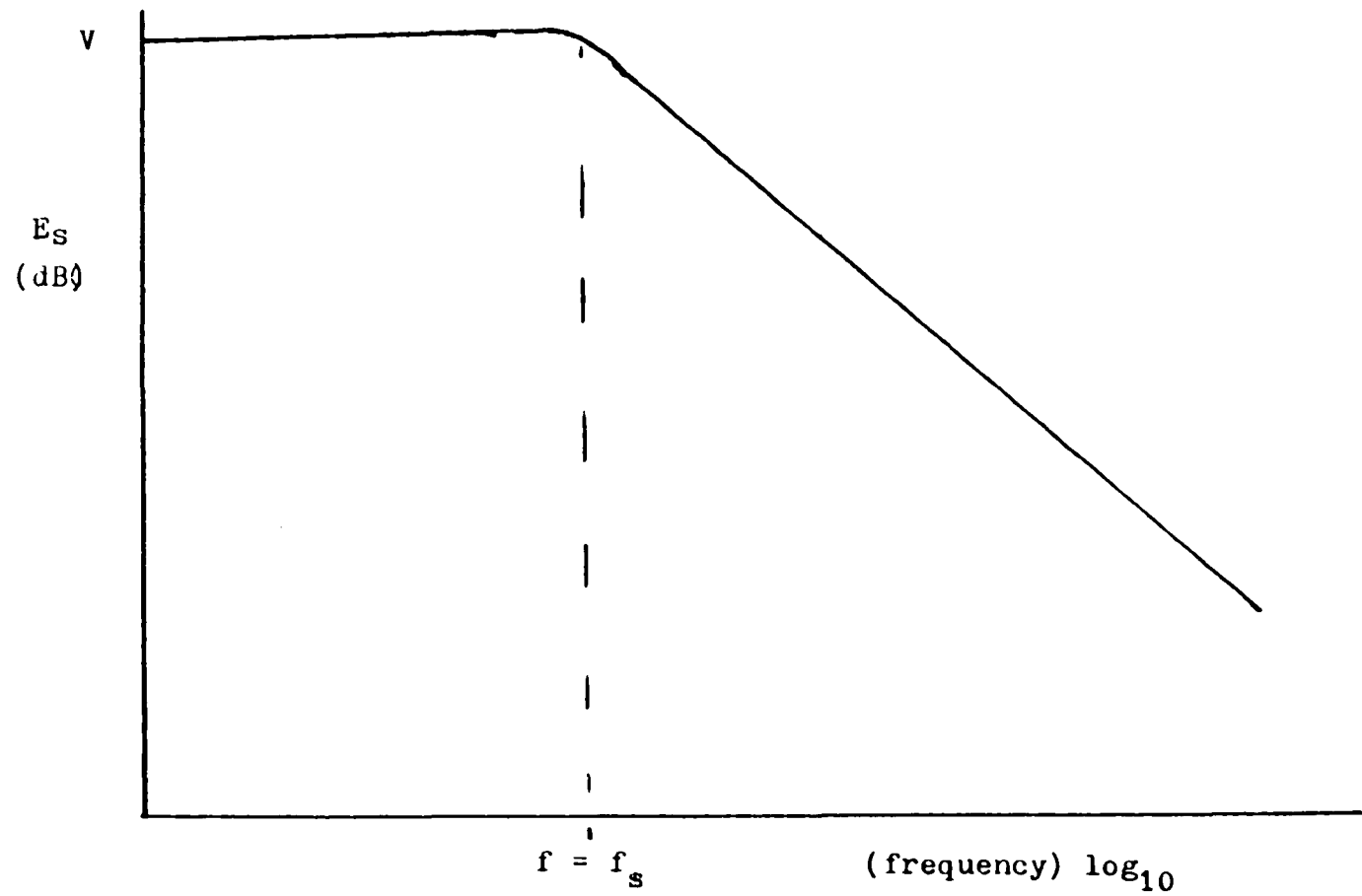


Figure 3.3-1 Slope overload characteristic for exponential DM (from Steele [59])

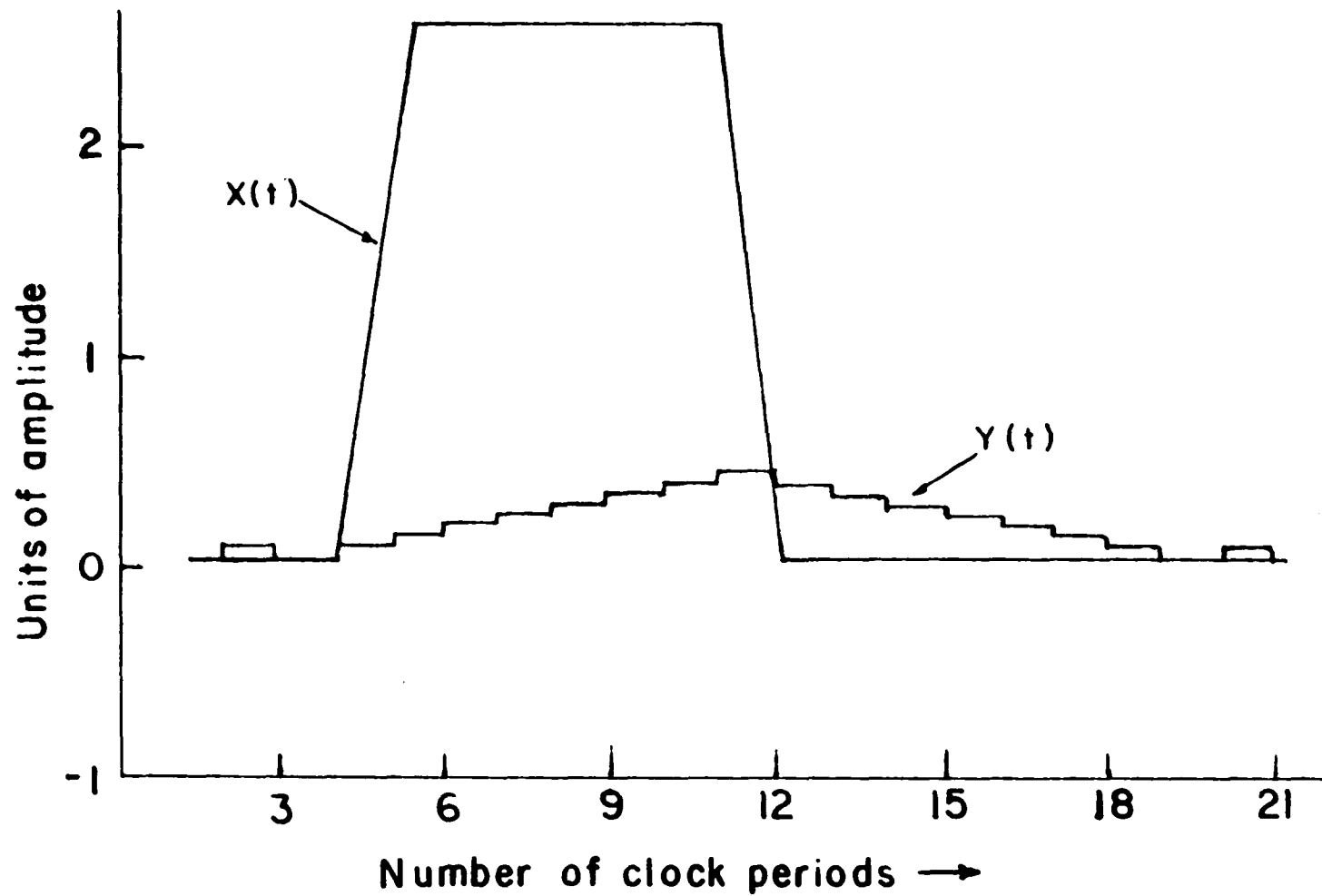


Figure 3.3-2 Non adaptive DM pulse response

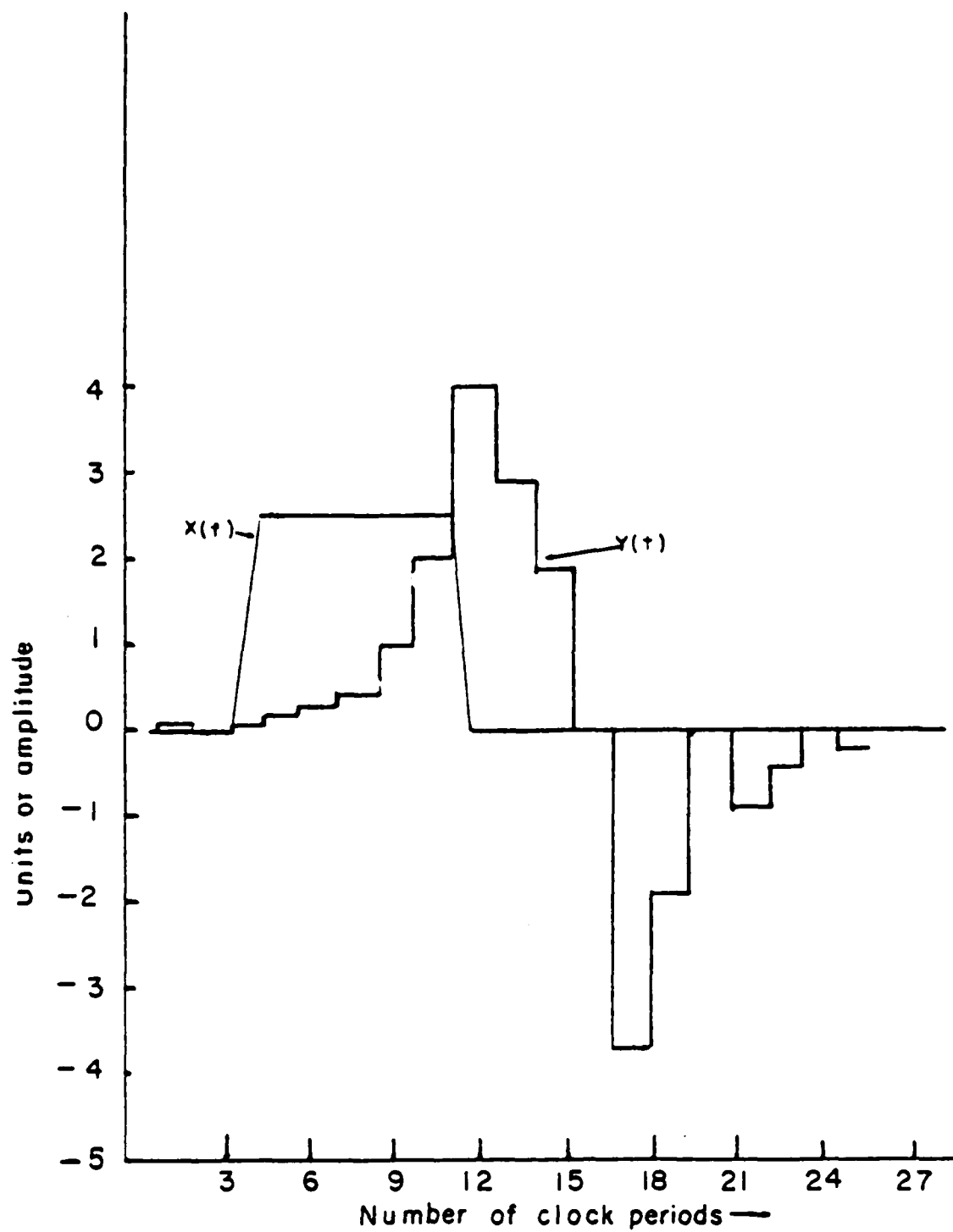


Figure 3.3-3 High information delta modulation pulse response

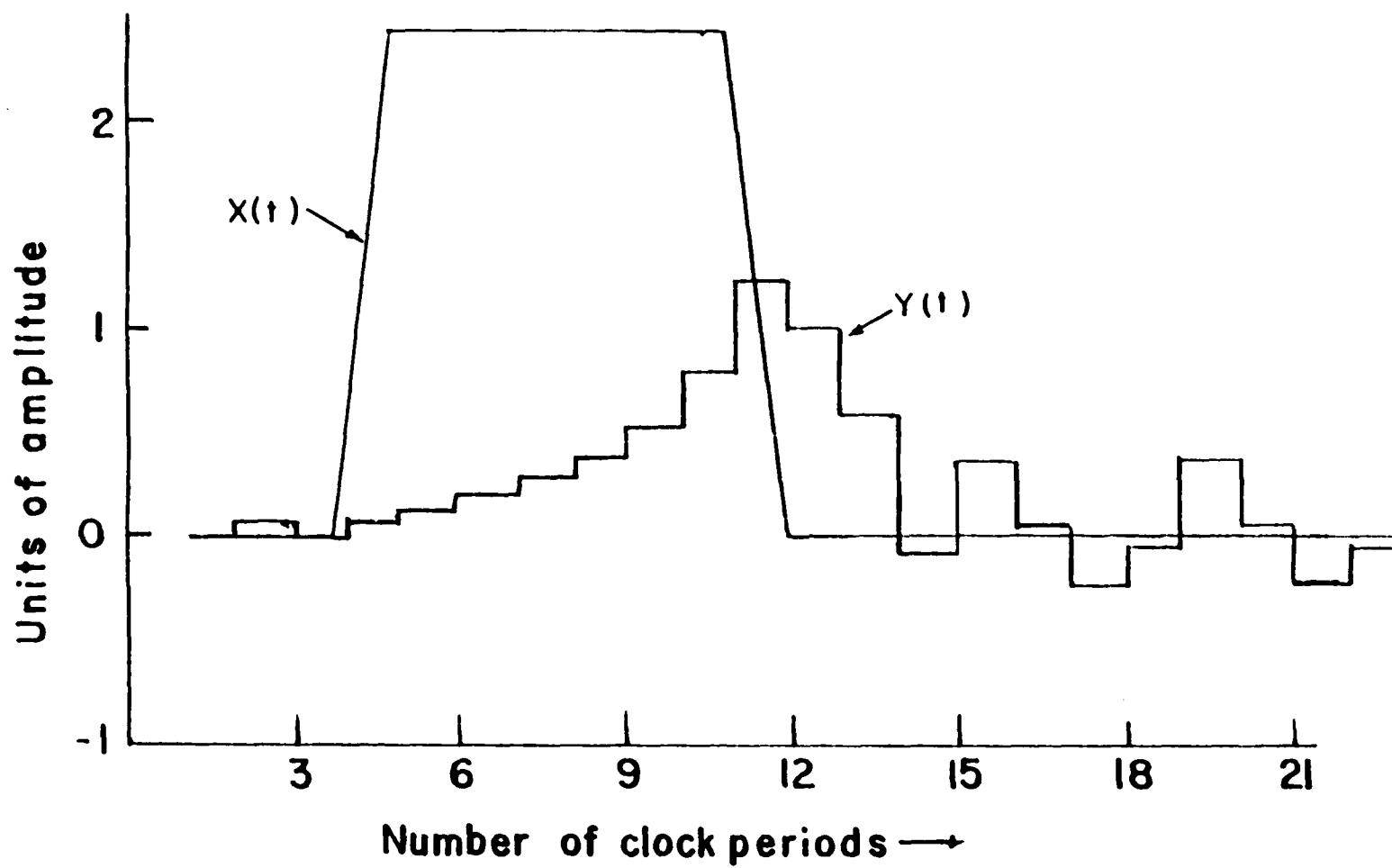


Figure 3.3-4 First order constant factor delta modulation pulse response

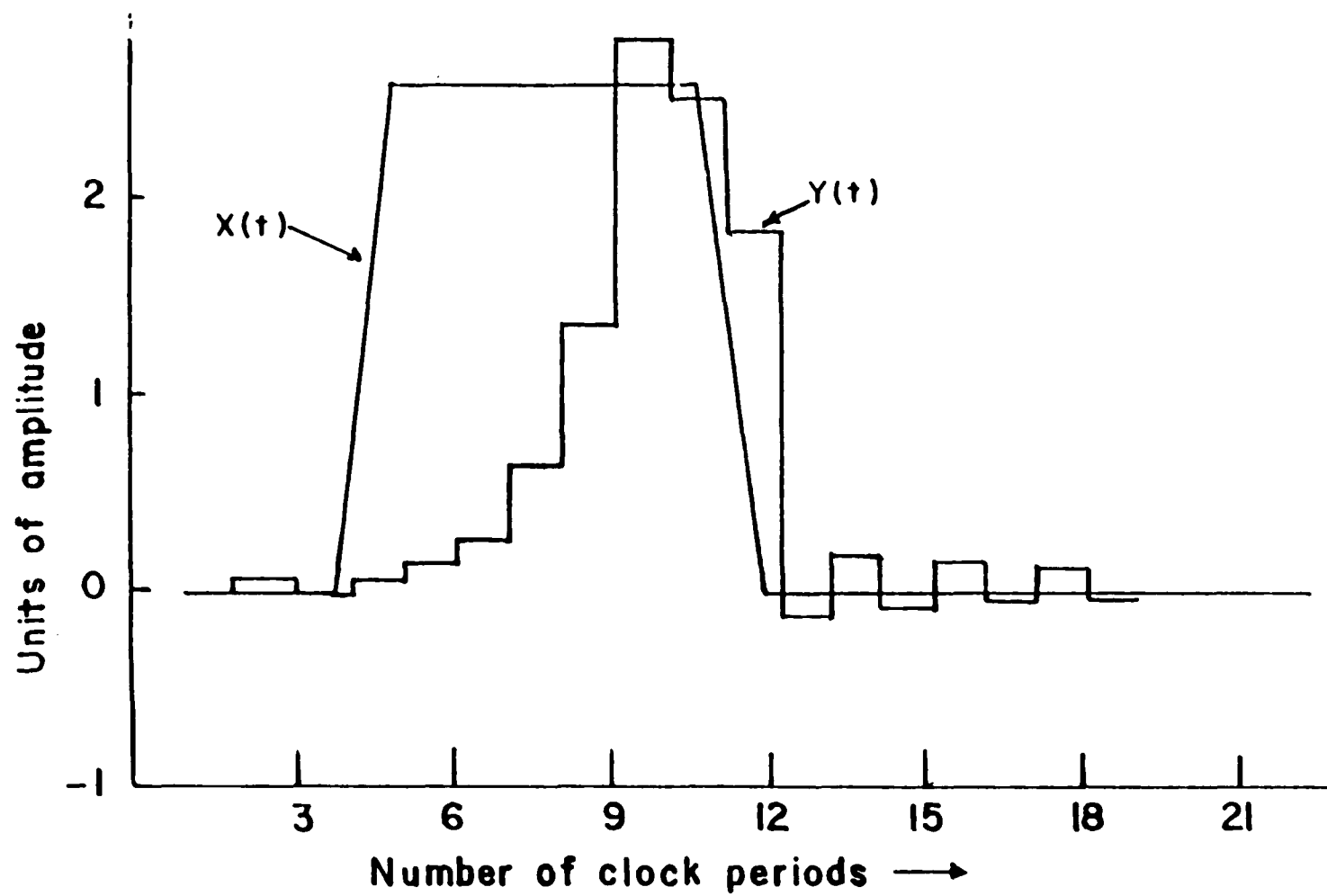


Figure 3.3-5 Second order constant factor delta modulation pulse response

large but it has a more rapid response than linear DM. Fig. 3.3-4 shows the pulse response for 1st order constant factor delta modulation (1st order CFDM). Response is seen to be slower than HIDM but the overshoot is reduced. Fig. 3.3-5 is the pulse response for a second order CFDM. Here we see the response is rapid and the overshoot decays rapidly.

Fig. 3.3-6 shows the response to the application of a step input to the first order CFDM encoder having an amplitude of 9 units. If the initial step is one unit, the trace will hunt about the step input according to [59].

$$H_5 = H_1 + AM + A^2M - BA^2M - BA^3M \quad (3.3-1)$$

for the adaptation values chosen by Jayant [103] namely  $A = 1.5$  and  $B = .66$  [curve a].

The Robust ADM due to Schilling and Song [82] which is optimized to minimize the overall mean square error for a Markov-Gaussian source, behaves like 1st order CFDM, where the adaptation values are  $A = 1.5$  and  $B = 0.5$ . This gives the curve of Fig. 3.3-6b, which does not continue to hunt about large values but reduces its step size.

As Steele notes [59], "...first order CFDM codecs operating at  $[10 \times 10^6 \text{ bits/sec}]$  this low

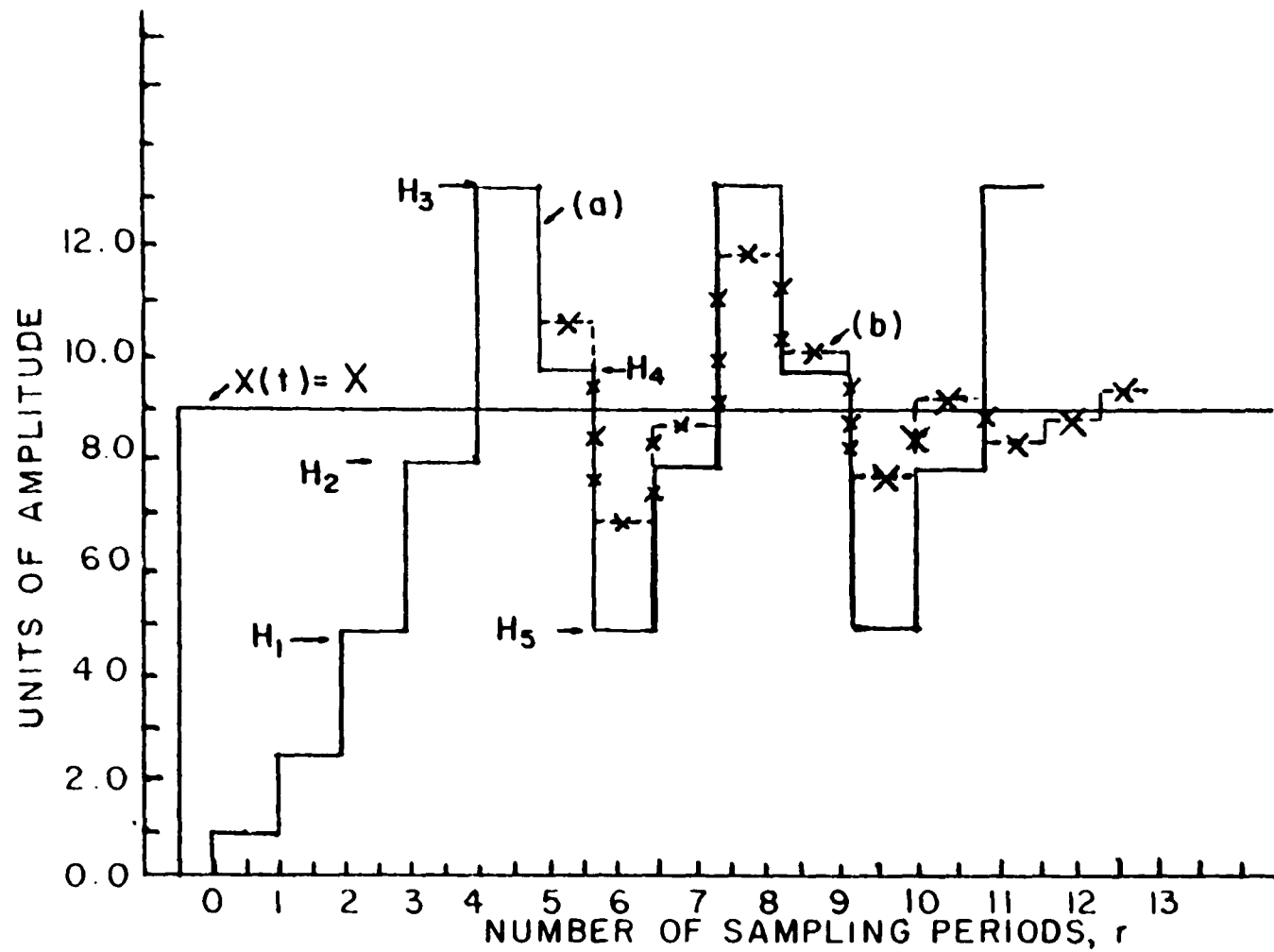


Figure 3.3-6 First order constant factor delta modulator response to pulse of 9 units  
 (a)  $A = 1.5, B = .66$  (b)  $A = 1.5, B = .5, AB = .75$

clock rate are not as efficient as compared to a PCM system operating at  $20 \times 10^6$  bits/sec when the television signal changes rapidly from black to white and vice versa as these sudden changes produce a hunting effect which appeared as a twinkle in the picture....this objectionable twinkle effect should be removed...."

### 3.3-2 ADM Edge Noise Characteristics

We have covered some of the various ingenious schemes for compression in terms of improved subjective image quality that have been devised. Variations of temporal image presentation and sampling rates for both still and moving images have been implemented in systems that produce compression. Many of these interframe as well as intraframe techniques that exploit the observer's reduced temporal, spatial and chromatic sensitivity to noise in different bands obtain compression based on the subjective quality change by placing the noise where it is not as disturbing or distracting. For our application of optical preprocessing we attempt to improve the quality of the video reconstruction of images sampled at low rates.

In this section we cover edge noise experiments in low rate ADM encoding in order to obtain



a quantitative and qualitative measure of how the sampling rate affects the reconstructed edge noise as a function of orientation and sampling rate.

A simple test system that included a Vidicon camera, focused on our test orientation object, was connected to the ADM encoder. The output of the ADM encoder was sent over noiseless channel to the decoder whose reconstructed output was displayed on the video monitor. The pulse response at various rates for various width black bars on a white background were photographed from the monitor using Type 55 P/N film Polaroid. This allowed for negatives as well as positives of the response to be produced so that the edge response could be enlarged and viewed in detail.

Figures 3.3-7a-d were taken from the monitor at a sampling rate of 14.7 Mbits/sec. The distance of the camera and its focus were adjusted so that the width of the line was 2-3 scan lines. The object was mounted on a rotational stage that allowed for different input orientations to be tested. With the rapid pulse (short spatial duration) the input orientation angle at  $0^\circ$  to the scan reconstructed free of noise (Fig. 3.3-7a). This is due to the elimination of changes transverse to the scan direction so that the encoder

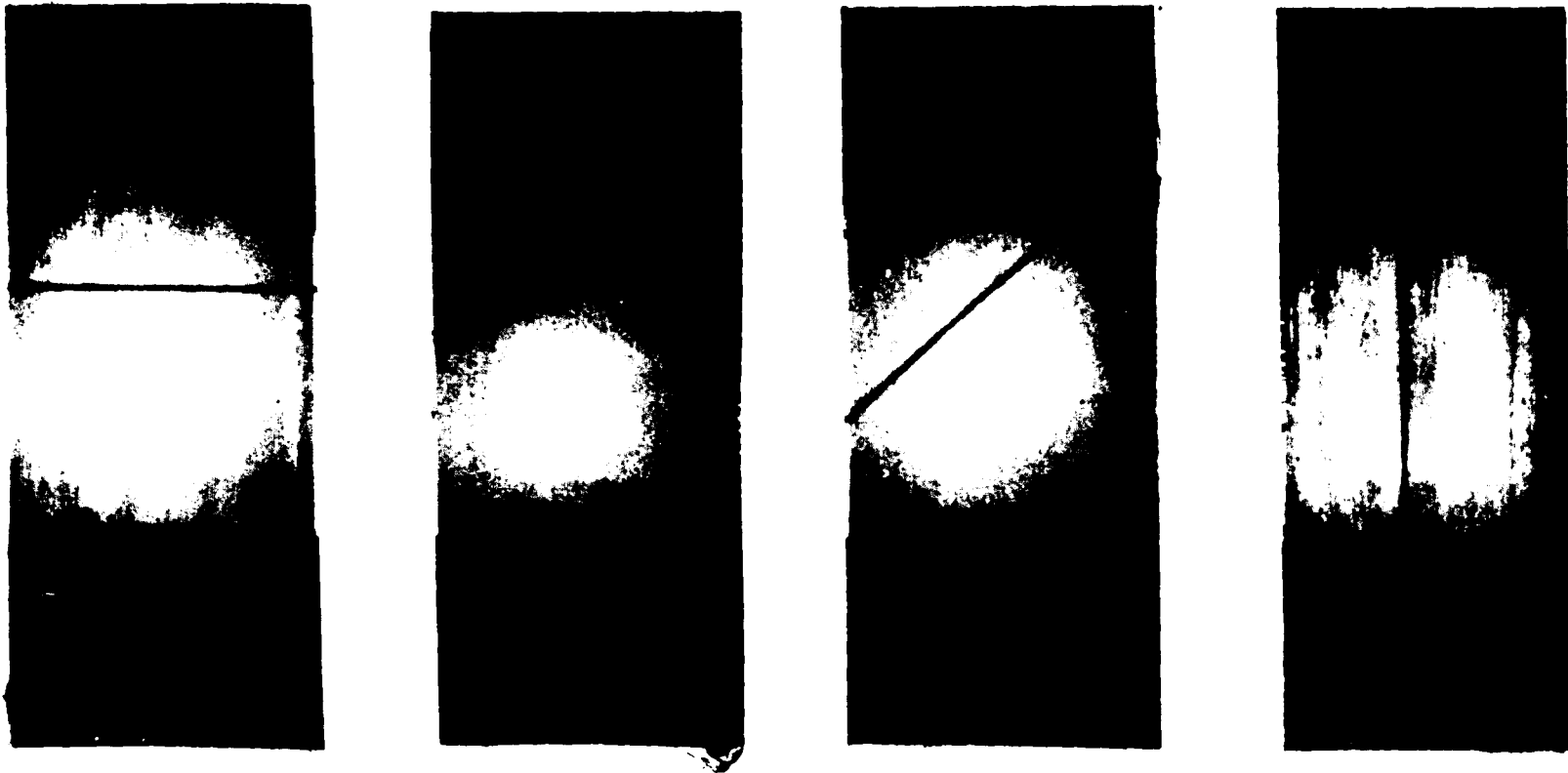


Figure 3.3-7 Monitor Photograph of rapid pulse reconstructed from ADM sampled at 14.7 Mb/sec.  
(a) 0° to scan (b) 30° to scan (c) 60° to scan (d) 90° to scan



Figure 3.3-7 (e) Monitor photograph of rapid pulse reconstructed from ADM sampled at 6.4 Mb/sec.

only received a constant value to be encoded. At 30° to the scan direction, no noise appears to be visible. This may be attributed to the integration of the transition along several positions of the scanning spot so that the transition and signal are gradual and overshoot does not appear. At 60° to the scanning direction, we begin to see a visible noise component along the edge due to the more rapid transition of the signal. This may be attributed to the increase in overshoot and line to line difference of the initial predictive state upon encountering the pulse. At an orientation of 90° to the scan direction, the extent of the noise, both spatially and temporally, appears to be greatest, causing a  $\pm 1$  scan line width deviation from the central position. The above scan orientations to the input pulse for 30°, 60° and 90° are shown, respectively in Figs. 3.3-7a-d. Figures 3.3-8a-d show enlarged portions of these reconstructed scans. The orientations for 0°, 30°, 60°, and 90° are shown, respectively for the enlarged images in Figs. 3.3-8a-d.

We then lowered the encoder sample rate to 6.4 megabits per second. At an orientation of 90° to the scan direction, the pel size and accompanying overshoot increased. This is shown in Fig.



(a)



(b)



(c)



(d)

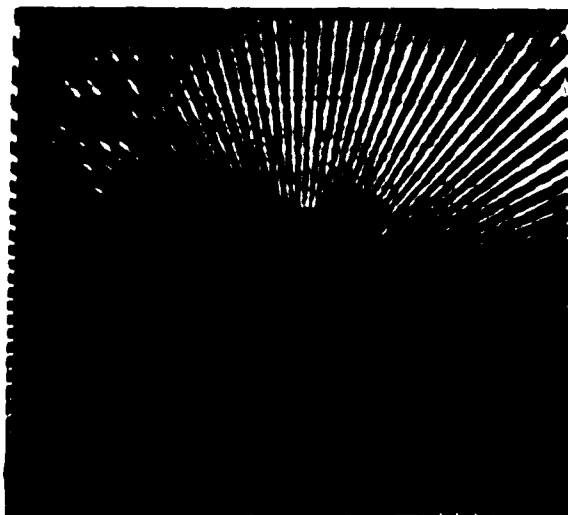
Figure 3.3-8 Enlarged portions of ADM video reconstructions from negatives of Figs. 3.3-7 (a) - (d)

3.3-7e. Even without magnification this transverse pulse can be seen to have broadened to a width of  $\pm 2$  scan lines in addition to losing contrast. The disturbing time dependent nature of this noise cannot be seen in these photographs.

To see the effects upon the reconstructed noise as the width of the pulse is changed at different orientations, a spoke test target was employed as an input. Figs. 3.3-9a-b and 3.3-10a-b show the ADM reconstructed signal sampled at 14.7, 8.9, 6.4 and 5.0 Mbits/sec., respectively. In addition to edge instabilities, aliasing errors were observed. These aliasing errors may be seen as Moiré patterns where dark bands appear in areas that should be white and light bands appear in areas that should be dark.

As the sampling rate is lowered, fine detail and resolution are lost, followed by a decrease in contrast. These effects cannot be compensated for since we are below the bandwidth needed to represent these details properly.

The edge noise instability was found to be asymmetric, a property not generally recognized to exist. This asymmetry appeared to depend upon resolution and orientation. The edge noise reconstructed near the edge also was seen to contain



(a)



(b)

Figure 3.3-9 Monitor of ADM reconstructed signal  
(a) 14.7 Mb/sec.  
(b) 8.9 Mb/sec.



(a)



(b)

Figure 3.3-10 Monitor of ADM reconstructed signal

(a) 6.4 Mb/sec.

(b) 5.0 Mb/sec.



regions of periodicity which are related to noise generated near the horizontal scanning frequency. These results indicated that the size of the object as well as its orientation were an important noise parameter.

In order to determine how the edge noise changes as a function of pulse width, a wide bar pulse input was used and determined the subjective noise effects. Fig. 3.3-11a-c show the reconstruction of the wide bar target at  $30^\circ$ ,  $60^\circ$ , and  $90^\circ$  respectively to the scan direction encoded at 6.4 Mbit/sec.

The magnified image of the transitions of bars is shown in Fig. 3.3-12a-c. These photographs show clearly the asymmetric or different way in which the reconstructed video instability noise appears on a white to black transition versus a black to white transition (as encountered by the scan). The hunting around a black to white transition contained gradually increasing steps and little visible ringing noise after the white level was reached. This differs from the white to black transition where ringing noise in the black area is much more visible. These effects appeared to be due to the overshoot and large pixel size at low sampling rates. As the sampling rate is lowered, reconstructed edge excursions on white to black



(a)

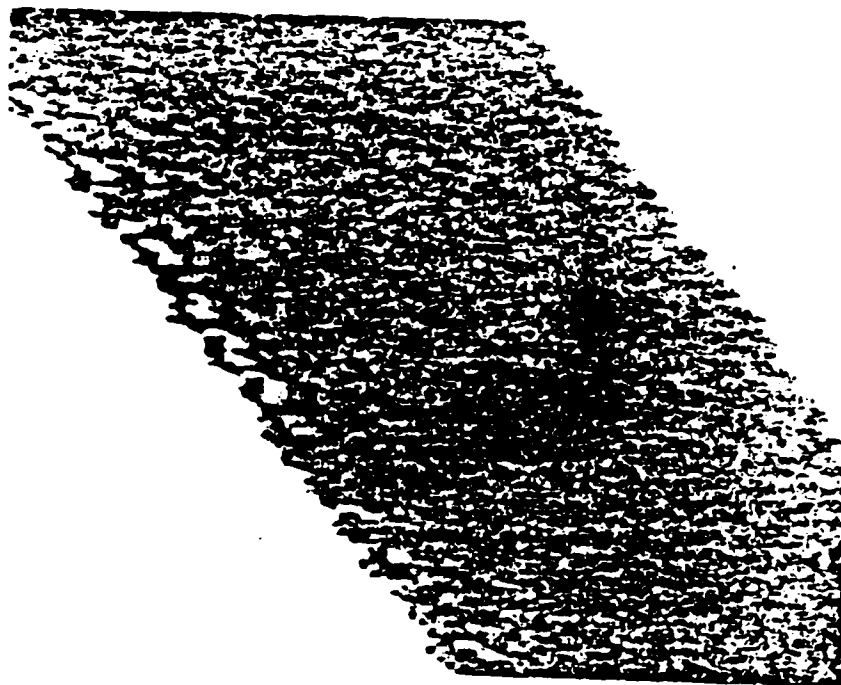


(b)

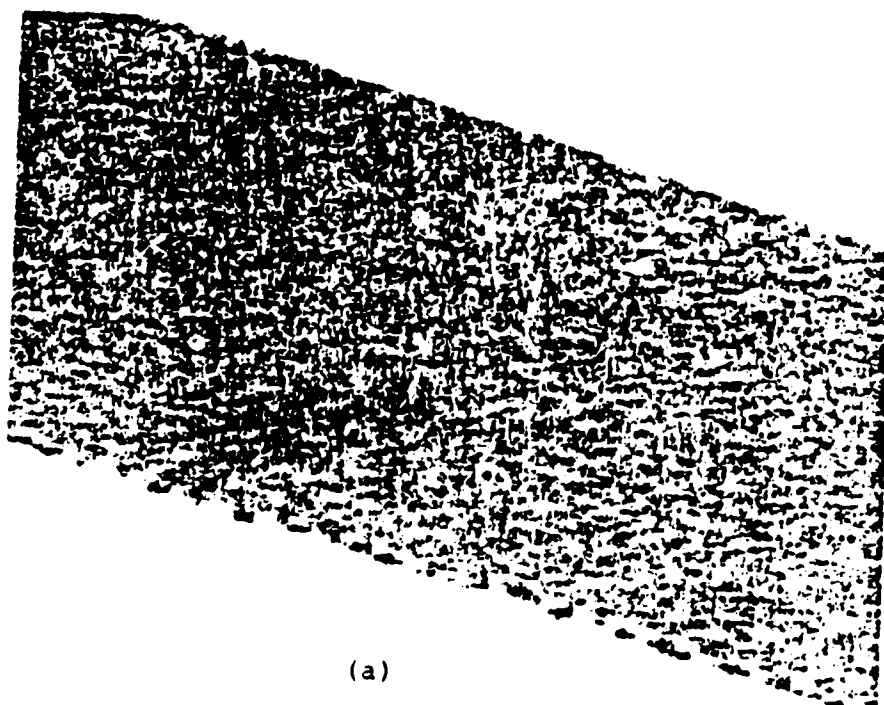


(c)

Figure 3.3-11 ADM reconstruction of wide bar pulse at 6.4 Mb/sec.  
(a) 30° to scan  
(b) 60° to scan  
(c) 90° to scan



(b)



(a)

Figure 3.3-12 Magnified image of Fig. 3.3-11  
at 6.4 Mb/sec.  
(a) 30° (b) 60°

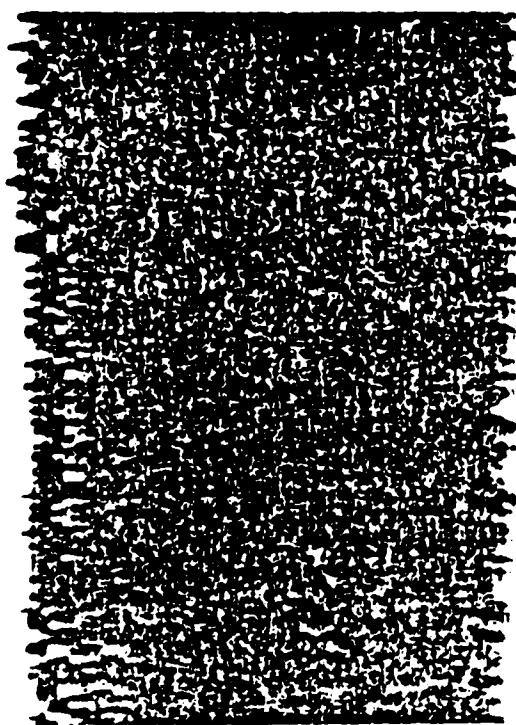


Fig. 3.3-12 (c) Magnified image of Fig. 3.3-11  
at 6.4 Mb/sec. at  $90^\circ$

transitions were measured to have an average visible width of 4-5 pixels and black to white transitions had visible pixel width of 2-3 pixels. The **white** to black transition thus appeared to be more **subjectively** noisy.

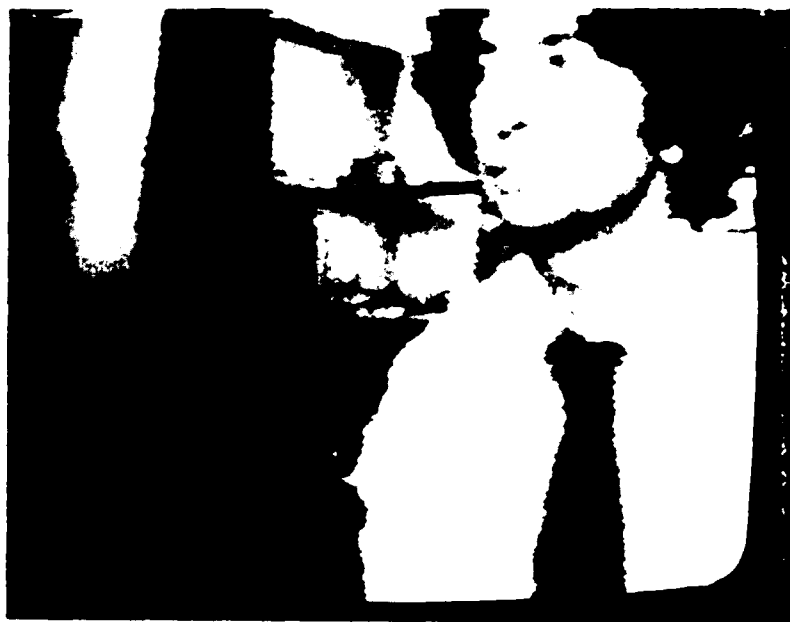
This information was used to determine that **large, white** to black transitions should be optically modified by preprocessing in a different manner than black to white transition. On this basis, the transform weighting filter that was used was designed to compensate for these noise characteristics. The black to white transitions of high contrast needed to be made more gradual to reduce the large overshoot. The white to black transitions needed to be made lighter to mask noise.

In order to see whether the asymmetric noise effects that occurred in the video reconstruction of simple test bar targets also occurred in real image scene content reconstructions, the same system was focused on the author and scanning was performed in both vertical and horizontal directions.

Fig. 3.3-13a-b show horizontally scanned head and shoulder scenes sampled at 8 Mbits/sec. and 5 Mbits/sec. The time of exposure for the camera was 1/30 sec. Fig. 3.3-14a-b shows the same scene scanned vertically at the same rates.



(a)



(b)

Figure 3.3-13 Horizontally scanned head and shoulder scene ADM reconstruction

(a) 8 Mb/sec.

(b) 5 Mb/sec.



(a)



(b)

Figure 3.3-14 Vertically scanned head and shoulder scene ADM reconstruction  
(a) 8 Mb/sec.  
(b) 5 Mb/sec.

We noted in these experiments that the large **black to white** transitions in natural scenes (i.e. the transitions on the two sides of the author's tie) showed the same characteristic asymmetric response in the horizontally scanned picture (Fig. 3.3-13a-b).

The asymmetrical processing of edge transitions would then appear to be the most logical approach in order to reduce picture-dependent reconstructed instabilities.

This approach, then, opens the possibility of retrieving additional information from the stabilized reconstruction by employing optical [ 3] or **digital** [111-114] restoration techniques. Information that is usually destroyed when resolution-bandwidth constraints are met using binary symmetric optical transform (low-pass filtering or image defocusing) may then be retained.

In the optical preprocessor that meets these asymmetrical rapid transition, edge modification requirements, a transition dependent phase encoding of the illumination angle is employed. In this way, both the size and sign of the slope of the image transition enter into the filtering operations. The introduction of these image dependent phase gradient surface reliefs occurs during the



film developing process.

The relief of rapid black-to-white transitions are opposite to the direction of increasing relief height of the gradients of the white-to-black transitions. This produces phase gradients the carrier angles of which are opposite in sign. This causes a different displacement of the transformed spectra of these details.

In the transform domain, the transform filter orientation, direction of increasing absorption, and central location of the attenuating profile are adjusted so that a visualized image, related to the derivative of the content-dependent phase gradients appears at the output plane. The phase image is added to the retransformed film absorption image. The transformed absorption image of the spatially slow varying details is known to act as a point-to-point bias of the irradiance level [115-116]. The superposition of these component images at the encoders vidicon modifies the high contrast condition asymmetrically to fit the reconstructed noise instability characteristics. Thus, an increase in stability in the reconstructed video display is accomplished by avoiding encoder overload at the high contrast edges that produce the highly visible noise.

Small amplitude transitions do not produce large phase gradients and thus receive less differential weighting since their spectra are closer lying to the optical axis. These small amplitude transmissions are reconstructed with less distortion than would occur if either binary symmetric or image defocus techniques were employed.

In the next section we discuss image evaluation related to determining the subjective quality of the hybrid encoder and the relative compression ratios based on the subjective quality.

### 3.4 Image Evaluation

Knowledge of the visibility of noise components in a television display is necessary in the evaluation and design of transmission systems for television systems.

As we have seen, bandwidth compression schemes introduce noise into the resultant display picture. The subjective response to the noise introduced into a picture is one measure that can be used for comparison of competitive transmission systems; it seems advantageous to design a system that introduces noise where it is less visible. Image evaluation methods have allowed proper placement of the chrominance information in NTSC compatible color systems where it would be least visible and image evaluation of moving video scenes has allowed for

bandwidth reduction so that one half inch video tapes could reduce the storage requirement of 3/4-inch video tapes used for non-still scenes [117]

Let us now review several methods that have been developed for evaluation of television picture quality. Fundamental methods involved psychophysical experiments with groups of subjects. There exist secondary or derived methods which rely on objective measurements of wave form distortion or examination of the reproduction process. But these will not be discussed in detail.

We will discuss evaluation techniques suitable for use in bandwidth compression studies. In particular those related to the evaluation of the edge busyness impairment. In bandwidth compression systems, where a certain amount of noise visibility is acceptable, a measure of subjective magnitude of impairment is made. Here the picture impairments tend to increase with the amount of compression. At low digital compression ratios of, say, 6 or 7 bits per picture element (pixel) versus 8 bits per pixel PCM, the quality is usually high. At higher compression ratios on the order of three bits per pixel and less, as in DPCM, the quality is degraded.

A good deal of effort has been expended to find a satisfactory quality scaling method for television pictures. The ultimate approach is to allow the subjects to view the television pictures of real-life scenes

under controlled conditions. The subjects are asked to perform tasks or make judgments, and their responses are used as indicators of the quality of the pictures.

These methods are time-consuming and full of the complexities of design and analysis associated with any psychophysical experiments. Nevertheless, they afford the only really satisfactory approach to the measurement of television picture quality.

In devising methods for the measurement of subjective picture quality, it is well to ask whether anything is known of the psychological factors which influence judgments of picture quality. The answer to this is: relatively little.

Though studies into the functioning of the visual system give indications of gross retinal and cortical mechanisms; it appears that conflicting perceptual mechanisms exist. If one examines psychovisual data dealing with the viewer threshold or just perceivable visibility of a spatial grating that is presented at different temporal and spatial frequencies on a video monitor, one sees the response curves appear to have the shape of a temporal and spatial bandpass filters. On the other hand, if one looks at the eye scan data for viewing complex natural scenes, it is clear that the eye spends most of its time and attention on contours in the scene [ 49 ] and responds to the textural change in a

way unpredicted by spatial grading data [23]. Since these conflicting results tend to cloud what mechanisms are operating during perception, most of the designs of quality or impairment scales discussed in the video encoding literature use pragmatic common sense reason with a particular engineering need in mind.

The category-judgment method [118-119] is the most widely used and broadcast television field. In the U.S., it has been used for picture quality evaluation by Bell Telephone Laboratories [ 120 ], by NTSC [121], and by the Television Allocation Study Organization (TASO) [122-125]. This rating, also known as opinion scaling, requires the subjects to classify impairments into categories. Table 3.4-1 shows various impairments or quality scales used by various organizations in the U.S. and abroad. Studies to relate these different scales at Bell Labs [47] was obtained using 105 pairs of comparison among 15 category descriptions made by 21 subjects. The results provide us with matchings of the different scales and give an idea of how they are related (Table 3.4-2).

Different types of subjects and viewing conditions are used and are an important consideration in comparing the results of various investigations. Table 3.4-3 gives a cross-section of some of the important parameters that were used in different tests.

In investigating a particular type of impairment,

Table 3.4-1

Domestic and Foreign Quality and Impairment Scales

A. Five-grade quality scale

- A (Excellent)
- B (good)
- C (Fair)
- D (Poor)
- E (Bad)

B. Six-grade impairment scale

- 1 Imperceptible
- 2 Just perceptible
- 3 Definitely perceptible but not disturbing
- 4 Somewhat objectionable
- 5 Definitely objectionable
- 6 Unusable

C. Six-grade quality scale

- 1 Excellent
- 2 Good
- 3 Fairly good
- 4 Rather poor
- 5 Poor
- 6 Very poor

D. Five-grade impairment scale

- 5 Imperceptible
- 4 Perceptible but not annoying
- 3 Somewhat annoying

- 2 Severely annoying

- 1 Unusable

E. Five-grade quality scale

- 5 Excellent
- 4 Good
- 3 Fair
- 2 Bad

- 1 Very Bad

F. Six-grade quality scale

- 1. Excellent - The picture is of extremely high quality, as good as you could desire.
- 2. Fine - The picture is of high quality providing enjoyable viewing. Interference is perceptible
- 3. Passable - The picture is of acceptable quality. Interference is not objectionable.
- 4. Marginal - The picture is poor in quality and you wish you could improve it. Interference is somewhat objectionable.
- 5. Inferior - The picture is very poor but you could watch it. Definitely objectionable interference is present.
- 6. Unusable - The picture is so bad that you could not watch it.

Table 3.4-2

Impairment and Quality Scale Relations (from Carroll [120])

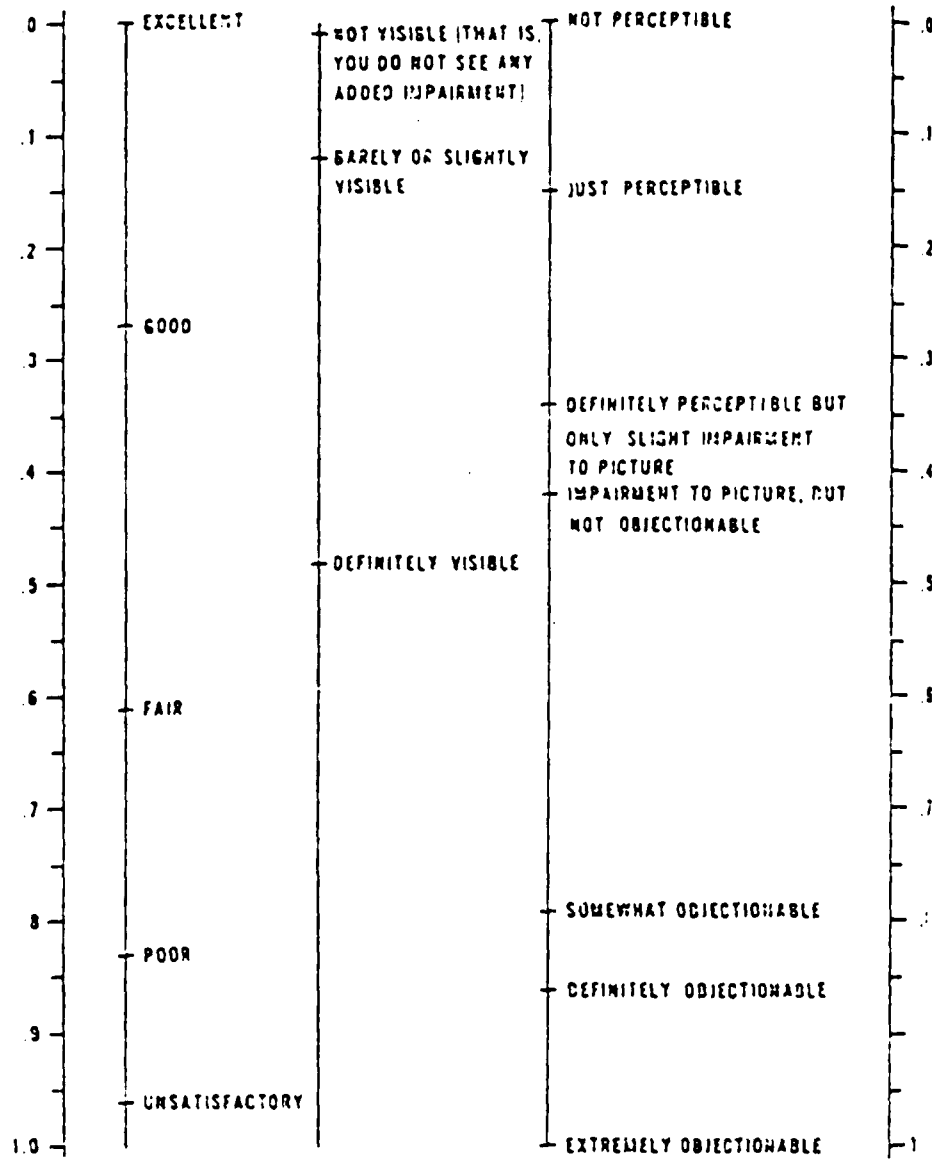


Table 3.4-3

## Parameters Used in Subjective Evaluation

BY C.C.I.P.

| Countries where used                                               | U.K.                                        | EUROPE                                      | JAPAN                                       | U.S.                                          |
|--------------------------------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------|
| <u>Scale</u>                                                       |                                             |                                             |                                             |                                               |
| Type                                                               | Quality                                     | Impairment                                  | Quality                                     | Quality                                       |
| categories                                                         | 5                                           | 6                                           | 5                                           | 6                                             |
| number of                                                          |                                             |                                             |                                             |                                               |
| <u>Subjects</u>                                                    |                                             |                                             |                                             |                                               |
| Type                                                               | non-expert                                  |                                             | non-expert                                  | non-expert                                    |
| Number                                                             | 20-25                                       | greater than 6                              | 20-25                                       | Approx. 200                                   |
|                                                                    |                                             |                                             |                                             | expert 10                                     |
|                                                                    |                                             |                                             |                                             | non-expert greater than 20                    |
| <u>Test Pictures</u>                                               |                                             |                                             |                                             |                                               |
| Number                                                             | 4-8                                         | 5                                           | more than 3                                 | 2-8                                           |
|                                                                    |                                             |                                             |                                             | 3-4                                           |
|                                                                    |                                             |                                             |                                             | Approx. 5                                     |
| <u>Viewing Conditions</u>                                          |                                             |                                             |                                             |                                               |
| Picture height to viewing distance ratio                           | 6                                           | 4-5                                         | 6-8                                         | 6-8                                           |
|                                                                    |                                             |                                             |                                             | 4                                             |
|                                                                    |                                             |                                             |                                             | 6                                             |
| Peak screen luminance (cd/m <sup>2</sup> )                         | 50                                          | 41-54                                       | Approx. 400 (mono)<br>74-84 (color)         | 70                                            |
|                                                                    |                                             |                                             |                                             | 170 (mono)<br>34 (color) (at 50 field)<br>sec |
| Contrast range                                                     | Not Specified                               |                                             | 30:1 to 50:1                                | Not specified                                 |
| Ambient luminance of screen (cd/m <sup>2</sup> )                   | 0.5 less than                               | 0.5                                         | Approx. 5 (mono)<br>0.7 - 2.0 (color)       | less than 0.<br>(at 50 field)<br>sec          |
| Ambient luminance of backcloth (cd/m <sup>2</sup> ) (Illuminant C) | 1                                           |                                             | Not specified                               |                                               |
| Room illumination (lx)                                             | 3                                           |                                             | Not Specified                               | 6.5                                           |
| <u>Presentation</u>                                                |                                             |                                             |                                             |                                               |
|                                                                    | Random Sequence of pictures and impairments | Random Sequence of pictures and impairments | Random Sequence of pictures and impairments | Random Sequence of pictures and impairments   |



the method of presentation of the impairment is important.

These presentation techniques include comparisons of impaired and unimpaired images [117, 126-130], presentation of weighted multiple impairments in the same scene [131], anchoring methods that use a standard image for comparison [132,133], and waveform testing methods [118].

In the work done on edge busyness evaluation at Bell Labs, the comparison method was used. This requires the subject to respond by saying which of the two pictures they prefer. This is important in bandwidth compression studies where it is desired to know whether a new method of picture encoding is superior to an existing method [130]. The two methods are presented sequentially on the same monitor and the subject indicates their preference. This procedure avoids the complication of adaptation level changes that arise in category judgments. In the comparative technique the subject is concerned merely with evaluating the difference in the quality between the two pictures.

Limb has used comparison methods in evaluating white random noise as a reference for edge busyness noise in order to obtain an edge noise power/white noise power ratio or an equivalent signal to noise ratio of the standard reference. This measure, however, may have the problem of transitivity. If an impairment A is found

equivalent to a reference B and a different impairment C was found equivalent to the same magnitude of reference B, would A and C be found to be equivalent? Since different visual channels are excited by different stimuli which are picture [6] and texture [117] dependent, this would not seem to be the case.

In the next chapter a description of method followed by a simplified section analysis of the optical preprocessor and resulting hybrid encoder are given

### 3.5 Method

The coherent hybrid optical-digital source encoder described in this chapter was developed for the purpose of reducing the effective bandwidth of video signals to be transmitted. The method of optical preprocessing covered here accomplishes this task by increasing the subjective quality of the ADM reconstructed video image over non-preprocessed ADM video quality when the signal is encoded at low sampling rate.

Fig. 3.5-1 shows a block diagram of the hybrid system.

The image to be encoded is recorded on photographic film and developed with a relief producing chemical process. The phase gradient encoded image transparency is then placed in the input plane of a coherent Fourier optical transform processor. The transparency is transilluminated with a spatially filtered coherent collimated beam

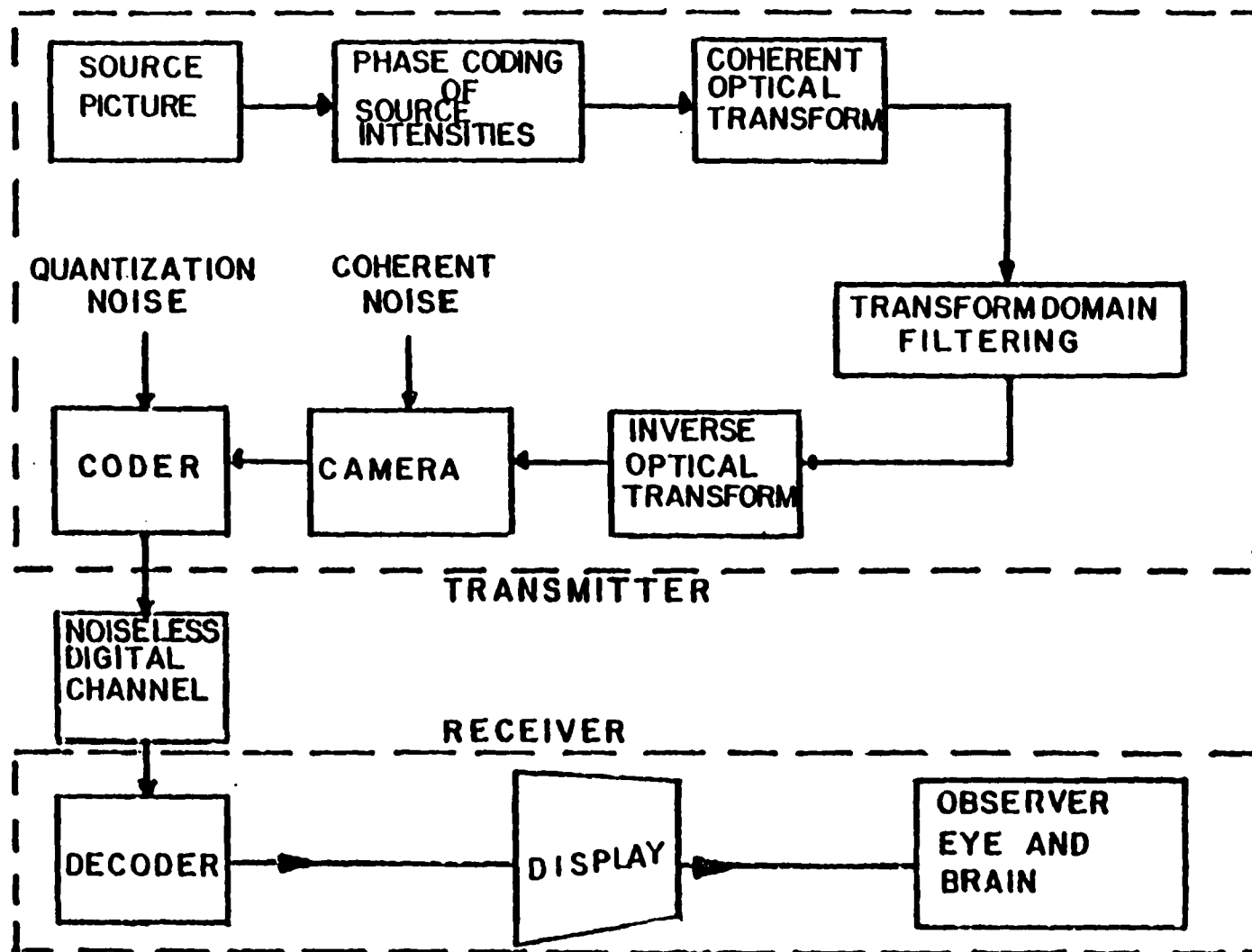


Figure 3.5-1 Block Diagram of Hybrid System

and the diffracted signal spectra from the encoded object are optically transformed by the first transform lens. The transformed spectra are then weighted by an optical filter, the asymmetrical absorption profile of which modifies the high contrast edge detail energy that is transmitted. The weighted spectra are then inverse transformed by the second transform lens and an inverted image is focused on the vidicon face of the camera where it is electronically raster scanned.

The information, now in one-dimensional format is sent to the ADM encoder where it is sampled, quantized and encoded as an error signal. This encoded error signal is transmitted over a noiseless digital channel and input into the ADM decoder. The decoder reconstructs the video signal which is then fed into a video monitor where it is displayed as a two-dimensional image. The monitor is viewed by the observer and the subjective quality of the stabilized video reconstruction is then compared with the non-stabilized video image obtained by removing the optical weighting filter. The amount of effective compression for the stabilized versus non-stabilized video reconstruction at different sampling rates is then determined.

The optical transform preprocessing operates on the image of the input film object by differentially modulating the transmitted power of the phase encoded

edge energy around a low spatial frequency absorption image bias [115-116]. Due to the difference in the lateral position of the transformed energy spectra between the black to white and white to black transition (displaced by the transition dependent phase gradient produced angular carrier) asymmetrical filtering passes more energy of the gradient of one sign than the gradient of the other sign. Depending upon the orientation of the filter, energy can be extracted from the positive or negative gradient, perpendicular to the scanned direction or in any orientation desired. The degree of differential energy extraction depends upon the central position of the filter profile and is continuously adjustable.

The system is then seen to be a modified phase gradient visualization system. Phase gradient visualization systems [134-136] are generally used in microscopy to investigate the structure of almost transparent objects, i.e. cells, bacteria, etc. In our application the object contains a very definite absorption profile and phase gradients are introduced in order to modify the slope of high contrast transitions, so that upon encoding overload noise is avoided.

### 3.6 Simplified Analysis

The film relief surface of the input object to be coherently processed is shown schematically in Fig. 3.6-1.

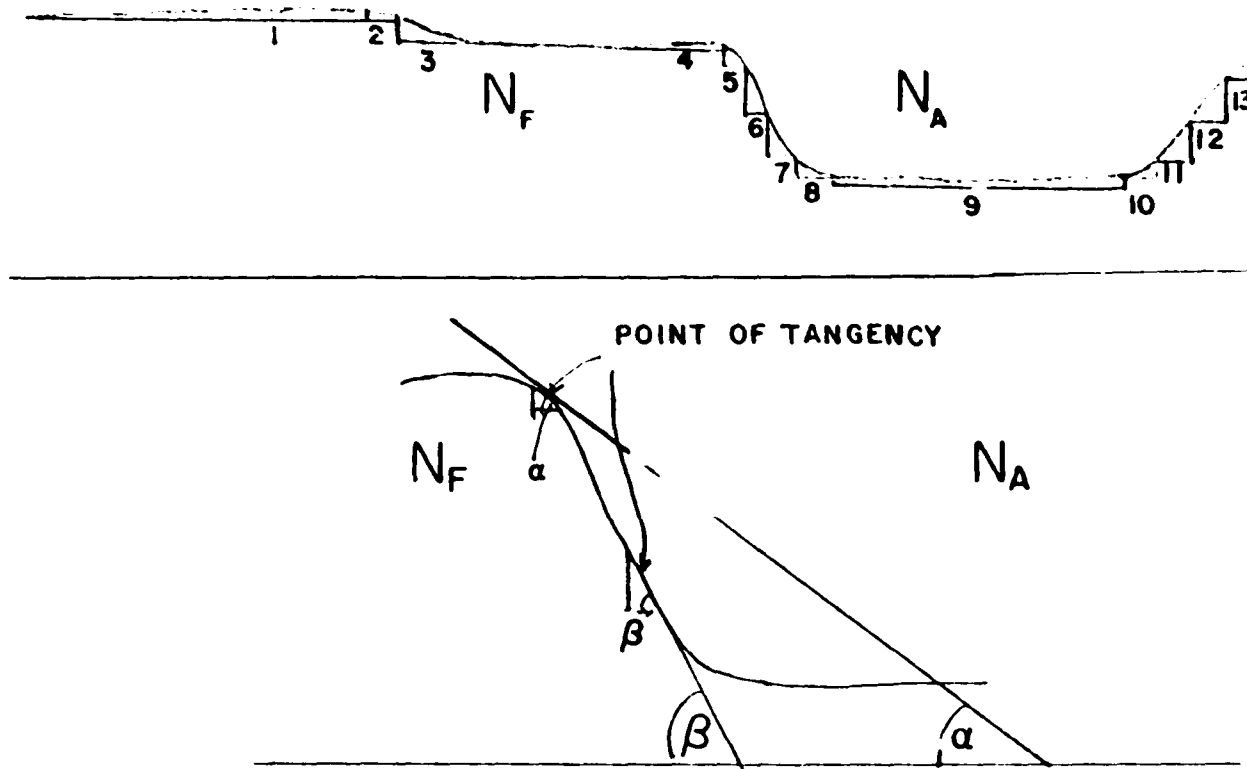


Figure 3.6-1 Phase relief surface showing continuously changing optical gradients as "prisms"

The complex input object may be viewed as a tandem combination of a purely phase varying surface relief and a purely absorbent image distribution. A combination can be viewed to have an amplitude transmittance  $O_1(x_1)$  that may be described as

$$O_1(x_1) = b_1(x_1) \exp ik\phi(x_1) \quad (3.6-1)$$

If the object is illuminated by a plane wave of monochromatic light, then the Fraunhofer diffraction pattern formed by a lens  $L_1$  in the conjugate source plane is a spatial Fourier representation of the input [144,145].

The Fourier transform,  $\bar{O}_1(kx)$ , is modified by passing through a photographic transparency where the amplitude transmittance varies linearly with position.

$$\tau(x_2) = \alpha(x_2 + x_0) = \frac{\alpha f}{k} (k_2 + k_0) \quad (3.6-2)$$

where

$f$  = the focal length of the transform lenses

$$k = \frac{2\pi}{\lambda}$$

$\alpha$  = a constant

$x_2$  = the transform plane coordinate

$x_0$  = the filter central position bias.

A second lens,  $L_2$ , performs a Fourier transform on the product  $(\bar{O}_1)(\tau)$  to produce an amplitude distribution  $O_2(x_3)$  in the  $x_3$  plane. This image is related to the differentiated phase object image, biased by

the absorption image [115];

$$O_2(x_3) = -i \frac{\alpha f}{k} O_1'(-x_3) + \frac{\alpha f}{k} k_0 O_1(-x_3) \quad (3.6-3)$$

$$\begin{aligned} &= -i \frac{\alpha f}{k} [i\phi'(-x_3) O_1(-x_3) + b_1'(-x_3) \exp i k \phi(-x_3)] \\ &\quad + \frac{\alpha f}{k} [k_0 O_1(-x_3) \\ &= \frac{\alpha f}{k} \left[ k_0 + \frac{k \phi'(-x_3)}{\alpha} - i \frac{b_1'(-x_3)}{b_1(-x_3)} \right] b_1(-x_3) \exp i k \phi(-x_3) \\ &= \frac{\alpha f}{k} \left[ k_0 + \frac{k \phi'(-x_3)}{\alpha} - i \frac{b_1'(-x_3)}{b_1(-x_3)} \right] O_1(-x_3) \end{aligned} \quad (3.6-4)$$

#### Case 1

For a complex input object in areas where  $O_1(x_1)$  is constant and  $b_1'(x)$  is zero or slowly varying  $b_1'(-x_3)/b_1(-x_3) \approx 0$  the phase  $\phi(x_1)$  will also be constant so  $\phi'(-x_3) \approx 0$ . The image amplitude is related to

$$O_2(x_3) = \frac{f}{k} k_0 O_1(-x_3) \quad (3.6-5)$$

and the intensity will be

$$I_2(x_3) = \left( \frac{\alpha f k_0}{k} \right)^2 b_1(-x_3)^2 \quad (3.6-6)$$

This represents an image which is a scaled amplitude inverted image of the input.



Case 2

In areas of the input object where rapid transitions of the amplitude occur with no phase gradient for a purely absorbing object, ( $x_1 \approx \text{constant}$  so  $\phi'(-x_3) \approx 0$ )

$$O_2(x_3) = \frac{\alpha f}{k} [k_0 - i(b'_1(-x_3)/b_1(-x_3))] O_1(-x_3) \quad (3.6-7)$$

$$\begin{aligned} I_2(x_3) &= O_2(x_3) O_2^*(x_3) = \left( \frac{\alpha f}{k} \right)^2 \left[ k_0^2 + \frac{b'_1(-x_3)^2}{b_1(-x_3)^2} \right]^2 (b_1(-x_3))^2 \\ &= \left( \frac{\alpha f}{k} \right)^2 k_0^2 (b_1(-x_3))^2 + \left( \frac{\alpha f}{k} \right)^2 (b'_1(-x_3))^2 \end{aligned}$$

This represents the scaled image plus a term representing the intensity due to the derivative of the amplitude image if the filter aperture is assumed to be infinite.

Case 3

In areas where transitions of amplitude occur using phase encoded film or an appropriate real-time photo-refractory spatial light modulator [115], there will be resultant phase gradients across these transitions and the output amplitude will be related to the total expression of eq. (3.6-4).

a) If  $b_1(x_1)$  is a slowly varying function, then  $b'_1(-x_3)/b_1(-x_3) \ll 1$  and

$$O_2(x_3) \approx \frac{\alpha f}{k} \left[ k_0 + \frac{k}{\alpha} \phi'(-x_3) \right] \left[ (b_1(-x_3))^2 \right]^{\frac{1}{2}} \quad (3.6-8)$$

This results in an output intensity

$$I_2(x_3) \approx \left( \frac{\alpha f}{k} \right)^2 (k_0 + \frac{k}{\alpha} \phi'(-x_3))^2 (b_1(-x_3))^2 \quad (3.6-9)$$

b) If  $b_1(x_1)$  is a rapidly varying function with a large difference in initial and final edge transition value then  $\phi_1(-x_3)$  will also be large and

$$\begin{aligned} O_2(x_3) &= \left( \frac{\alpha f}{k} \right) (k_0 b_1(-x_3) + \frac{k}{\alpha} b_1(-x_3) \phi'(-x_3) \\ &\quad - i b_1'(-x_3) \exp i k \phi_1(-x_3)) \quad (3.6-10) \\ &= \frac{\alpha f}{k} k_0 O_1(-x_3) + \frac{k}{\alpha} O_1(-x_3) - i b_1'(-x_3) \exp i k \phi_1(-x_3) \end{aligned}$$

Therefore, the relative magnitude of the real and imaginary parts determine whether the amplitude is diminished or increased relative to the bias image amplitude value. The effect of limiting the extent of the transform filter profile upon the phase gradient angularly shifted spectra is to change the energy of the detail that produces an angular sideband. If the profile of the filter passes the positive sideband and blocks the negative sideband, then these details will appear to have irradiances that are greater and less than

respectively, the bias image.

We now present a heuristic filter analysis based on a virtual source interpretation of the phase encoded edge dependent asymmetrical transform preprocessor.

### 3.6-1 Phase Encoding of Step Intensities--Virtual Sources

Let us assume a quasi monochromatic coherent illumination of a non-grating like object as shown in Fig. 3.6-2. Here, Köhler central illumination (illumination by a plane wave incident normally to the object plane) is used. A typical point  $x, y$  of an object plane detail is assumed to be positioned in the back focal plane of the first transform lens. If the lens has an equal front and back focal lens  $f$ , it will create a disturbance at the front focal plane that is related to the Fourier transform of the object distribution  $F[x, y]$ . Assuming the small angle approximation with transform coordinates  $(\xi, \eta)$  where

$$\xi = pf, \quad \eta = qf \quad (3.6-11)$$

where  $p = \cos \psi$  and  $q = \cos \beta$  are the direction cosines of the diffracted orders to the  $x$  and  $y$  axes respectively.

The disturbance can then be written in the

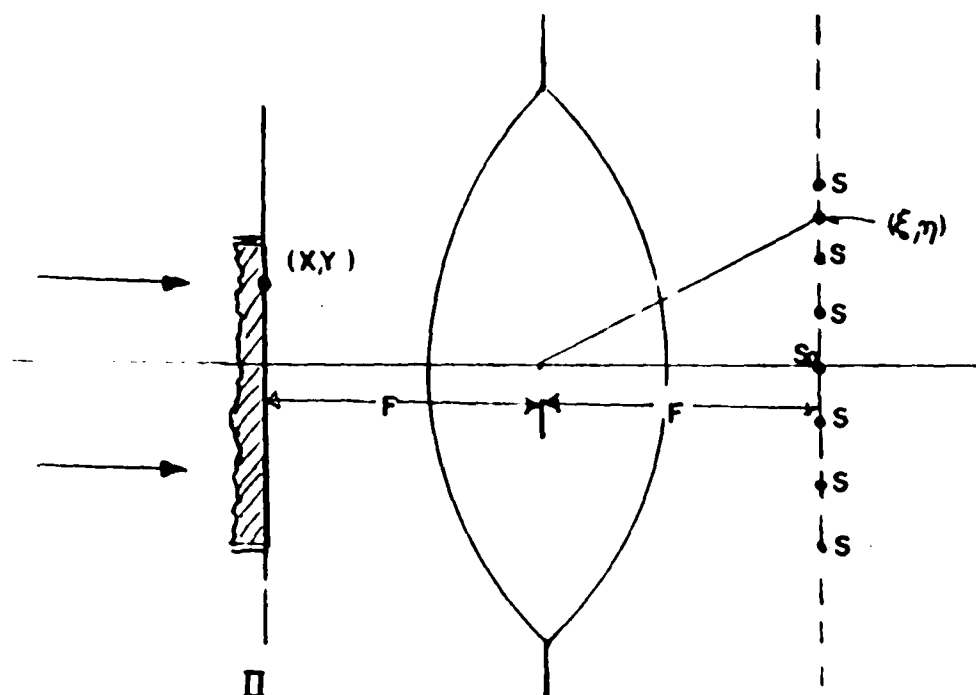


Figure 3.6-2 Parallel Illumination of a non-grating object

form given by [151] from Born and Wolf,

$$U(\xi, \eta) = C_1 \iint_A F(x, y) \exp \left\{ -ik \left[ \frac{\xi}{f} x + \frac{\eta}{f} y \right] \right\} dx dy \quad (3.6-12)$$

Here,  $C_1$  is a constant, and the integration is taken over the area  $A$  of the object plane II covered by the object.

Referring to Fig.3.6-2, let us now consider the positions of the transformed diffracted maxima of the orders of a transmission grating-like object if it were to be placed in input plane II.  $S_{-2}, S_{-1}, S_0, S_{+1}, S_{+2}, \dots$  denote the centers of the maxima of successive transformed orders. For a spatially coherent point source, the shape of each of these transformed orders would have the distribution of an aperture limited diffraction pattern of an effective off-axis illuminating point source, scaled by the slit-width, period, and having an envelope determined by the grating geometry.

Thus it can be seen that these transformed maxima may be considered to be the conjugent focused images of virtual point sources displaced in the illuminating source plane. This is shown in Fig. 3.6-3.

For a periodic grating-like object,

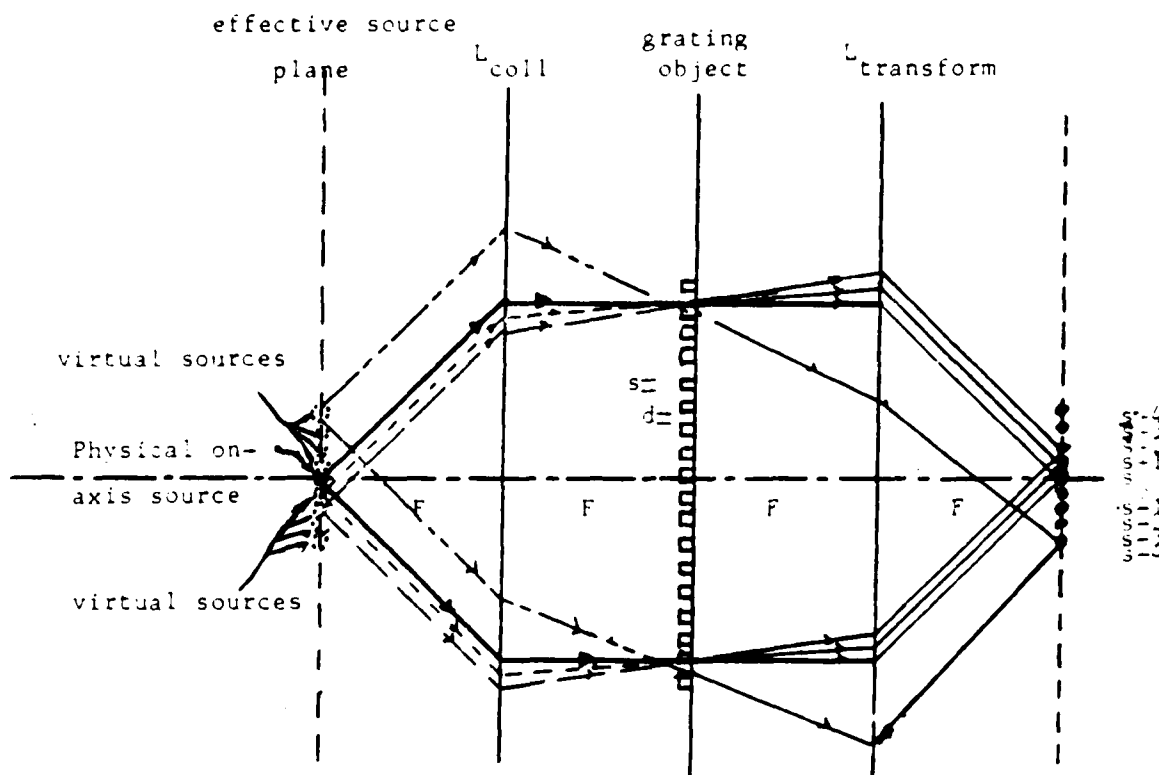


Figure 3.6-3 Virtual source points produced by grating-like object and conjugate focused images

consisting of  $N$  equidistant congruent slits of width  $s$ , separated by opaque regions with period  $d$ , and a rectangular aperture with two parallel sides to the slits, the disturbance in the transform domain in one dimension may be given by

$$U(\xi) = C_1 \left[ \text{sinc} \frac{k\xi s}{fs} \right] \times \left[ \frac{1 - e^{-iNkd\xi/f}}{1 - e^{-ikd\xi/f}} \right] \quad (3.6-13)$$

This represents a symmetrical distribution of variable intensities virtual point sources illuminating a clear rectangular aperture  $N_d$  separated by distance of  $\Delta\xi = \frac{f}{d} = \frac{2\pi f}{kd}$ . We have assumed here that the condenser collimating the source point before illuminating the object has the same focal distance so that the magnification is unity.

With the concept of virtual sources in mind, let us now look at how we may describe a non-periodic point  $(x,y)$  containing a phase-gradient that modulates the input plane waves. At this detail, the source of parallel illumination produced by the carrier modulated angle will appear to arise from a collimated beam derived from an off-axis virtual point source. The disturbance in the transform domain will then be shifted from

$$U(\xi, \eta) \text{ to } U(\xi'; \eta'); \quad \xi' = (p + \Delta p)f, \quad \eta' = (q + \Delta q)f \quad (3.6-14)$$

where  $\Delta p$  and  $\Delta q$  are determined by the details phase gradient under the small angle assumption.

For a relief object, where the index of the film is assumed for this analysis to be constant and the gradient is due to the optical path difference caused by the change in film thickness, we can, for the sake of simplicity, approximate the film relief as a series of piece-wise linear one-dimensional "prism" like reliefs [137].

Fig. 3.6-1 shows a diagram of the film relief with continuously changing optical phase gradients represented as "prisms," for  $N_A = 1$ , and  $N_F = n$ . Referring to Fig. 3.6-4a, we may write the path difference  $\Delta$ , the angular carrier  $\Delta p$ , and the angular shift in spatial frequency  $\Delta v$  as:

$$\Delta = (n-1)MM' = (n-1)\sin \phi \Delta x \quad (3.6-15)$$

$$\Delta p = k(n-1)\sin \phi \Delta x = \frac{2\pi}{\lambda}(n-1)\sin \phi \Delta x \quad (3.6-16)$$

$$\Delta v = \Delta p / 2\pi \quad (3.6-17)$$

With reference to Fig. 3.6-1,  $\Delta p$  is positive at the gradients labeled 2,3,5,6,7,8, negative at 10,11,12,13 and close to zero at 1,4 and 9 for the same  $\Delta x$ . Note that the displaced position  $(\xi', \eta')$  of the details' transformed spectra maximum may now be viewed as a conjugate virtual source point image. The position is different for high contrast rapid



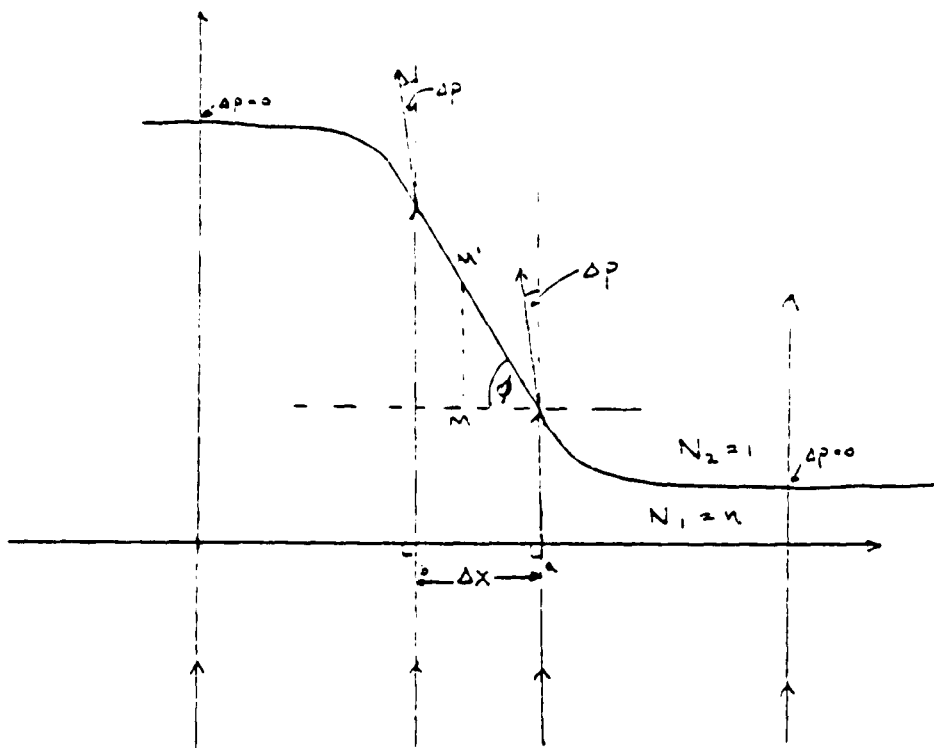


Figure 3.6-4 (a) Enlarged "prism" representation of phase relief

transitions from the virtual source positions caused by low contrast rapid transitions. The phase gradients of high contrast transitions of the same orientation will receive the same angular carrier and thus be shifted to the same position in the transform domain. Whereas the maximum positions of low contrast transitions of the same orientation as the high contrast transitions will have different phase gradients and thus the positions of their maxima (produced by different virtual sources), will lay closer to the axis. The transform filter operating on the energy from different virtual source points attenuates these edge energies asymmetrically. Resulting energies that are transmitted will therefore be a function of the filter position and phase gradient direction. This is shown in Fig. 3.6-4b.

We will now discuss another approach to describe the operation of the filtering system based on a modified modulation contrast technique.

### 3.6-2 Zero Order Carrier Encoding

Let us assume a simple one-dimensional phase filtering system where the filter can be described as having three regions of constant differing attenuation. In order to understand the modification of the zero order energy that occurs upon filtering, due to phase

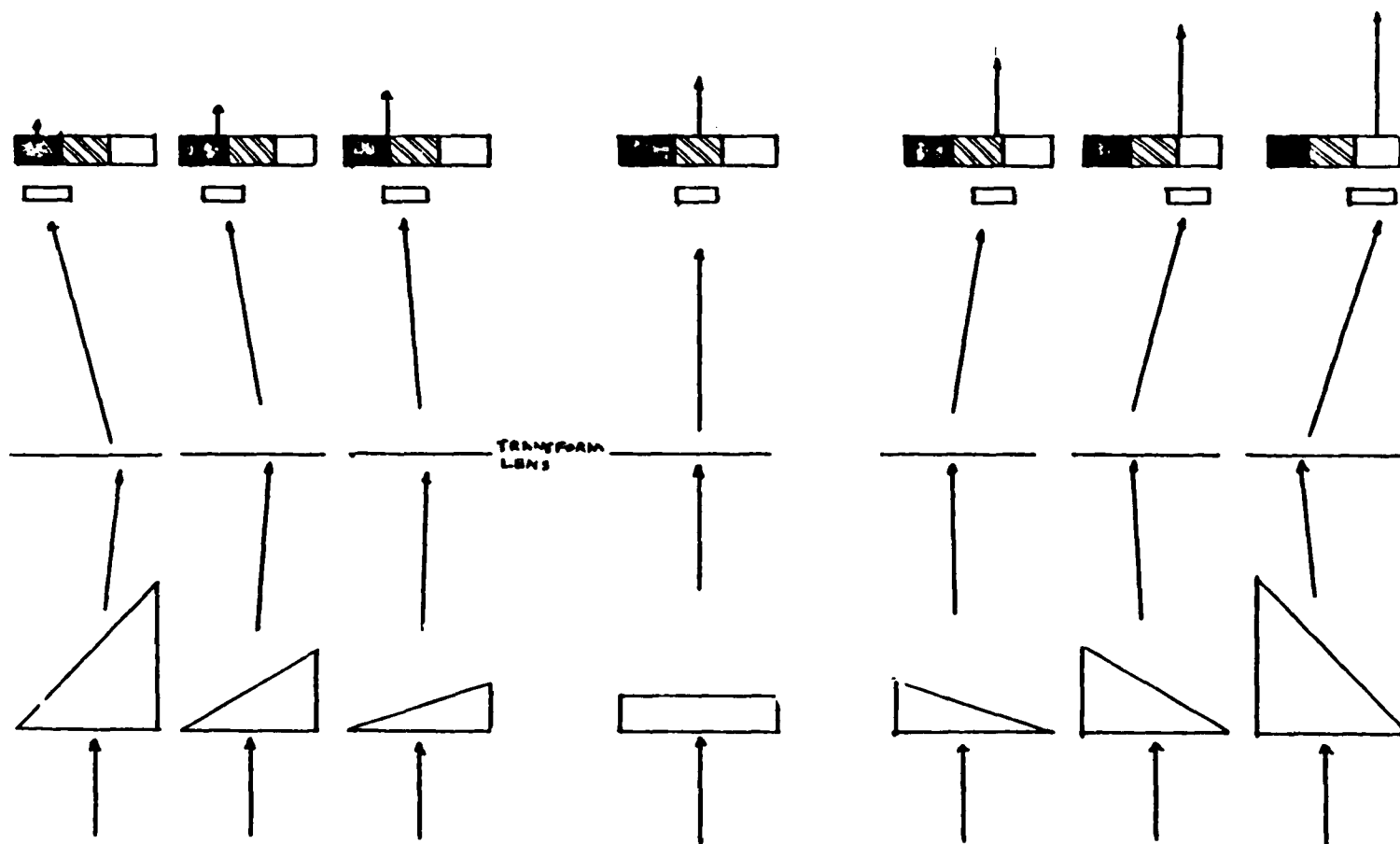


Figure 3.6-4(b) Diagram illustrating how filter produces intensity variations within a range of optical gradients. Length of arrow after filter indicates intensity.

gradient modulation, let us consider a simple object. If we illuminate an object  $F(x)$  that is a complex object with a field  $P_A(x)$  having an illumination area of  $A$ , then the amplitude transmitted by the entire plane of illumination may be given as

$$U(x) = P_A(x) + P_a(x)F(x) - P_a(x) \quad (3.6-18)$$

where  $a$  is the length of the object assumed to be rectangular pulse. For an opaque object,  $F=0$

$$U(x) = P_A(x) - P_a(x) \quad (3.6-19)$$

The field at the Fourier plane is proportional to  $U(x)$ , the transform of which can be written as

$$\bar{U}(x) = U(\xi) = \bar{P}_A(x) - \bar{P}_a(x) - 2A \sin A\xi / A\xi - 2a \sin \xi / a\xi \quad (3.6-20)$$

The retransformed image then has amplitude given

$$\text{by } U(x') = U(\xi) = P_A(x') - P_a(x') \quad (3.6-21)$$

Referring to the Fourier plane, a filter having the same effect as the rectangular object in the input plane, can be seen to remove the zero order energy of the opaque subject from the zero order energy of the zero order incident field. This creates a "hole" in the zero order intensity at the retransformed output.

For a phase gradient where  $F(x)$  equals  $\exp(-i\phi x)$  this object removes a portion of the zero order energy of the incident illumination on the object field by displacing that portion in the Fourier plane. We may write

$$U(x) = P_A(x) + P_a(x)\exp(-i\phi x) - P_a(x) \quad (3.6-22)$$

and

$$U(\xi) = P_A(x) + P_a(x)\exp(-i\phi x) - P_a(x) \quad (3.6.23)$$

$$= \frac{2A \sin A\xi}{A\xi} + \frac{2a \sin a(\xi+\phi)}{a(\xi+\phi)} - \frac{2a \sin a}{a\xi} \quad (3.6-24)$$

where the terms in  $(\xi+\phi)$  represent the energy shifted away from the zero due to the detail phase gradient.

If this term is blocked or attenuated as shown in Fig. 3.6-4b in the Fourier domain, the image irradiances of these details at the output domain decrease with respect to the background bias amplitude image at locations of high contrast transitions. Thus the filtering modifies the slope of the edge by adjusting the central maxima of the shifted spectra of the edge detail in proportion to the intensity change at these high contrast transitions which produced large phase gradients. Fig. 3.6-5 shows a 3-step transform filter and a one-dimensional finite width source.

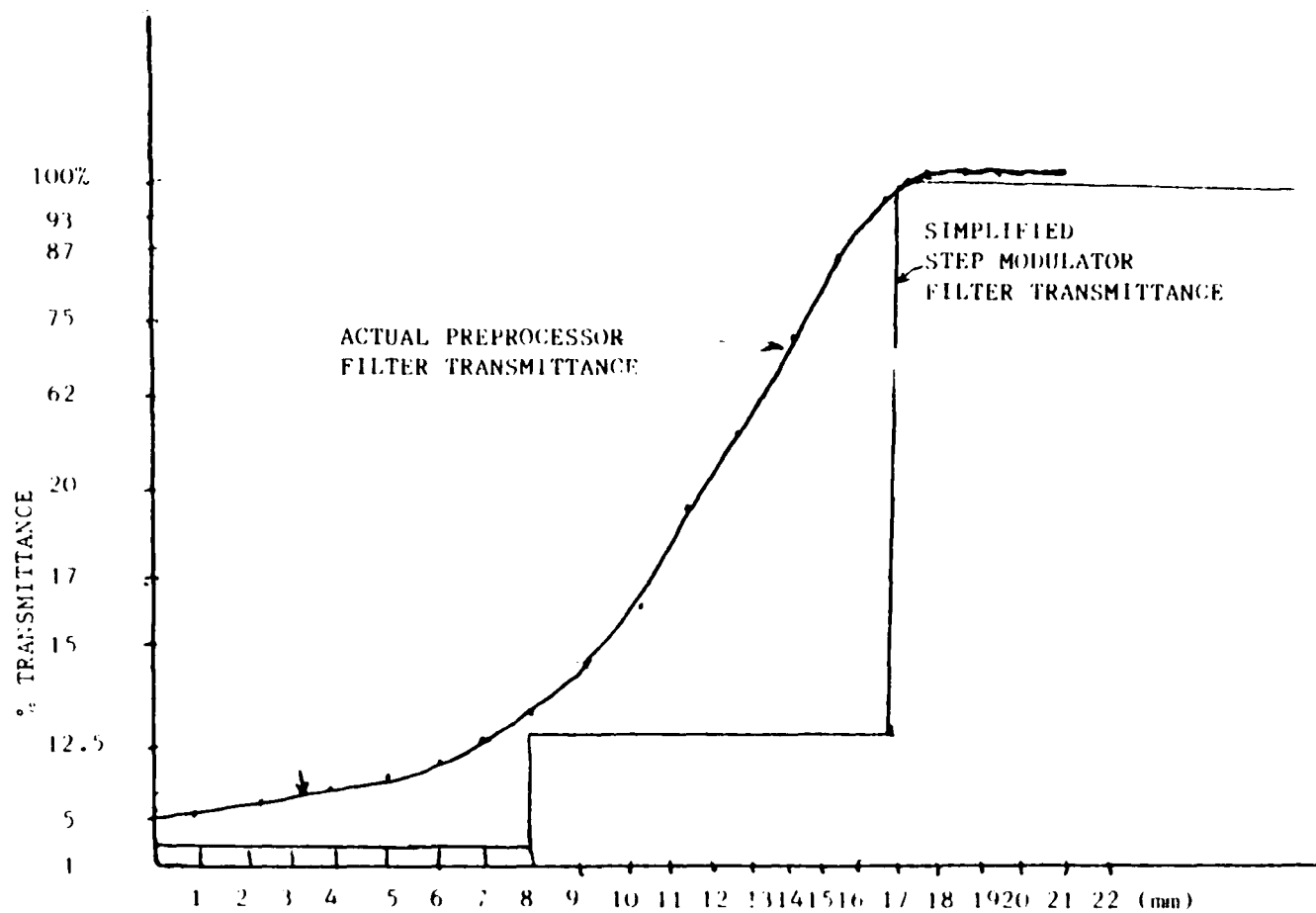


Figure 3.6-5 Profile of 3-step transform filter and modified encoding filter

The change in a positive or negative phase gradient oriented at an angle  $\gamma$  to the filter's gradient normal produces a resultant change of intensity that has been shown to have the form [138],

$$\Delta I^+ = I_0 f \Delta\phi (T_B - T_G) \cos \gamma / W \quad (3.6-25)$$

$$\Delta I^- = I_0 f \Delta\phi (T_G - T_D) \cos \gamma / W \quad (3.6-26)$$

where  $I_0$  is the zero shifted image intensity,  $f$  is the transform lens focal length,  $\Delta\phi$  is the shift introduced by the phase gradient. We see that the simplified transmittance of the three piecewise constant regions is given by  $T_B \geq 99\%$  transmission,  $T_G = 15\%$  transmission, and  $T_D \leq 1\%$  transmission.

In the next chapter we will discuss our filter as a modification of this piecewise linear filter.

In order to test whether the assumptions about edge modification discussed in above would produce the desired effect, phase encoded input objects were produced and transformed filtering implemented. The next chapter describes the implementation and testing of the filter.

## CHAPTER IV

### OPTICAL PREPROCESSOR--EXPERIMENTAL IMPLEMENTATION

The system that has been described has been implemented experimentally. This work forms the major part of this thesis and is now described in detail. Discussion has been divided into three chapters, each of which describes one phase of the experimental work.

#### 4.1 Monochromatic Coherent Optical Transform

##### Preprocessing

Several different types of complex objects were employed as inputs to the optical preprocessing system. The first test objects used were resolution test targets which were convenient for studying the spatial frequency response of the hybrid encoding system.

The input objects were produced by exposing a photographic film in contact with a 1951 U.S.A.F. test target. The latent image was developed by chemical processing and due to emulsion shrinkage and the byproducts of development, a resultant relief contour surface related to the original exposure was produced. This type of relief surface product is not uncommon and usually occurs in the commercial processing of photographic emulsions. A television resolution target was also employed as an input since the output of the system was to be



finally displayed as a reconstructed video image. The television resolution target input was processed using a standard SMPTE test target and chemical processing.

In addition to these test targets, several other naturally occurring scenes were used. These contained a distant scene, a close-up still life, and head and shoulder views of people, having high, low, and moderate resolutions, respectively.

Plus X Kodak Reversal Film and Panatomic X photographic emulsions were used. These emulsions were exposed and developed using a reversal processing to produce positive image transparencies with relief phase gradients.

The reversal process development is performed in a reel tank in the following manner:

|                 |         |
|-----------------|---------|
| First developer | 8 min.  |
| Water           | 5 min.  |
| Bleach          | 1 min.  |
| Clearing bath   | 2 min.  |
| Redeveloper     | 8 min.  |
| Water           | 1 min.  |
| Rapid Fix       | 5 min.  |
| Wash            | 20 min. |

The timing and temperature control of this process is important as well as the agitation of the chemicals at 30 sec. intervals.

The phase relief is enhanced by post-development

exposure after the clearing bath, and before the redevelopment. This increases the density and cross-linkage in the emulsion. The partially tanned gelatine of the dichromated bleached film changes its volume as a result of swelling during the first development step. This breaks up the continuous film surface in the exposed areas, which are washed away in the second stage of development [139].

The linearity of exposure was tested using a Kodak T-14 test exposure strip that contained fourteen steps of increasing density. Each step increased the density by .15 units. Using this the ranges of reproducible gray scales were tested. Fig. 4.1-1 is a photograph of a magnified portion of a rebleached television test target that was made on Plus X Emulsion and reversal processed. The phase profile was made visible by the use of a modulation contrast phase microscope. The spatial response of the film was measured to range from 30 lp/mm to 120 lp/mm, depending upon the exposure level. The gradient also depended upon the film type and length of development. Although photographic film is a nonlinear encoding material, a graph of the density vs. the log exposure for a given emulsion will contain a straight line portion. If the slope of this portion of the exposure curve is  $\gamma_1$  for the negative processing and  $\gamma_2$  for the subsequent positive reversal processing. We can expose so that



Figure 4.1-1 Photograph of magnified portion  
of rebleached test target input  
made on Plus X Emulsion and  
reversal process

the resultant developed positive image will be in the linear portion of the curves.

#### 4.1-1 Spatial Filter Production--Photographic

##### Procedure

The transform weighting filter was produced in an analog fashion in order to overcome the problems associated with digital point-by-point exposure techniques. It is well known [140] that these point-by-point techniques have inherent problems when producing high resolution profiles due to the pre- and post-exposure overlap that occurs when the writing beam is a diffraction limited laser spot. Analog production allows for compensation of film and exposure nonlinearities while creating a rapid enough transition across the small region of the transformed domain. This type of transition produces the difference in the imaging of the modified high-contrast edges that produce error instabilities upon ADM encoding.

The filter was produced using a one-step exposure process, a beam from a spatially filtered (40X objective, 25 $\mu$  pinhole) 25 mw He-Ne laser. The beam from the spatial filter was expanded in order to expose a 2" x 2" Kodak 649F High Resolution plate. This fine grained film emulsion was used because it is much less noisy in a coherent

system than other films.

In order to obtain the rapid transition desired, D-19 high contrast developer was used. The Kodak 649F emulsion was cup-processed in the following manner:

|                    |                |
|--------------------|----------------|
| Develop D-19       | 6 min.         |
| Wash               | 15 sec.        |
| <b>Stop</b>        | <b>30 sec.</b> |
| <b>Wash</b>        | <b>15 sec.</b> |
| Rapid Fix          | 2.5 min.       |
| Wash               | 11 min.        |
| 50% methyl alcohol | 5 min.         |
| 50% water          |                |

Dry in still air.

Methyl alcohol is used to remove the anti-halation backing on the photographic plates.

A microdensitometer was not available in order to determine the exposure profile, therefore we constructed a measurement device for this task. The arrangement for this measuring system that product a plot of the filter transmittance vs. mask position is shown in Fig. 4.1-2. The exposure head from an enlarger was placed on a vertical track 6' above the plane of a linear transport. On the linear transport a tracking rail with a vernier calibrated position mounting, mated to the track, was used to carry the detector head, a Pin 10 silicon photo diode.

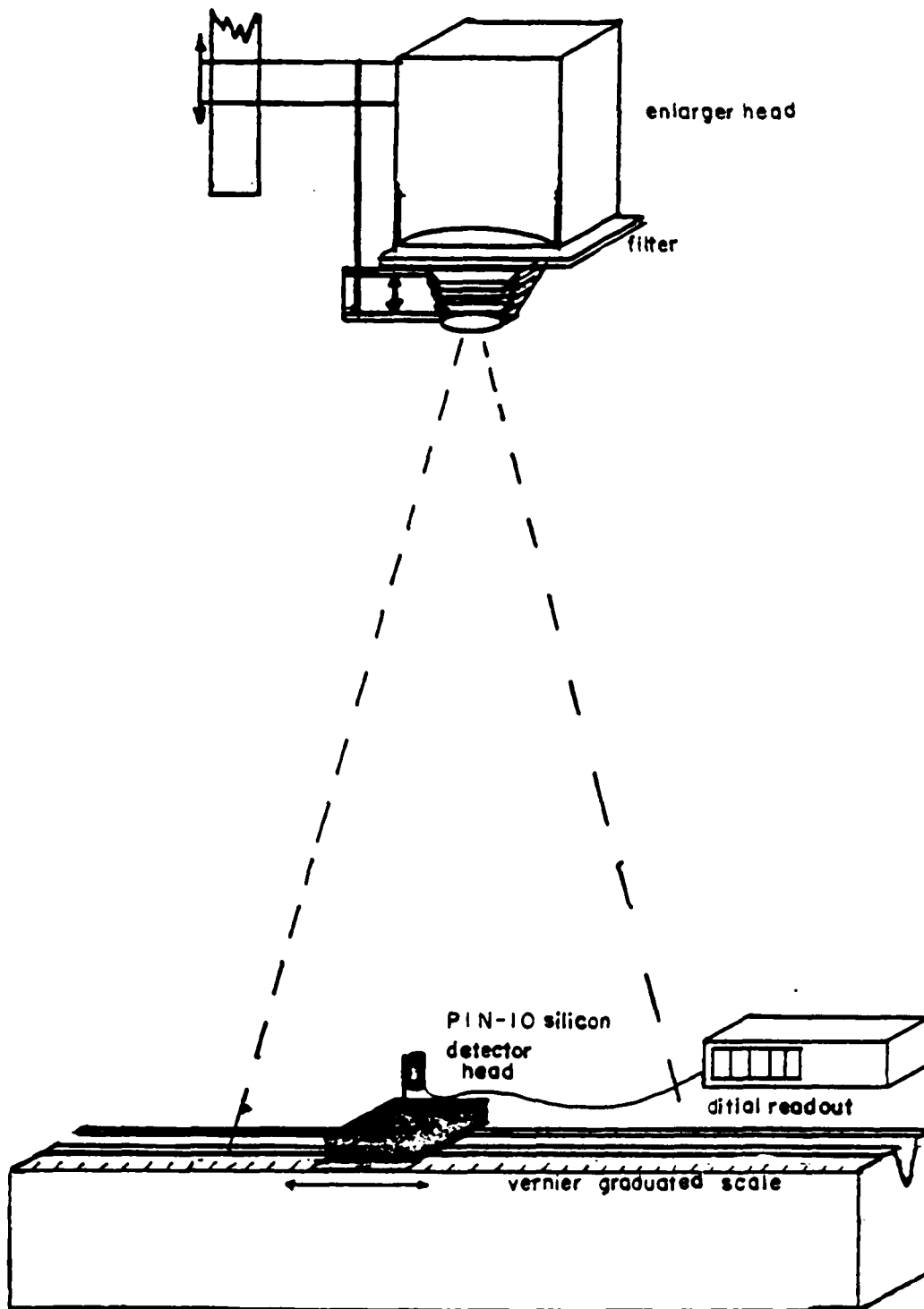


Figure 4.1-2 System for measuring filter function profile

Using the system with the filter placed in the enlarger carrier, the film transmittance versus position was measured by scanning the projecting irradiance at the transport plane. In order for these readings to be meaningful, a scan was first made with no filter in position in the carrier. The irradiance at the plane of the transport bed was scanned by moving the carrier 5 mm per reading. This served as a baseline reading. The filter was now placed in the carrier and the magnified irradiance was scanned from the region of center saturation out to the emulsion cut-off region. The maximum transmission measured was used to normalize the readings after corrections for the lamp irradiance were made. The normalized transmittances were determined and the exposure was adjusted to produce the desired profile. Table 4.1-1 lists the measured readings after correction, the normalized transmittance, and the calculated amplitude transmittance. The exposure was adjusted to produce an essentially linear amplitude transmittance in the non-saturated regions of the plate.

Although this technique for mask production is accurate and simple, great care must be taken in order to assure mask cleanliness and uniform density in the saturated and clear areas. Dust on the mask will cause nonuniform and incorrect exposure. Fig. 4.1-3

Table 4.1-1

Measured Readings After Correction, normalized transmittance,  
and calculated amplitude transmittance

| meas.<br>I | $T = \frac{I}{I_{max}}$ | $\sqrt{T}$ | meas.<br>I | $T = \frac{I}{I_{max}}$ | $\sqrt{T}$ | meas.<br>I | $T = \frac{I}{I_{max}}$ | $\sqrt{T}$ |
|------------|-------------------------|------------|------------|-------------------------|------------|------------|-------------------------|------------|
| 171.0      | 1                       | 1          | 96.0       | .561                    | .748       | 42.4       | .247                    | .497       |
| 170.9      | .999                    | .999       | 92.0       | .538                    | .733       | 40.5       | .236                    | .486       |
| 168.9      | .987                    | .993       | 88.1       | .515                    | .718       | 38.1       | .222                    | .472       |
| 166.9      | .976                    | .987       | 84.8       | .495                    | .704       | 36.4       | .213                    | .461       |
| 163.5      | .956                    | .977       | 79.9       | .467                    | .689       | 35.2       | .205                    | .453       |
| 158.3      | .925                    | .961       | 76.8       | .449                    | .670       | 33.3       | .194                    | .441       |
| 155.6      | .909                    | .953       | 74.2       | .434                    | .658       | 31.3       | .183                    | .427       |
| 151.3      | .884                    | .940       | 72.2       | .422                    | .649       | 29.2       | .173                    | .413       |
| 146.9      | .859                    | .928       | 70.1       | .409                    | .640       | 27.2       | .159                    | .398       |
| 142.0      | .830                    | .911       | 68.5       | .400                    | .632       | 25.5       | .149                    | .386       |
| 138.3      | .808                    | .899       | 66.6       | .389                    | .624       | 24.1       | .140                    | .375       |
| 134.4      | .785                    | .886       | 64.3       | .376                    | .613       | 22.7       | .132                    | .364       |
| 129.1      | .755                    | .868       | 62.3       | .364                    | .603       | 21.3       | .124                    | .352       |
| 124.4      | .727                    | .852       | 60.3       | .352                    | .593       | 19.8       | .115                    | .340       |
| 118.1      | .691                    | .837       | 58.5       | .342                    | .584       | 17.7       | .103                    | .321       |
| 115.2      | .674                    | .821       | 55.3       | .323                    | .568       | 15.6       | .09                     | .310       |
| 113.1      | .661                    | .813       | 52.1       | .304                    | .552       | 13.8       | .079                    | .280       |
| 108.2      | .633                    | .795       | 49.2       | .287                    | .536       | 12.4       | .072                    | .268       |
| 103.9      | .607                    | .779       | 46.7       | .273                    | .522       | 11.3       | .066                    | .256       |
| .99.5      | .581                    | .762       | 43.9       | .257                    | .507       | 10.6       | .061                    | .247       |



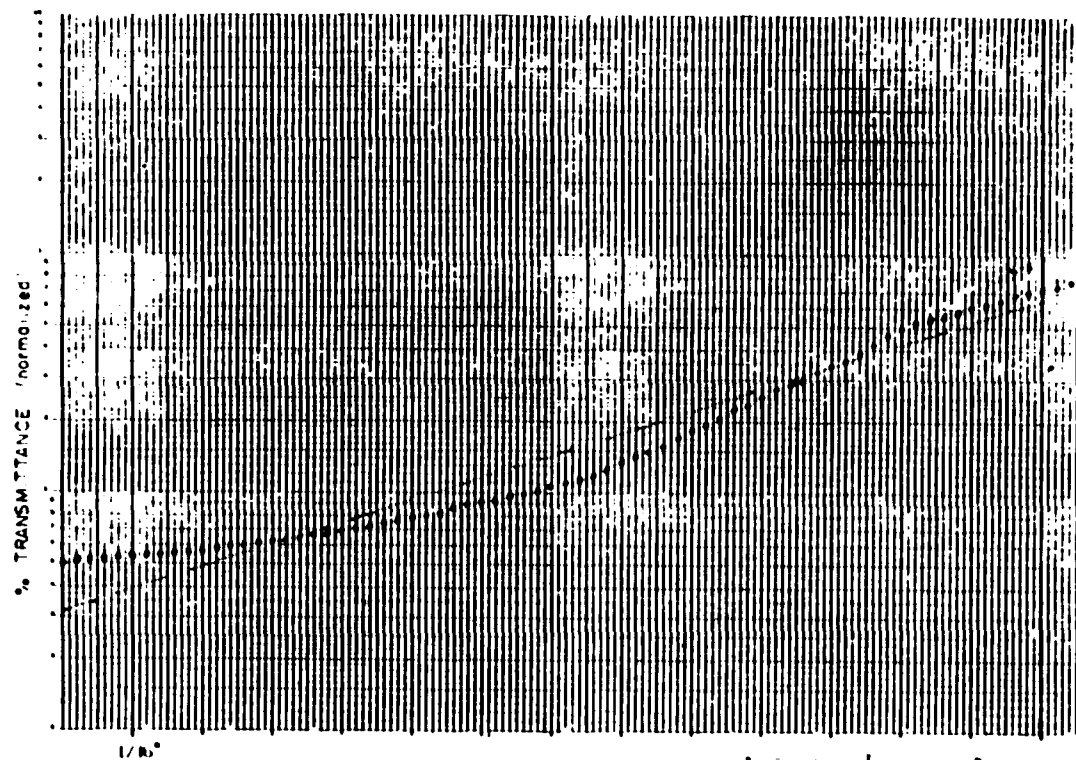


Figure 4.1-3 Normalized transmittance before correction for lamp irradiance distribution

shows a plot of the normalized filter transmittance before corrections for the lamp irradiance distribution were made.

#### 4.1-2 Coherent Monochromatic Fourier Transform

##### Filtering System

In order to determine the imaging properties of the optical preprocessor, a monochromatic optical transform architecture was constructed.

The optical alignment of the arrangement is shown schematically in Fig. 4.1-4. The alignment of the lenses was achieved without the need to resort to the use of an auto-collimator. This was done by the iterative axial beam alignment of the central ray. This central ray was first aligned with a level axis point to produce a reference target. Each lens was successively introduced into the central ray so that the directions of the first and second surface reflections as well as the transmitted ray exiting from each lens were coaxial with the reference axis.

Space Optics Research Laboratory FX 15/5 lenses were mounted and aligned on a 12 ft. vibration isolated table. A 50 mw Jodon He-Ne laser was used as the source of illumination.

The system went through a series of tests and checked to determine the resolution that could be obtained without filtering when the output was imaged

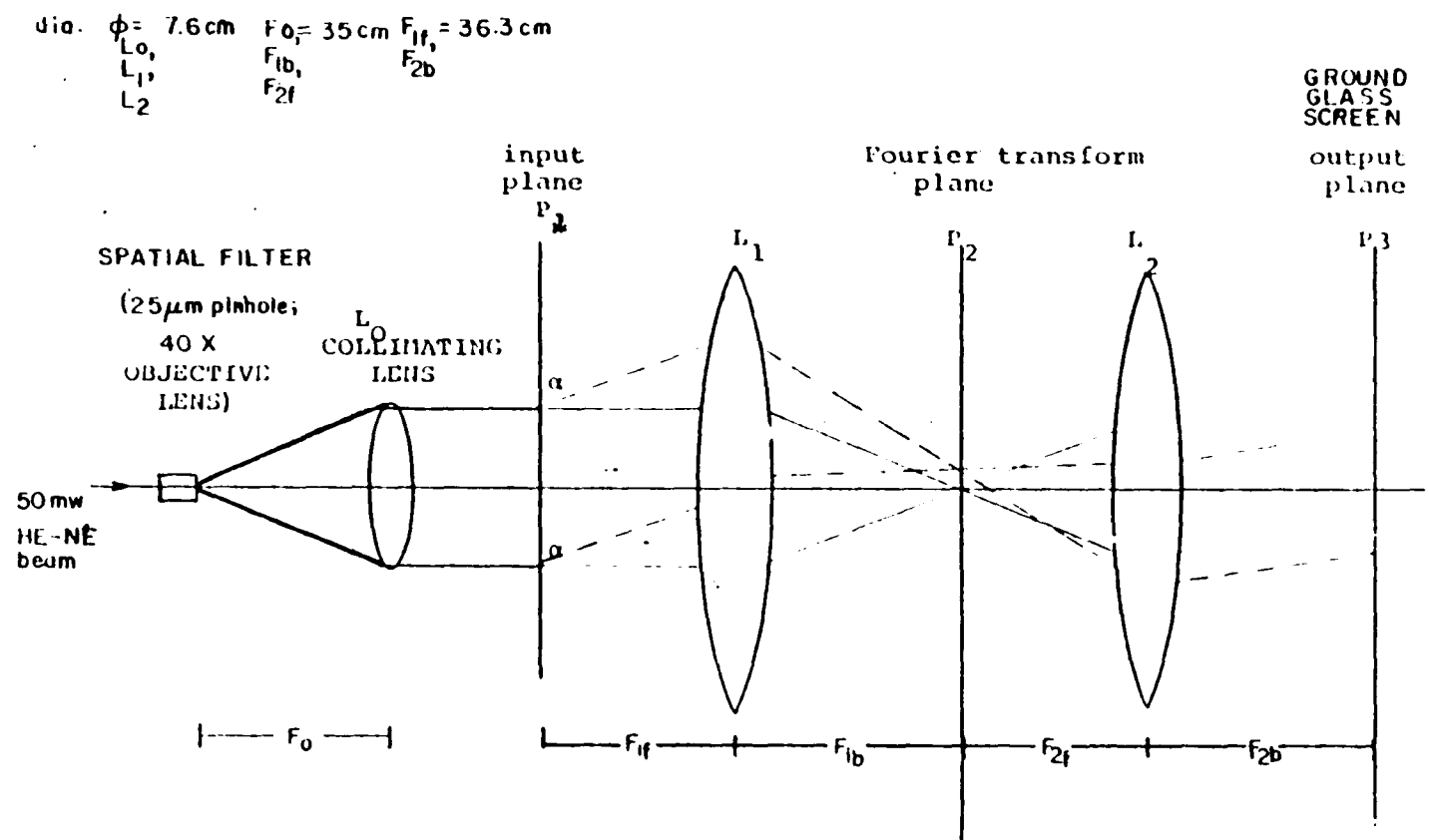


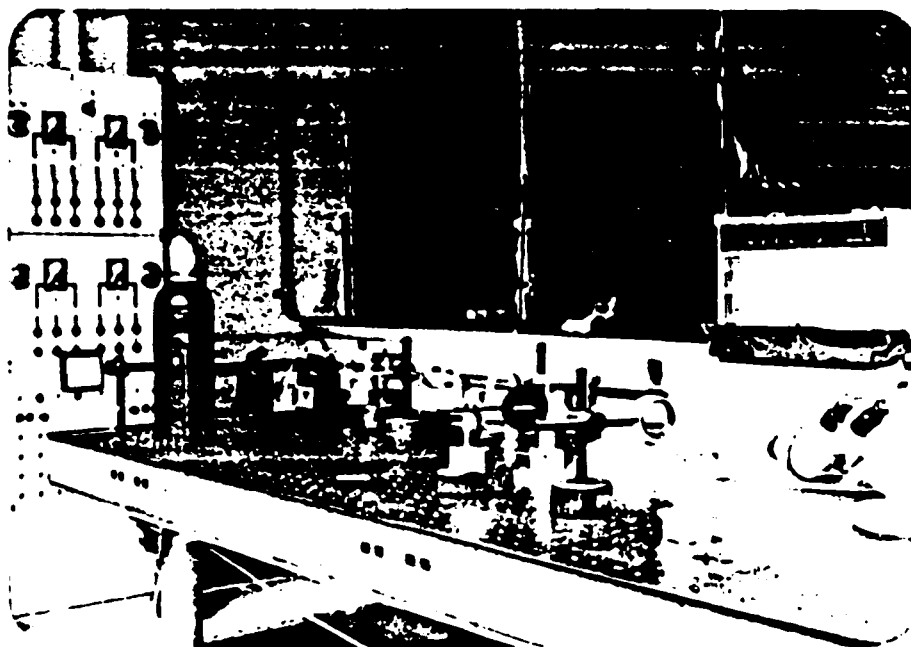
Figure 4.1-4 Coherent monochromatic Fourier transform filtering system

onto a ground glass screen placed in the output plane. Photographs of the transformed system and the ground glass screen, being examined under a microscope to determine image resolution, are shown in Figs. 4.1-5a and 4.1-5b, respectively. With the ground glass screen in the output plane, the resolution of the output image produced by the system fell below 20 lp/mm as opposed to 50 lp/mm imaged without the ground glass screen as seen through the microscope at the output plane. This reduction of resolution is due to the size of the pits of the diffusing surface of the screen.

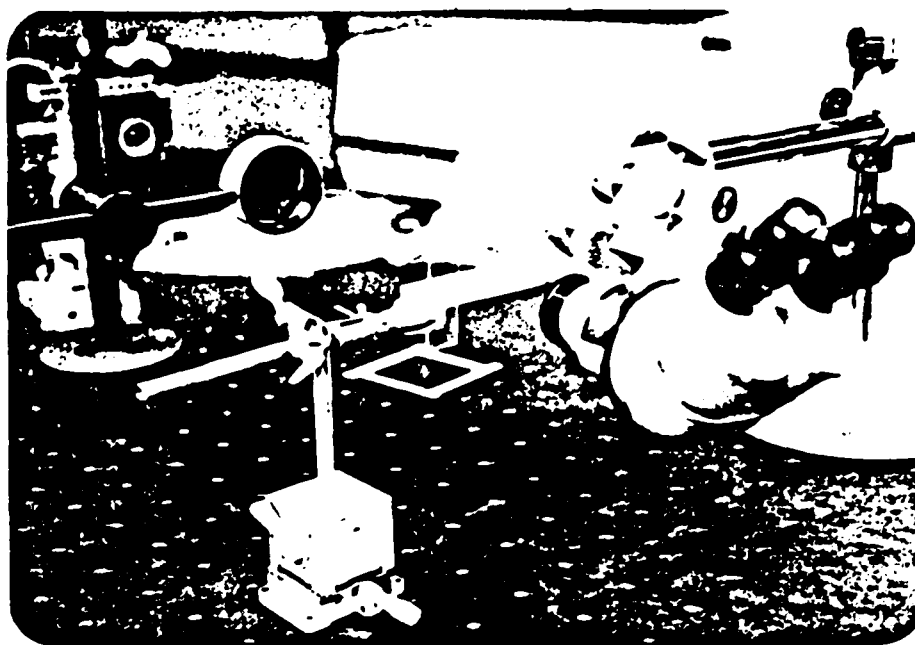
In order to correct this problem, several hot-pressed polymethylmethaculate screens were fabricated to reduce the size of the defusing pit elements. Though the screens allowed for a slightly higher resolution (25-37Lp/mm), the light loss at the output plane did not allow the vidicon camera to operate in a linear region. The optical system thus limits the resolution that could be obtained.

The solution to this problem was found by totally eliminating the output screen and imaging retransformed output directly on to the vidicon face. Careful attention must be given to attenuating the output irradiances or irreversible damage to the vidicon photocathode may occur.

Great care was taken to protect the vidicon face.



(a)



(b)

Figure 4.1-5 Output examination system  
(a) System on isolation table  
(b) Close-up examination of output on  
ground glass screen

In addition to placing a variable neutral density filter ( $\gamma = .01-3$ ) before the input beam entered the spatial filter, an enclosure was built to house the entire transform and isolation table system so that the vidicon would not be inadvertently damaged by direct exposure to bright room light. This was done combined with the usual light-tight window shielding used in optical laboratories.

The vidicon face must also be kept dust-free or artifacts will appear in the reconstructed signal. This was accomplished by flooding the area of the vidicon face with a jet of low pressure dry nitrogen.

Using this arrangement, the resolution of the vidicon scan now became the limiting factor of resolution. The Cohu 4410 camera was used with a low light level Panasonic Nu vicon S4075 as the scanning tube. This low light level pickup tube is composed of a cadmium and zinc tellurised photoconductive target. The standard 525 lines per TV picture frame, using 30 frames per second, and a standard 2:1 interlace scanning format were used to produce the EIA RS-170 output signal which was fed into the ADM encoder.

To determine the effect of lowering the sampling rate on the reconstructed video image, a USAF 1951 test target was used as an input to the system. This test was conducted without the transform filter

in the transform plane.

Figs. 4.1-6a and b are photographs of the output of the test target taken off the monitor of the coherent system when the variable clock sampling rate was adjusted to 8 Mbit/sec and 6 Mbit/sec respectively. Fig. 4.1-6c shows the same image sampled at 22 Mbit/sec.

It was seen that the breakup in the reconstructed picture occurred when the sampling rates were lowered, as expected, at the edges of the bar patterns transverse to the scan direction; in this case the scan direction is in the vertical orientation.

We also notice that interference fringes due to the use of spatially coherent illumination of the vidicon faceplate cover glass appeared in the reconstructed display.

A noticeable breaking up of the bars transverse to the vertical scan, was clearly visible in group 2 of the lower right hand set of bars. Unfortunately, the disturbing time varying nature of the reconstructed edge instability noise is not captured in the still photographs. Due to the fact that these photographs were made with a leaf shutter rather than a single reflex shutter, the band artifact usually seen across the photograph of an image of a monitor is absent.

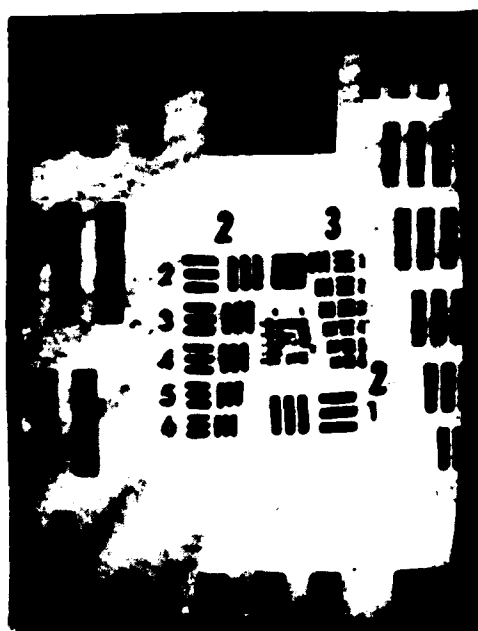
In order to determine whether the assumptions



(a)



(b)



(c)

Figure 4.1-6 Monitor output of coherent hybrid system  
vertically scanned  
(a) ADM encoding at 8 Mb/sec no filtering  
(b) ADM encoding at 6 Mb/sec no filtering  
(c) ADM encoding at 22 Mb/sec no filtering



concerning the gradual weighting optical transform filter were, in fact, correct, and did produce results similar to the piecewise constant modulation contrast filter we performed a series of experiments. Substituting the optical transform gradual weighting filter that we fabricated into the filter carrier of a partially coherent modulation contrast base microscope system, we compared the imaging properties. The physical arrangement of the lenses in this phase microscope system is essentially the same as the transform lens filtering system. This is seen in Fig. 4.1-7a.

We compared the results obtained with our filter and those obtained using the three-segment filter. The use of this system was graciously provided by Robert Hoffman [137], to whom I am indebted.

The one-dimensional schematic of the three area step filters is shown in Fig. 4.1-7b.

The limited aperture three-step transform filtering technique produces a resultant intensity image of phase gradients by modulating the transition intensity of opposite gradients above and below the unshifted background image value, thereby preserving the sign of the gradient. Though a similar result can be achieved with a differential interference technique, the three-step technique is simpler to implement and is less sensitive to chromatic effects [137] since

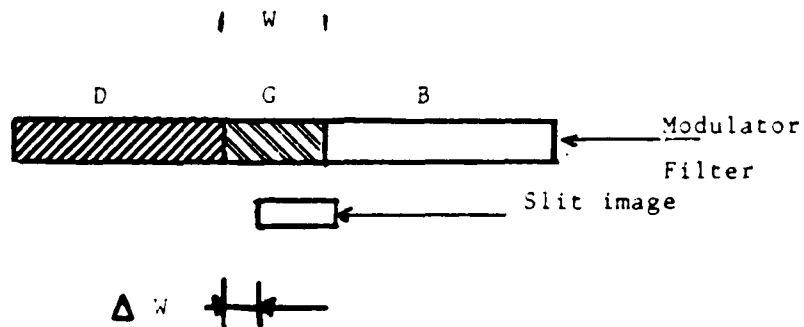
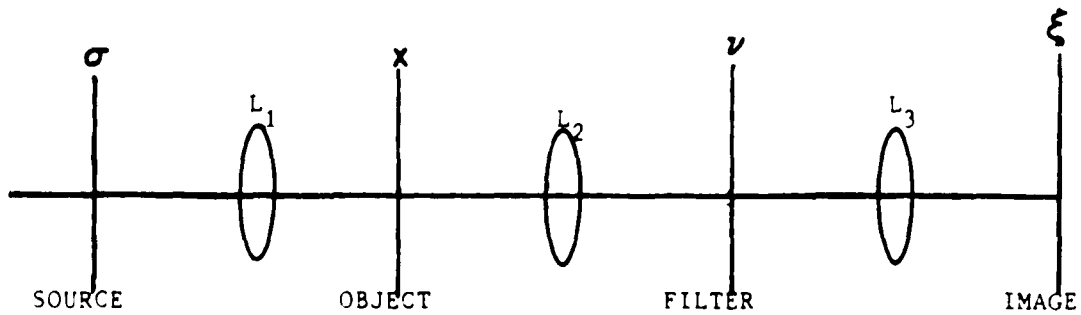


Figure 4.1-7 (a) One-dimensional scheme of a modulation contrast optical microscope system  
 (b) Filtering of the slit source image

it does not depend upon interference but superposition of modified "zero" order shifted energies.

The aperture limited three-step filter is most sensitive to phase gradients, normal to the filter gradient orientation. Thus, the system is directional. This is a property well suited to the hybrid pre-processor, since, as discussed, and determined by experiments, the image is encoded in a directional fashion based on the scan orientation. The signal modification needed to produce a more stabilized reconstruction, must therefore depend on these directional video signal amplitude gradients.

The magnified image of a portion of a phase encoded film object containing both amplitude and phase information, is shown in the photographs of Fig. 4.1-8. Here we can see the direction in which the phase gradients are made visible depends upon their orientation with respect to the transform filter. In these sets of photographs the three step Hoffman transform filter was used. In Fig. 4.1-8a the filter gradient orientation is perpendicular to the top of the letter "T" so that the retransformed image now contains a shadowing along one of the phase gradients. The degree of visibility and orientation of this shadowing depends upon the filter's central position and gradient orientation. We see in Fig. 4.1-8a that the shadowing is bright on

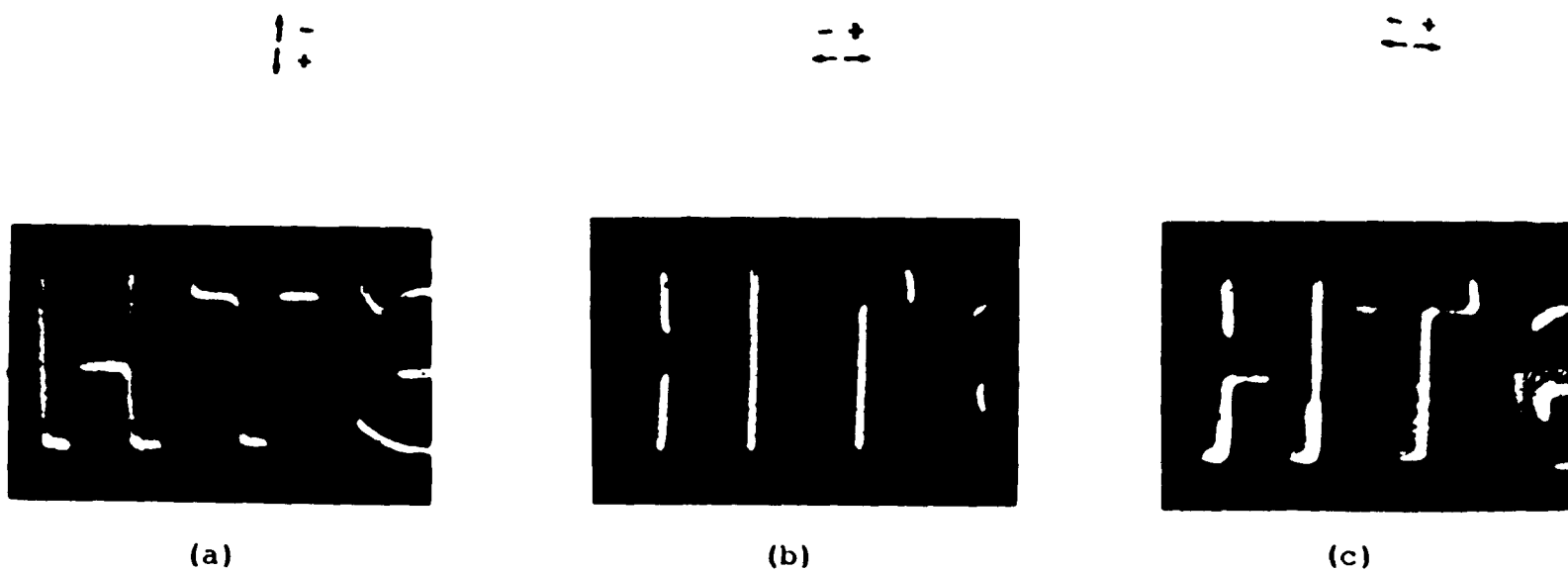


Figure 4.1-8 Visualized phase gradients of complex object using three-step Hoffman transform filter at different filter orientations. Arrows indicate direction of filter gradient

- (a) filter gradient perpendicular to top of "T"
- (b) filter gradient parallel to top of "T"
- (c) filter gradient nearly parallel to top of "T"

one side and dark on the other. In Fig. 4.1-8b the filter was rotated  $90^\circ$  and the shadowing is now seen to be shifted from the top of the T to the left side of the T. The transition at the top of the T is now due solely to the change in the absorption of the film input object. In Fig. 4.1-8c the filter was rotated not quite  $180^\circ$  from its position in Fig. 4.1-8a. The bright and dark shadowings are thus seen to be reversed. The arrows above these photographs indicate the direction of the filter gradient; the plus indicates maximum transmission and the minus indicates the direction of decreasing phase of the filter.

For phase microscopy the filter is designed so that the output visualizes both small and large gradients. This is desirable for microscopy applications but for our purposes of image edge modification we are only interested in the visualization of high contrast transitions that produce large phase gradients so that we can modify the reconstructed edge noise. For our purposes the filter profile should be continuously varying across the central region of the transform as opposed to a uniform transmitting level [138] but still allow for the directional filtering effect. Figs. 4.1-9a-c show the effect of the continuous weighting filter that we fabricated and its ability to produce the desired results. This filter had the modified profile shown in Fig.

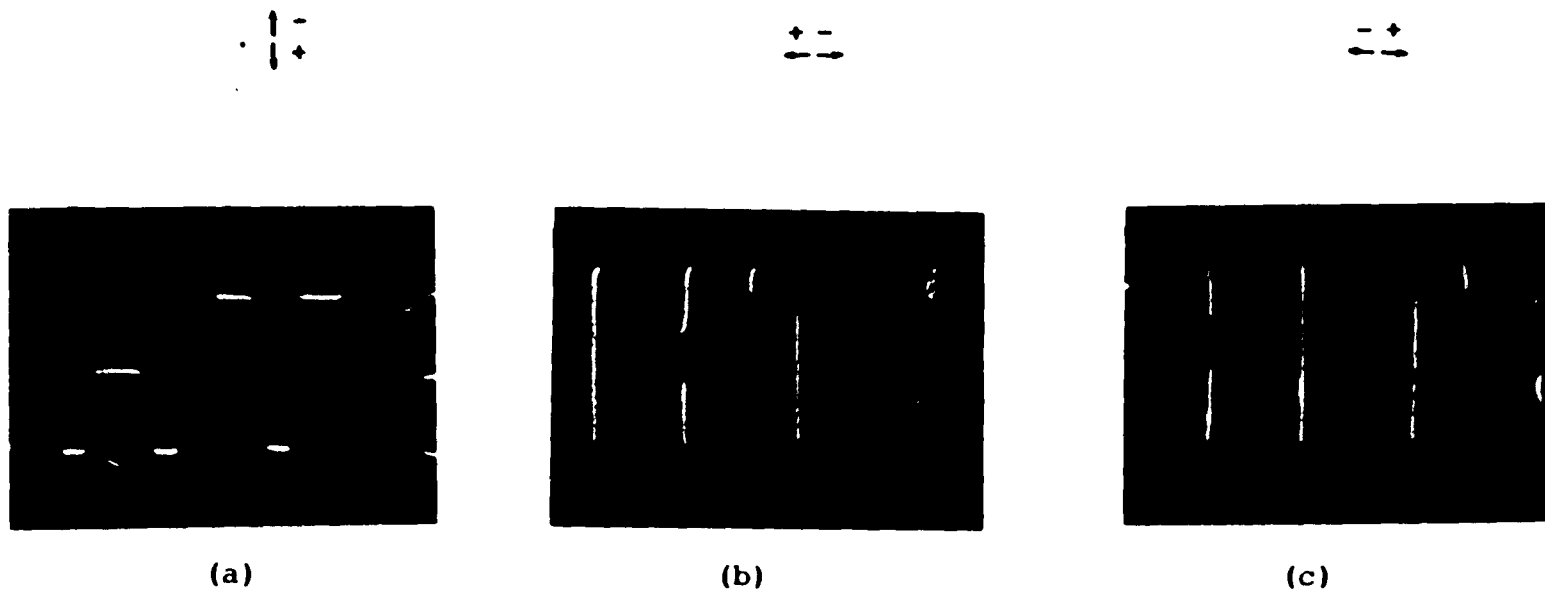


Figure 4.1-9 Visualized large phase gradients of complex object using gradual transition transform filter at different filter orientations.

- (a) filter gradient perpendicular to top of "T"
- (b) filter gradient parallel to top of "T"
- (c) filter gradient rotated nearly 180° to (b)

3.6-5. As can be seen from Fig. 4.1-9a-c only the large phase gradients produced by edge transitions and filtered by our continuous weighting filter create significant light and dark shadowing of the edges.

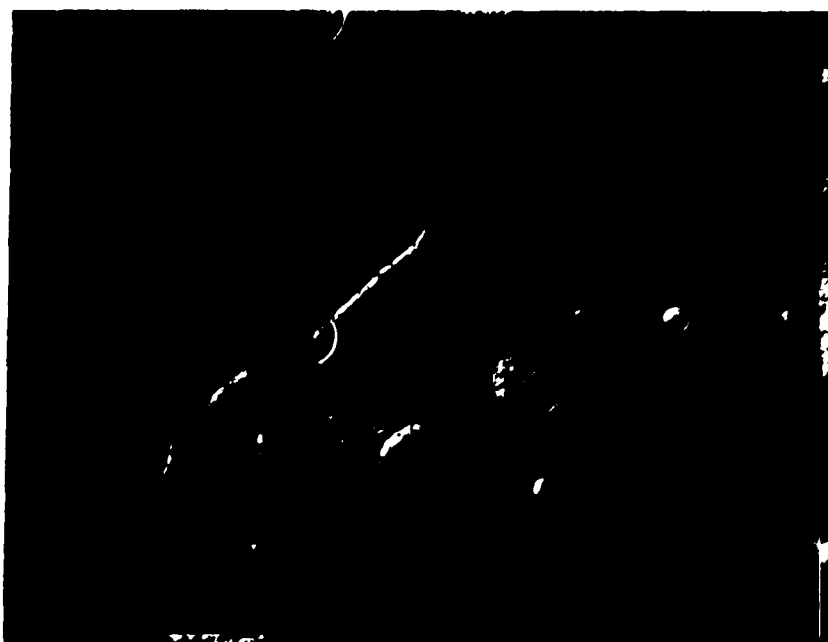
In both filter profiles the relationship between the shifted and the unshifted phase encoded filtered spectra can be written

$$U(\xi'^+, \eta'^+)_{\text{maximum}} \begin{matrix} < \\ > \end{matrix} U(\xi, \eta)_{\text{maximum}} \begin{matrix} < \\ > \end{matrix} U(\xi'^-, \eta'^-)_{\text{maximum}} \quad (4.1-1)$$

This implies that unlike the pure amplitude absorption object, where the spectra are centered around the image of the physical conjugate on-axis source point, the spectra of the complex object produce a distribution of shifted central maxima according to the carrier angles introduced by the distribution of large or high contrast transitions. The filter thus operates to control the image output intensity by modifying the relative magnitudes of the low spatial frequency energy of the step details. Fig. 4.1-10a and b show the output of the limited aperture weighting filter used in a hybrid processor. Fig. 4.1-10a shows the output when the filter is oriented so that strong step transitions at the top of the girl's shoulder are modified with a bright area and the transition at the light to black edge is



(a)



(b)

Figure 4.1-10 Limited aperture weighting filter used in the hybrid processor



reduced. Fig. 4.1-10b shows the output when the filter is rotated  $180^\circ$  so that the edge is darker near the end of the neckline on the horizontal edge. The film was spotted in order to allow for easy detection of the filter gradient direction. The shadowing of these reliefs is reversed in Fig. 4.1-10a and b.

Since the filter profile varies slowly and operates primarily on the phase shifted zero orders, it has the possibility for being used for color imaging coding. This is possible as long as the dispersion in the output plane is less than pixel width for a given sampling rate.

#### 4.2 Spatially and Temporally Coherent

##### Hybrid Optical-Digital Encoding

With the characteristics of the weighting filter measured, we performed a series of experiments to determine the effect of the filter under reconstructed output of ADM encoded images.

With the weighting filter in place in the temporally and spatially coherent transform preprocessor shown in Fig. 4.1-4, the edge noise in the reconstructed video image was reduced at sampling rates of 8 Mbit/sec. and 6 Mbit/sec. An additional improvement in the image quality was obtained by adjusting the source luminance and varying the central filter position so that the

high contrast transitions transverse to the scan were modified before encoding. Fig. 4.2-1a and b are photographed showing the reconstructed video output with optical filtering at 8 Mbit/sec and 6 Mbit/sec respectively.

The subjective effects of ADM noise, sampling degradation and optical filtering were evaluated by a direct viewing of the kinescopedisplay. Such real time displays are not only superior in quality to the photographs obtained by still computer simulation, but also exhibit true frame-to-frame degradations making the evaluation more accurate. Further, the real-time kinescope display is a more realistic representation of the real world situation for more picture transmission applications and provides instant feedback from the observer. As previously discussed, this method is particularly valuable in the evaluation of noise in delta modulation systems [24]. Using this system of evaluation, the subjective optimum picture for a given transmission rate and filter setting can be determined.

As cited in the previous chapters, the quality of a television picture cannot be judged by the simple unweighted signal to noise ratio. In the ADM, quantization noise is exhibited in four subjectively different ways: as grain or granularity noise; slope overload noise; contouring; and edge busyness [59]. This is perhaps a significant advantage of ADM over other digital

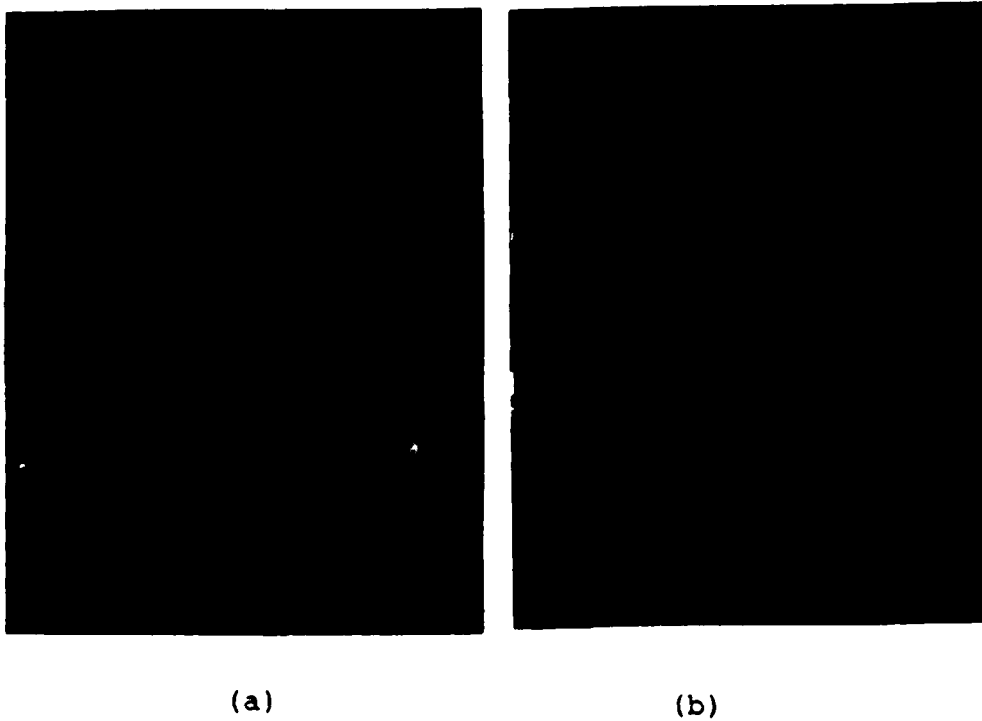


Figure 4.2-1 Monitor output of vertically scanned ADM reconstructions with optical preprocessing  
(a) 8 Mbit/sec  
(b) 6 Mbit/sec

transmission systems because an observer normally judges the quality of a television picture by the most severe degradation rather than by jointly considering several different types. Though analytic results of physical measuring signals are often helpful in making coarse judgments of system response, it is the perceptual significance of distortions which is the critical factor in determining the merit of a transmission system. Only a subjective evaluation can lead to a meaningful judgment in the evaluation of picture quality.

#### 4.2-1 Evaluation and Subjective Testing

The experimental procedure may be best understood by considering the various blocks of the monochrome transmission system shown in Fig. 4.2-2. The subjective evaluations we consider assign a comment on the degradation perceived for pictures encoded with no optical processing relative to those encoded with processing for various sampling rates. The comments were chosen from a comments' scale that ranges from "definitely more objectionable" to "definitely less objectionable," as shown below.

##### Comment Scale

1. Definitely more objectionable
2. Somewhat more objectionable
3. The same impairment

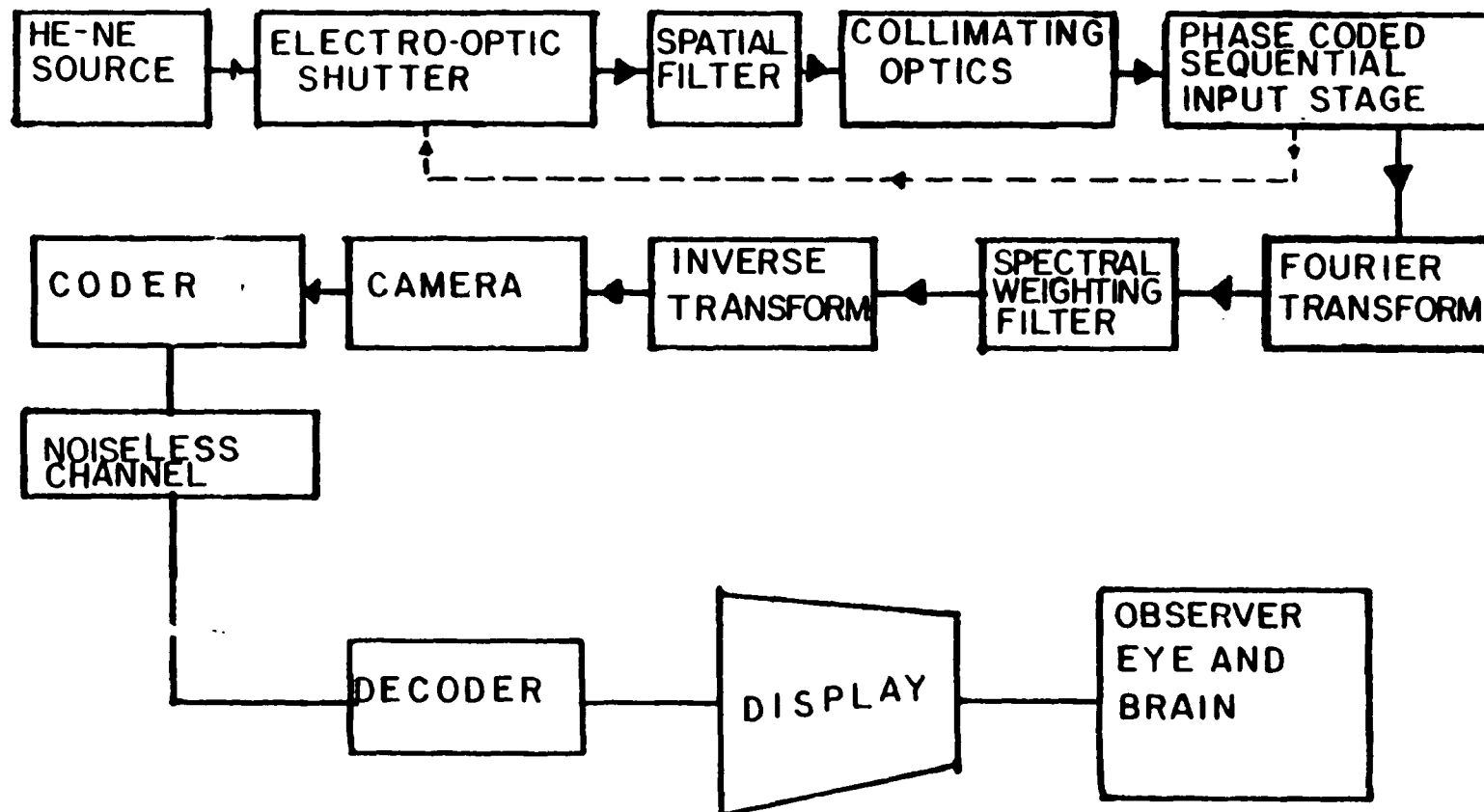


Figure 4.2-2 Block Diagram of Hybrid System

4. Somewhat less objectionable
5. Definitely less objectionable.

The results displayed on a high quality black and white monitor were viewed at a distance of four to eight picture heights. The screen highlight brightness was kept at 30 ft-Lamberts. Observers had normal vision and were not allowed to influence each other during evaluation, but were shown the type of degradation to look for by displaying to them the worst cases.

Several different types of still scenes with varying degrees of tone, content and details were used for the tests. Four to six subjects were used.

A photographic record of the monitor under various conditions was made only for the purposes of illustration. It must be emphasized that the photographs are not an accurate replica of the actual monitor presentations because the photographic process introduces its own distortions and the dynamic effects of edge instability noise cannot be captured by a single exposure. A great deal of frame-to-frame integration may occur during exposure needed due to the low brightness of the monitor screen. In order to reduce the exposure time, Kodak TRI X film ASA 400 was used so that an exposure of 1/30 sec. was possible. Critical

judgment of a video display should not be made by looking at black and white still photographs, although they provide a rough indication of the results, the reader is cautioned against using them for the evaluation of the system.

The results for the ADM with and without optical processing filter in place for still inputs are summarized in Table 4.2-1 and plotted in Fig. 4.2-3.

Various parameters, such as filter position and illumination level were adjusted to obtain the best subjective effect at a particular bit rate.

Table 4.2-1  
Mean Subjective Scores for Coherent  
Hybrid Optical Encoder

| Mb/sec | ADM with Optical Filtering vs. ADM<br>w/o Optical Filtering (Mean Scores) |               |             |
|--------|---------------------------------------------------------------------------|---------------|-------------|
|        | Still Life                                                                | Outdoor Scene | Test Target |
| 22     | 1.0                                                                       | 1.0           | 1.0         |
| 14     | 1.9                                                                       | 1.6           | 1.8         |
| 11     | 2.3                                                                       | 2.1           | 2.0         |
| 8      | 3.7                                                                       | 4.2           | 3.9         |
| 5      | 4.5                                                                       | 4.8           | 4.6         |

Coherent interference noise was seen to effect the overall quality of the reconstructed

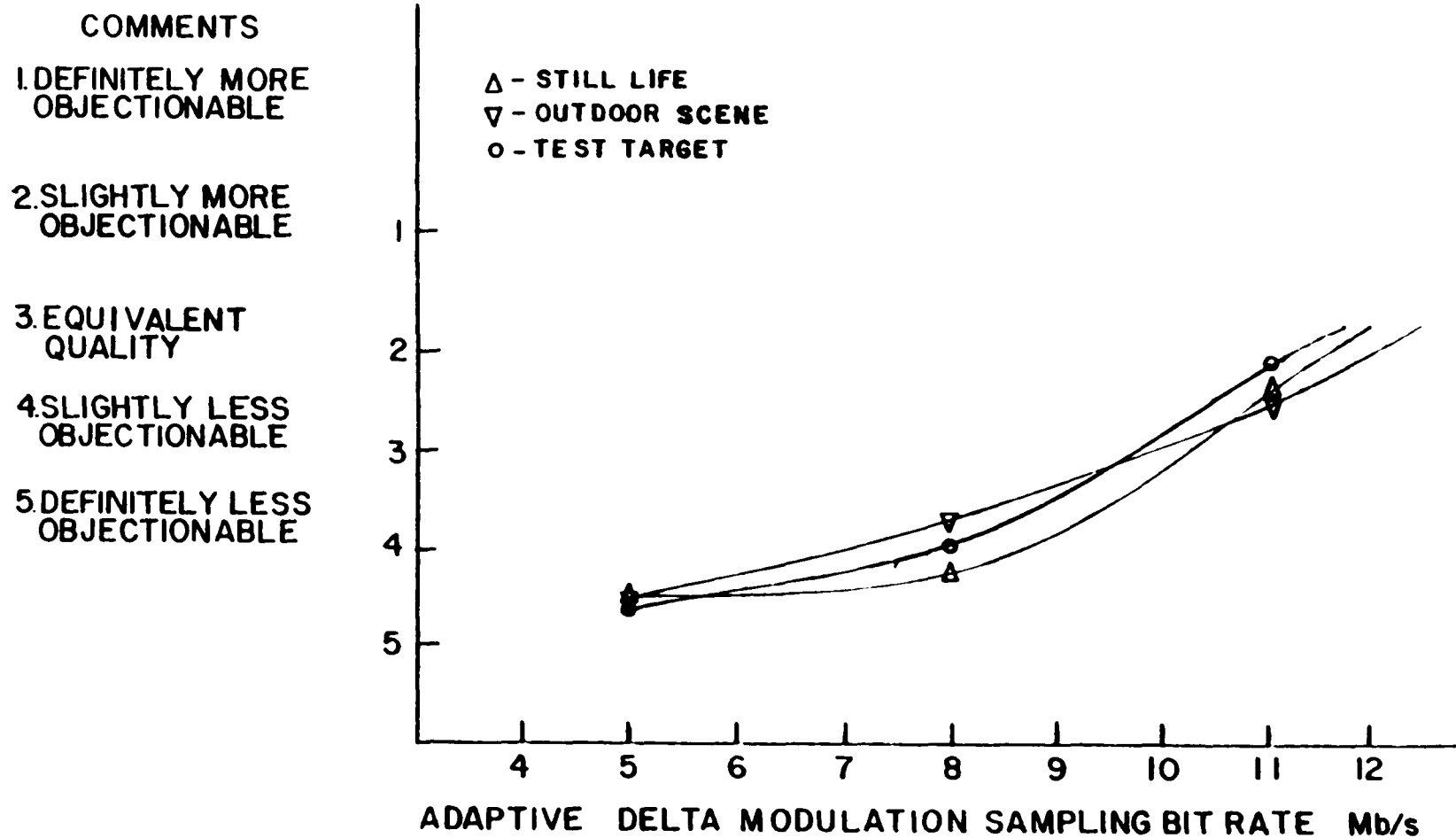


Figure 4.2-3 Subjective noise quality of ADM reconstruction with optical filtering vs. w/o optical filtering for various sampling rates for coherent illumination



image as well as dust artifacts produced by coherent diffraction from the dust on the lens surfaces.

#### 4.2-2 Other Experiments and Conclusions

The ADM sampling rates at which the optically preprocessed video reconstruction had a subjective quality judged to be better than without optical preprocessing were recorded. In addition, the rates at which an ADM reconstruction without preprocessing and the rates at which ADM reconstructions with preprocessing were judged to have equal quality were recorded.

These sampling rates that differed for reconstructions with vs. reconstructions without optical preprocessing were used to compute the effective bandwidth compression ratio [25]:

$$C = \frac{\text{Sampling rate w/o preprocessing ADM encoded}}{\text{Sampling rate with preprocessing ADM encoded}} \quad (4.2-1)$$

Table 4.2-2 shows the mean comment scores for the coherently illuminated monochrome still life input that was ADM encoded, reconstructed and displayed. The scores rate the image quality of the reconstruction with and without optical preprocessing. Fig. 4.2-4 plots the results for rates where compression is achieved.

Table 4.2-2  
Mean Subjective Quality Scores for  
Coherent Hybrid Optical Encoder

| Mbit/sec | Mean Scores for Still Life coherently<br>Illuminated with and w/o Filter |                             |
|----------|--------------------------------------------------------------------------|-----------------------------|
|          | ADM Output with<br>Filtering                                             | ADM Output w/o<br>Filtering |
| 22       | 2.5                                                                      | 1.2                         |
| 12       | 2.6                                                                      | 2.3                         |
| 11       | 2.7                                                                      | 2.9                         |
| 8        | 2.9                                                                      | 3.3                         |
| 7        | 3.1                                                                      | 3.9                         |
| 6        | 3.5                                                                      | 4.5                         |
| 5        | 4.1                                                                      | 5.0                         |

The above quality comments chosen were from a comment scale that ranged from "excellent" to "unsatisfactory" as shown below.

Comment Scale

1. Excellent
2. Good
3. Fair
4. Poor
5. Unsatisfactory.

The compressions that were achieved were a function of the scene type and sampling rate.

COMMENTS

1. EXCELLENT

2. GOOD

3. FAIR

4. POOR

5. UNSATISFACTORY

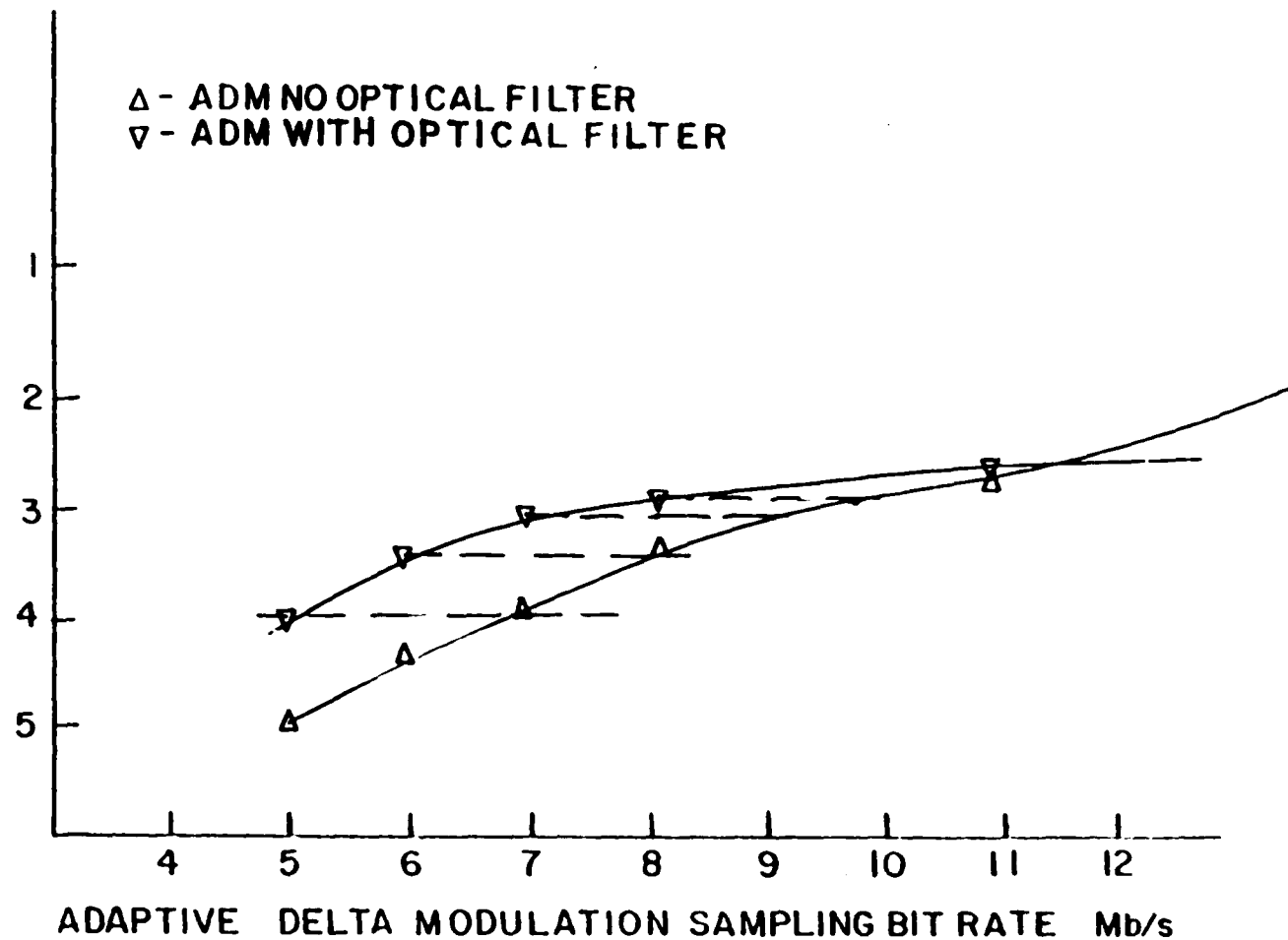


Figure 4.2-4 Mean Subjective Quality Scores for Coherent Hybrid Optical Encoder

The compression ratios ranged from  $C = 1.25$  for good to fair quality images and  $C = 1.40$  for fair to poor images.

The conclusions drawn from these results were

(1) that coherently illuminated still inputs, when ADM encoded at sampling rates that were high enough so that the edge pixel visual angle size of the error viewed by the observer was not perceivable or just perceivable but not objectionable. The observers preferred the ADM reconstruction without optical preprocessing over the ADM reconstructions with optical preprocessing.

(2) as the sampling rate was decreased below 11 Mbits/sec and depending upon the scene contrast and complexity, the edge pixel angular size viewed by the observer became definitely objectionable to extremely objectionable so that the optically preprocessed ADM reconstructions were preferred over the non-preprocessed ADM reconstructions. This is due to the visibly large edge instability.

(3) The hybrid optical-digital encoder provides for an increase in perceived quality when using sampling rates at which the encoder can no longer track the seam edge details without producing subjectively disturbing edge noise

instabilities.

Figs. 4.2-5a and b, 4.2-6a and b, 4.2-7a and b, 4.2-8a and b, and 4.2-9a and b are photographic records of the monitor at sampling rates where the image was judged upon reconstruction of the ADM encoded signal to be less noisy with optical pre-processing than without.



(a)



(b)

Fig. 4.2-5 10 Mbit/sec campus scene  
(a) without coherent preprocessing  
(b) with coherent preprocessing

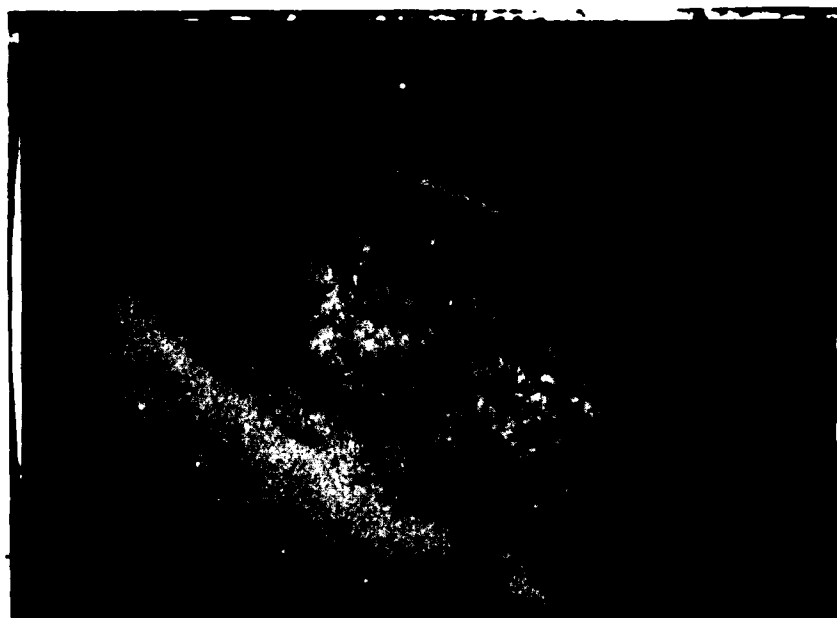


(a)



(b)

Fig. 4.2-6 8 Mbit/sec campus scene  
(a) without coherent preprocessing  
(b) with coherent preprocessing



(a)



(b)

Figg. 4.2-7 5 Mbit/sec campus scene  
(a) without coherent preprocessing  
(b) with coherent preprocessing



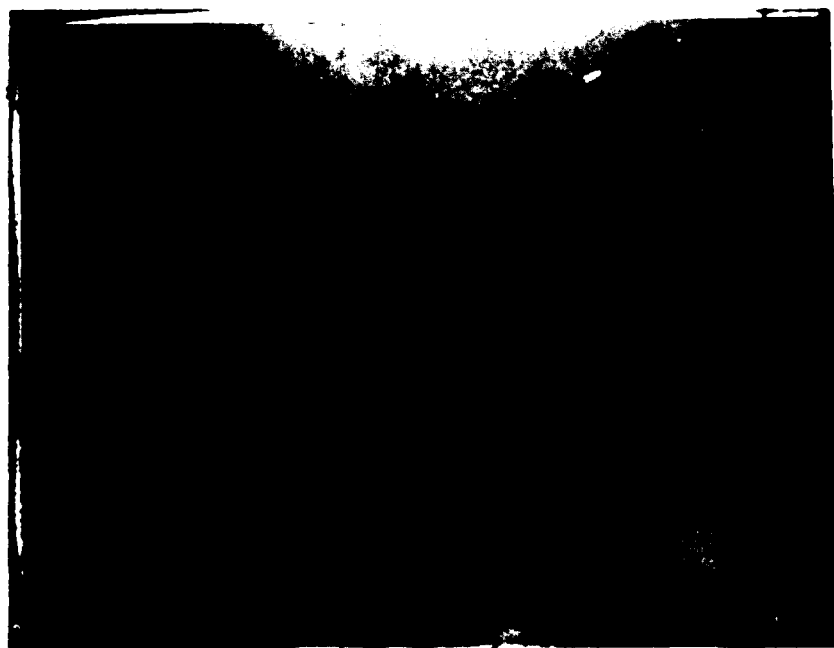


(a)



(b)

Figure 4.2-8 8 Mbit/sec still life  
(a) without coherent preprocessing  
(b) with coherent preprocessing



(a)



(b)

Figure 4.2-9 5 Mbit/sec still life  
(a) without coherent preprocessing  
(b) with coherent preprocessing

CHAPTER V  
HYBRID OPTICAL-DIGITAL ENCODER--REAL TIME  
SIMULATION

By incorporating a time sequential input stage into the front end of the optical print processor, it is possible to simulate real-time moving inputs. This, then, allows for more meaningful real-time subjective picture quality assessments of the video reconstructions produced by the hybrid source encoder under different sampling and filtering conditions.

The subjective noise reduction, due to the combined effects of optical preprocessing and the reduced sensitivity of the observer to local noise in displays with scene movement is explored.

With the potential noise advantage of this hybrid system, it is possible to lower transmitter power while still maintaining a picture that would be judged to have an equal noise content to that of the still input case.

In this chapter, three experimental implementations for sequential input hybrid optical-digital encoding are explored and the subjective video results are discussed.

#### 5.1 Film Loop Advance High Speed Stage

Fig. 5.1-1 shows the block diagram of the time sequential optical transmission system and the receiver used for display.

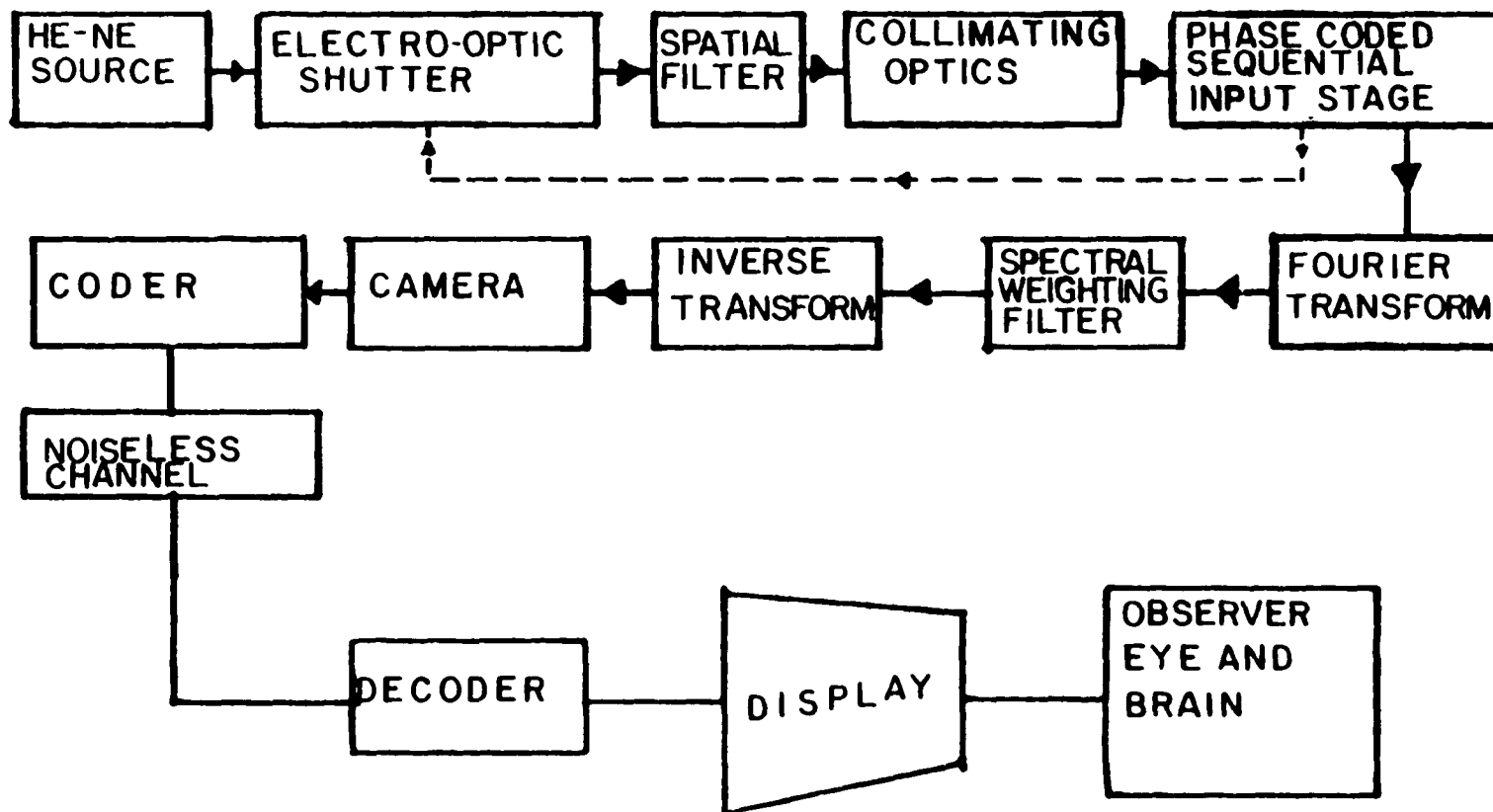


Figure 5.1-1 Block diagram of the time sequential hybrid system

A 25 mw vertically polarized He-Ne laser source is shuttered using an electro-optical modulator shown in Fig. 5.1-2a. This modulator derives its voltage pulses from a generator controlled by a cam switch in the film loop advance sequential transport stage, shown in Fig. 5.1-2b. This cam switch is activated, opening the shutter after the film has been advanced and has stopped. The electro-optic shutter consisted of an input polarizer,  $\lambda/4$  biasing plate, two tandem low voltage ADP E/O modulators, an output  $\lambda/4$  biasing plate and an output polarizer that served as an analyzer for the modulated beam. This system gave a modulation depth of .99.

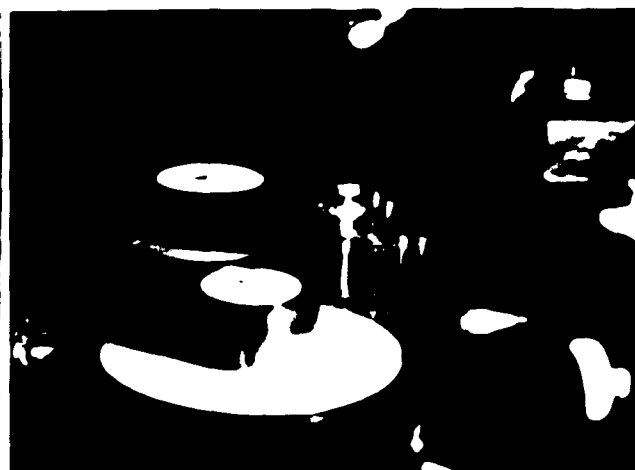
The modulated beam was then spatially filtered and collimated. The shutter controlled collimated beam illuminated a phase encoded input film that was held in the 35mm loop advanced transport stage placed in the input plane of the transform system.

In order to minimize mechanical vibrations that produced a position jitter in the frame to frame reconstructed video image, both the laser and transport were mounted on rubber dampened isolation stages shown in Figs. 5.1-3a and b.

The diffracted spectra from each phase encoded 35mm frame is then transformed. In the transform domain the spectra are filtered and then retransformed. The retransformed image is then focused on to the vidicon face



(a)



(b)

Figure 5.1-2 Electro-optical modulator shutter (a)  
and film loop advance sequential transport (b)



(a)



(b)

Figure 5.1-3 Vibrational damping stages  
(a) for laser  
(b) for transport

of the camera. The video signal is input in the video ADM encoder and transmitted over a noiseless channel consisting of a 75 Ohm shielded coaxial cable. The signal is then input into the ADM decoder, reconstructed and displayed on a video monitor. The subjective quality of the image is then judged.

Though great care was taken to minimize the frame-to-frame position vibrations, by isolation mounting and reducing the play in the gears of the film loop sequential transport this jitter of the horizontal position frame-to-frame was clearly the limiting factor of image quality. In all cases, the observer's attention was drawn to this artifact which made meaningful quality assessments for real time simulation impossible.

In order to correct this problem, another system was constructed. In the next section we describe this improved system.

## 5.2 Pin Registered Sequential Input Stage

A 16mm pin registered projector was purchased and modified so that the encoded input could be transilluminated with a collimated coherent beam. The projector lenses were removed and a mechanically dampened vibration isolation mount was constructed for the projector. This is shown in Fig. 5.2-1. In addition, the laser was removed from the optical table and placed on a separate vibration



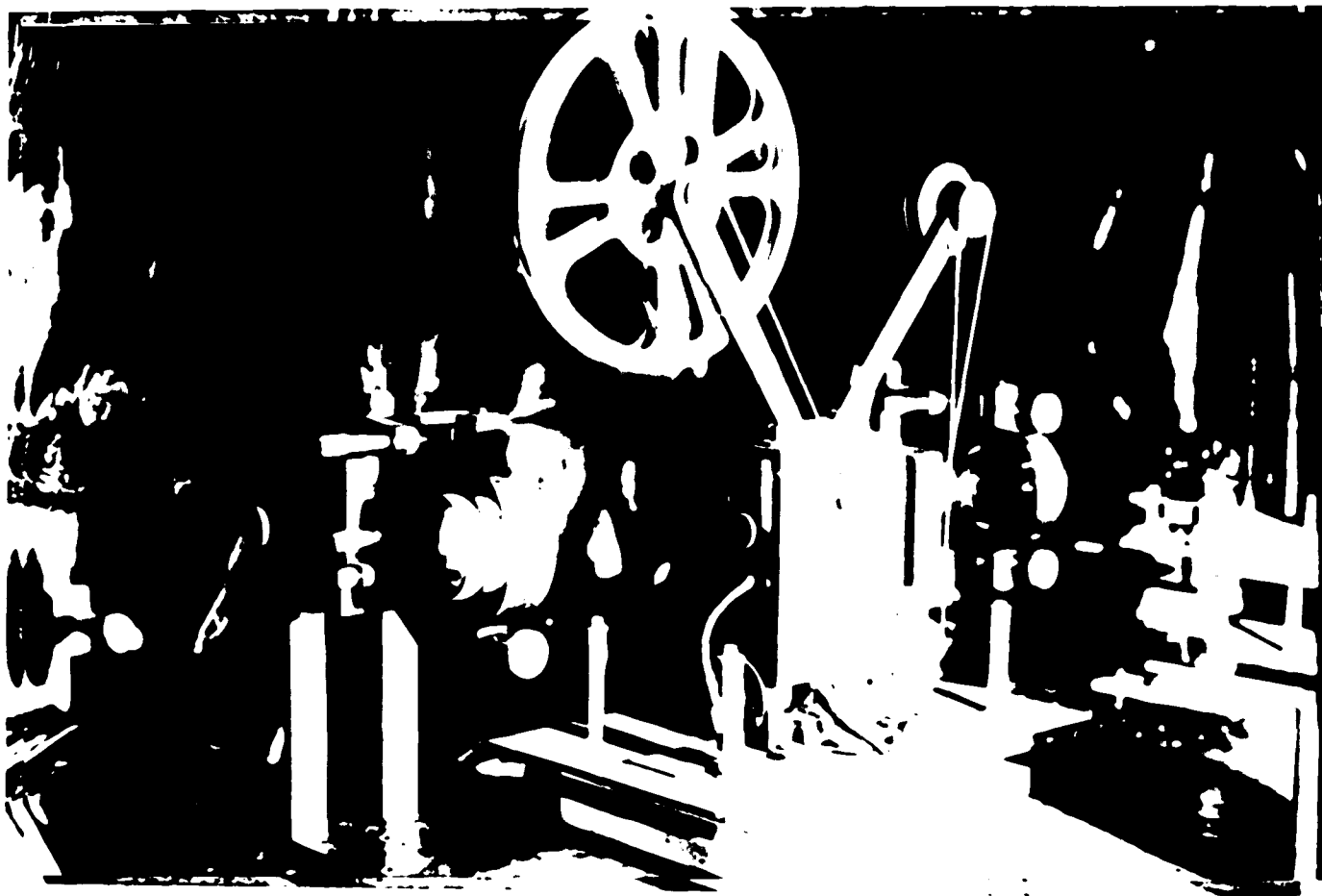


Figure 5.2-1 16mm pin registered modified and vibration isolated projector for coherent system

isolated stage. This was done in order to decouple the motor vibration of the transport stage. In this system, we choose to shutter the light using the spinning disk that was internal to the 16mm transport stage. This disk allowed the collimated light to transilluminate the phase encoded input frame when the pin register transport had completed advancing the frame and the film was stationary.

Input for the 16mm transport was produced in the lab by filming a still 16mm television resolution target and phase encoding the film by chemical reversal processing. Using this kind of input we were able to check the resolution of the system and determine the stability of the new transport arrangement by viewing the subjective quality of the reconstructed video image of the target.

This system improved the stability of the image and produced a pleasing reconstruction free of subjectively detectable jitter. Using this system the reconstructed noise, due to the encoder produced at low sampling rate, and the coherent artifact noise, caused by interference at the vidicon face plate and dust on the optics, became the two major sources of image degradation.

Fig. 5.2-2a shows a photograph taken from the optical image displayed on the monitor of the sequential input of a TV test target without ADM encoding or optical filtering. This photograph was made with a 35mm single



(a)



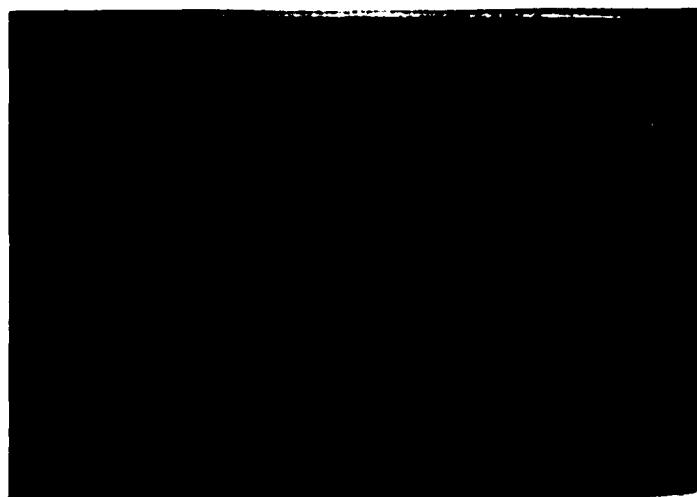
(b)

Figure 5.2-2 Monitor display of sequential input system  
using TV test target, no optical filtering,  
no ADM coding  
(a) Visible coherent artifacts  
(b) Illumination adjusted output

reflex shutter so that the diagonal dark line is an artifact of the photographic process and did not appear in the subjectively viewed image.

Coherent illumination produced a circular set of interference fringes and highly visible coherent dust noise. Both of these degradations added to decrease image quality. Some degree of improvement of this type of noise was made by increasing the level of input illumination in order to wash out the coherent noise artifacts. Those still visible to some extent, Fig. 5.2-2b shows how this compensation is accompanied by a loss of contrast in the image. We determined that these problems were natural constraints of the coherent imaging system and attempted to determine the relative degree of subjective degradation due to each noise component. Figs. 5.2-3a and b and Figs. 5.2-4a and b are photographs of the decoded sequential output at 5 Mbit/sec and 8 Mbit/sec. with and without optical filtering respectively.

The reader is again cautioned against using these slow photographs as a substitute for viewing the actual kinescope display since for system evaluation the time dependent component of the encoder noise is absent and the photographic reproduction process of these stills effects their subjective quality. Table 5.2-1 gives the subjective noise content responses viewed under the same conditions as the still input scenes.



(a)

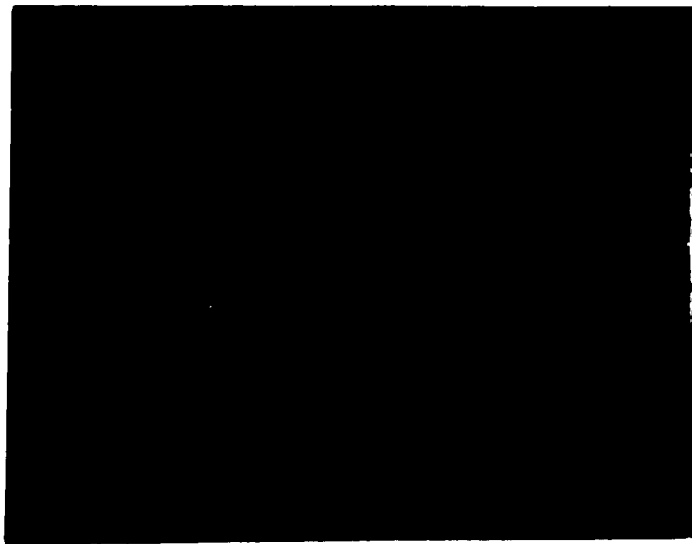


(b)

Figure 5.2-3 Decoded monitor display of coherently preprocessed sequential output at 5 Mbit/sec  
(a) without optical preprocessing  
(b) with optical preprocessing



(a)



(b)

Figure 5.2- 4 Decoded monitor display of coherently pre-processed sequential output at 8 Mbit/sec  
(a) without optical preprocessing  
(b) with optical preprocessing

Table 5.2-1  
 Subjective Picture Quality Comments on Noise  
 Content in Sequential Input-Real Time  
 Simulation - Coherent Illumination

| Mbit/sec. | ADM No Optical<br>Filtering   | ADM with Optical<br>Filtering |
|-----------|-------------------------------|-------------------------------|
| 22        | Clear                         | Less Sharp                    |
| 15        | Sharper but<br>more noisy     | Less Sharp<br>but Less Noisy  |
| 8         | Very noisy<br>Less Resolution | Less Noisy<br>Same Resolution |
| 6         | Extremely Noisy               | Much Less Noisy               |

We did not run mean score ratings on the image since we had determined it was extremely difficult to separate the effects of encoded noise from coherent noise. Instead, we devised a system to eliminate the coherent noise artifacts completely. In the next section we discuss the implementation of a partially coherent polychromatic hybrid optical-digital encoder.

### 5.3 Partially Coherent Polychromatic Hybrid Optical Digital Encoder

The coherent noise artifacts introduced by the coherent optical preprocessing produced unwanted effects in the reconstructed image and posed a significant problem in

determining the quality that was potentially possible with the hybrid encoder.

In this section we describe experiments which led to the construction of a partially coherent reflective transform architecture which solved several problems of coherent noise in the video image.

### 5.3-1 Coherent Noise Reduction

Coherent noise produced by interference of temporally coherent point sources of light may be reduced by increasing the source size so that less correlation exists between various points across the image. This type of source is termed partially coherent since, as was shown by Hopkins [158] both, totally coherent and totally incoherent models of light correlation are non-physically realizable and are only convenient idealizations.

Considine [141] showed that the effects of coherent illumination included edge ringing, shifting, speckling, and interference artifacts.

Leith and Roth [142] suggested the use of partially coherent systems because of their reduced noise advantage over laser sources.

In order to see whether a partially coherent system could reduce noise and still allow for the needed spatial spectral weighting of the phase encoded images, an experimental partially coherent



designed.

### 5.3-2 Partially Spatially Coherent Polychromatic Optical Preprocessor

The first source that was used to produce partially coherent light was a 150-Watt Hanovia-Canard Mercury-Xenon arc lamp. Although a rotating defuser could have been used in the illuminating beam of the coherent monochromatic system, the arc lamp was chosen due to its availability and its potential for being used with color input. The luminance distribution and normalized output vs. wavelength for this lamp are shown in Figs. 5.3-1 and 5.3-2, respectively.

The spatial transform of this extended source was too large to have the partial coherence necessary to produce the image biased difference across the transform dimension for the phase encoded input gradients. In order to correct this, the constant central area of the source distribution was imaged onto a 370  $\mu\text{m}$  pinhole that limited the spatial extent of the source and thus its conjugate image in the transform domain. Figs. 5.3-3 and 5.3-4 compare the coherent He-Ne spatial Fourier transform photographed on Kodak Fine Grain Positive #5302 emulsion to the point spread function of the broadband spatially filtered point source.

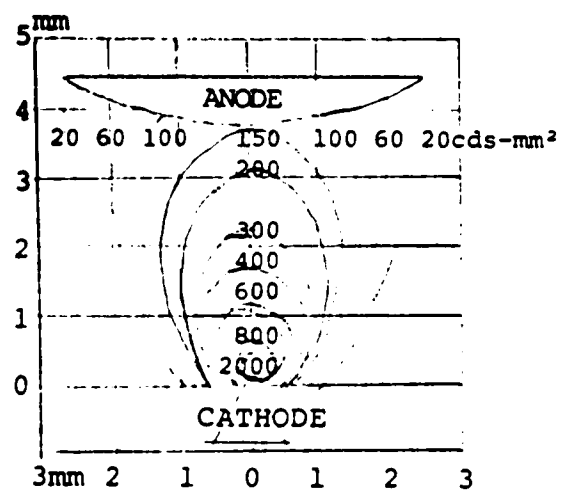


Figure 5.3-1 Luminance distribution in arc of typical compact arc lamp at 100 Amps

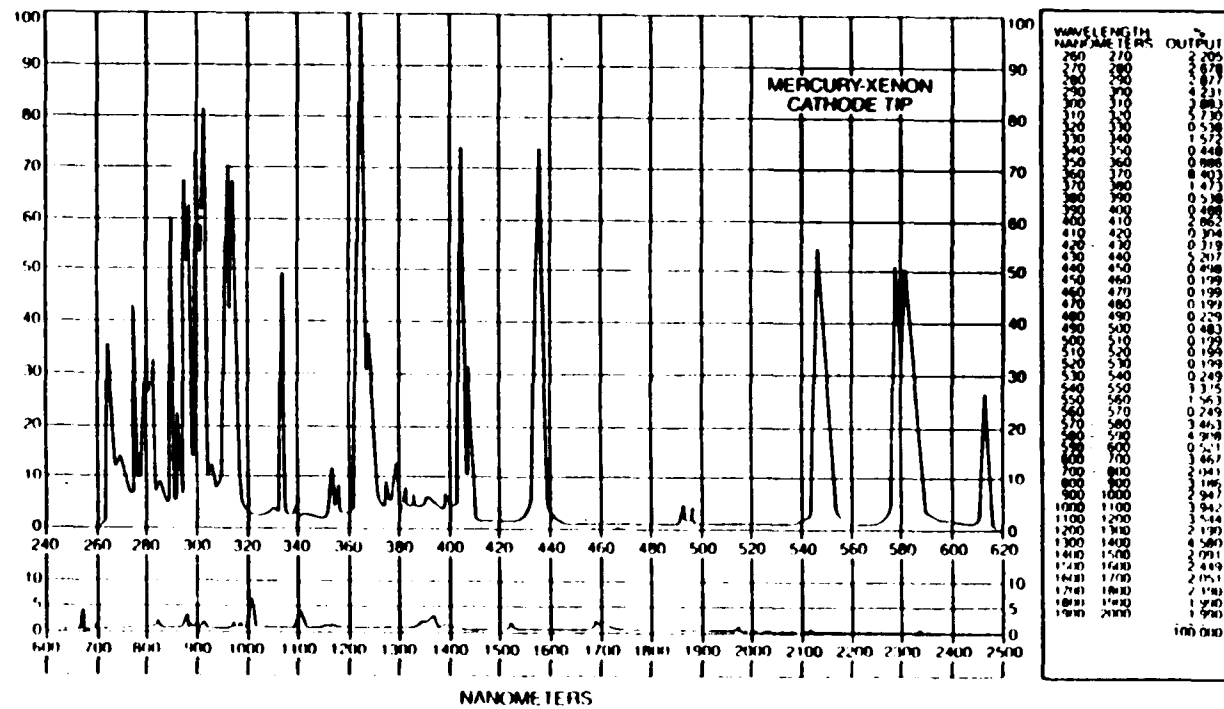


Figure 5.3-2 Spectral emission for Mercury/Xenon compact arc lamps

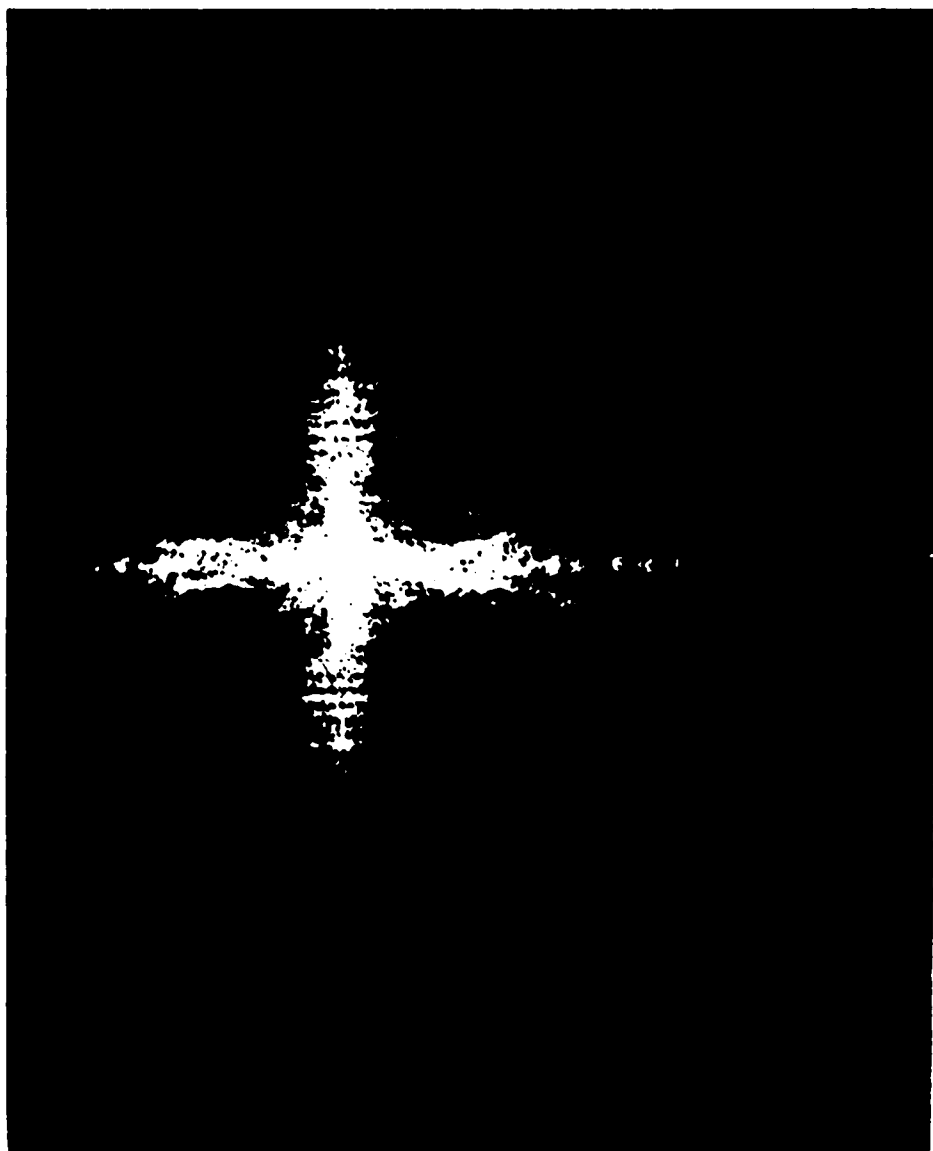


Fig. 5.3-3 Coherent He-Ne Spatial Fourier Transform

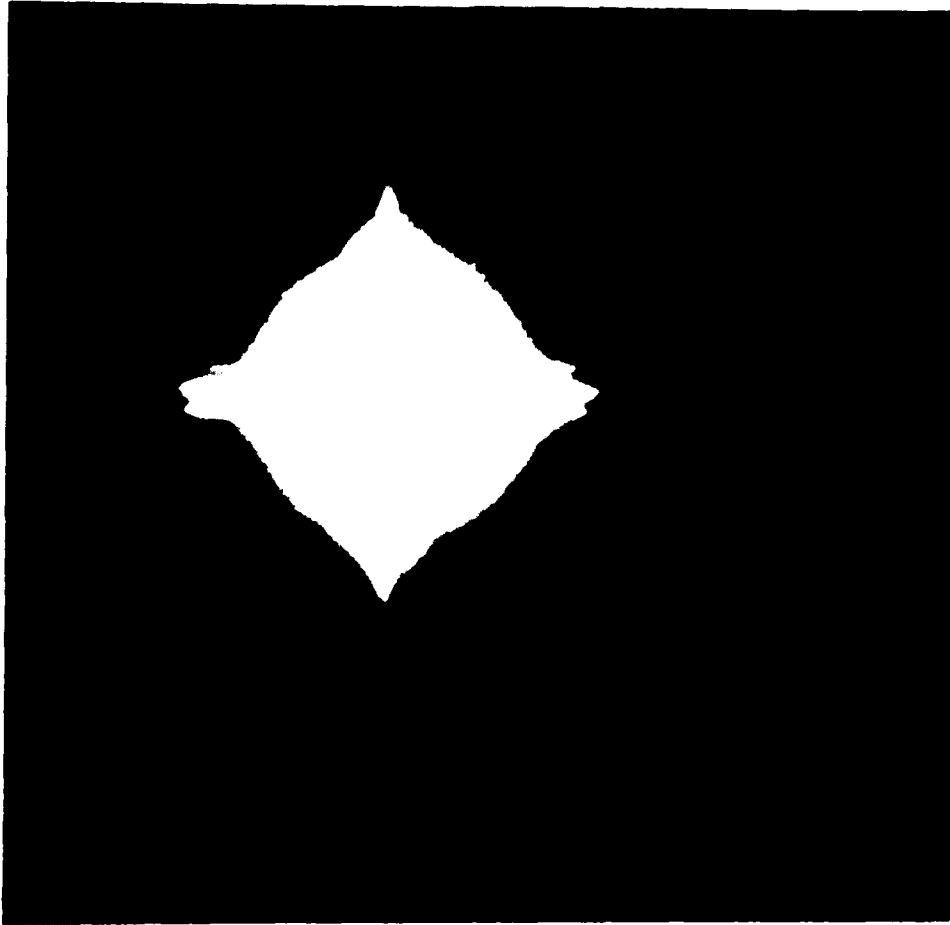


Figure 5.3-4 Point spread function of the broadband spatially filtered point source

5.3-3 Partially Spatially Coherent Processing of  
Still Monochrome Inputs for Hybrid Encoder  
Noise Reduction

Using the same transmission lens transform arrangement as was used for the coherent preprocessor, we compare the subjective quality of the ADM encoded reconstructed using the spatially filtered collimated partially coherent polychromatic light source. Fig. 5.3-5a and b are photographs taken from a video monitor showing the reconstructed output of the hybrid processor with coherent illumination and partially coherent illumination, respectively both with optical preprocessing filtering and encoded at a sampling rate of 15 Mb/sec. There is clearly an improvement in the quality of the reconstruction of the partially coherent illuminated system due to the absence of coherent edge ringing on high contrast transitions, large dust artifacts, and vidicon face plate interference fringes.

All observers prefer viewing the output produced by the partially coherent preprocessed image over the coherent preprocessed image.

To determine the effect of partially coherent illumination on the reconstructed output of continuous tone scenes rather than just binary level test targets, we produced a simulated tactical scene and

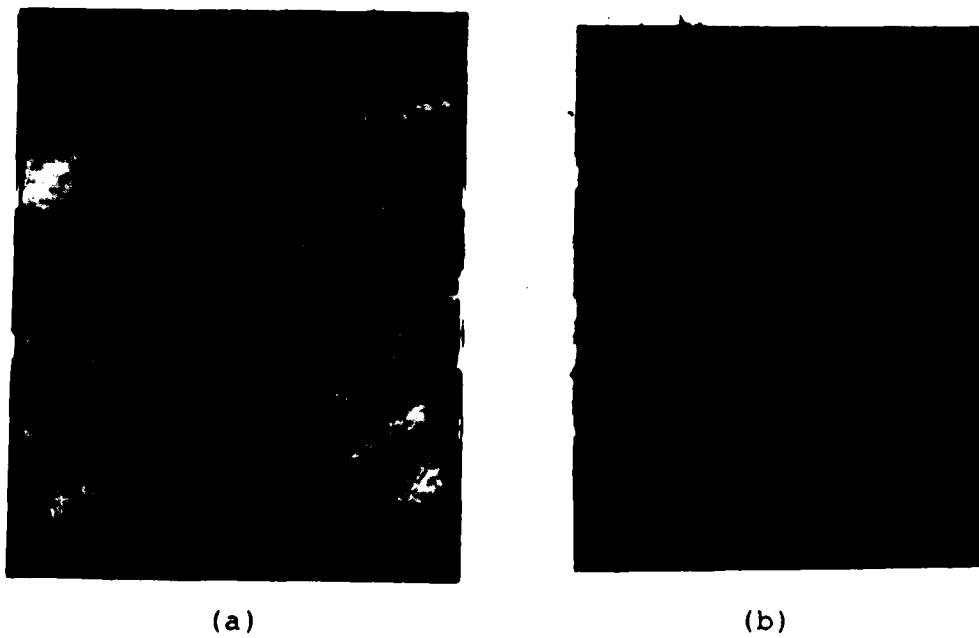


Fig. 5.3-5 Monitor output without optical filtering.  
ADM encoding at 15 Mbit/sec  
(a) coherent illumination  
(b) partially coherent illumination

photographed it. The film used was Panatomic X because of its ability to reproduce continuous tones. After exposure, the latent image was chemically processed using the reversal procedure previously outlined. This produced a phase-encoded positive input transparency of our mockup tactical scene. Figs. 5.3-6a and b show photographs of the unobstructed output taken from the monitor without optical filtering or ADM encoding. Fig. 5.3-6a is with coherent illumination and Fig. 5.3-6b is with partially coherent illumination. It was observed that in the partially coherent case although no edge ringing or large interference fringes were present in the coherent case, there were still some small dust artifacts from the lens surfaces. This is due to the fact that the spatially filtered arc source maintained a certain small but finite degree of spatial coherence.

In the next section we describe a reflective transform architecture that was configured to reduce the number of surfaces that the light needed to encounter during the optical preprocessing. This was done so that the remaining dust noise was minimized in addition to reducing the size and volume requirement of the optical preprocessor. We also compared the resolution of this reflective transform arrangement for the coherent and partially coherent cases.





(a)



(b)

Figure 5.3-6 ADM video reconstruction of sequential input. Tactical Scene. No optical filtering. No ADM encoding.  
(a) coherent illumination  
(b) partially coherent illumination

#### 5.3-4 Reflective Transform Architecture

The standard arrangement used to perform optical transform data processing discussed in the major textbooks covering this topic [124,145] is the transmissive lens architecture. In this architecture a pair of **refractive** transform lenses produces the **forward and inverse** transforms of the input data. In **this section**, experimental results show that it is **possible** and an advantage to use reflective optics, i.e. mirrors, to accomplish the forward transform and inward transform operations. Furthermore, since the first surface reflective optics introduce no chromatic aberrations, polychromatic partially coherent processing becomes feasible without the need to resort to expensive chromatically corrected refractive optics.

The surface noise problem due to dust on the refractive lens surfaces, of which there are four independent dust distributions, is reduced to two independent dust distributions in the reflective transform architecture. This is because the entrance and exit planes on each refractive optic are one and the same surface.

The reflective optical architecture has other advantages over its refractive counterpart.

The partially coherent polychromatic data

preprocessor using the reflective transform architecture becomes lightweight and dimensionally stable. This means that it does not require continuous readjustment due to the two independent transforming surfaces.

It is a well known property of a paraboloidal reflector that geometrical rays entering parallel to its optical axis are reflected from the mirror paraboloidal surface and focused to the same point. From a geometrical optical point of view, the small central arc of the paraboloidal mirror in essence acts as a thin-lens operator. This operator reflects light to a focus rather than refracting light to a focus. From a physical optics point of view [146-148] the spectra of a field diverging from the focal plane of a paraboloidal reflector will be re-imaged in the focal plane as the spatial Fourier transform of the object producing the spectra distribution. Similarly, if a plane first surface mirror is placed on the optical axis in the plane where the Fourier distribution is focused to, then the reflected field from a plane mirror, having a surface normal colinear with the axis of revolution of the paraboloid, will be reflected back to the paraboloidal mirror. Upon reflection and at a distance from the mirror plane, the distribution represents the optical

inverse transform.

To separate the input and output images in the focal plane of this system, it is necessary to place the input object distribution off the optical axis as shown in Fig. 5.3-7. Off-axis sources for paraboloidal reflectors are standard in the microwave antenna field and in large area telescopes [149-150].

The object and the transform plane can also be separated by an arrangement that uses secondary reflectors. The object distribution of spatial frequencies may then be filtered either in a reflected or a transmissive mode. See Figs. 5.3-7 and 5.3-8. In the reflective mode of filtering the desired spatial frequencies are reimaged through the use of a first-surface plane mirror with the appropriate absorbing filter profile distributed across the reflecting surface. These weighted spectra are reflected back to the primary parabolic reflector to a position symmetrically displaced from the axis. The filtered image then appears at a distance  $f$  from the mirror symmetrical to the input position. In the transmissive mode, two off-axis paraboloidal mirrors are placed to the right and left of their respective focal planes to form the optical filtering system seen in Fig. 5.3-8.

Compactness, cost, and ease of alignment favor

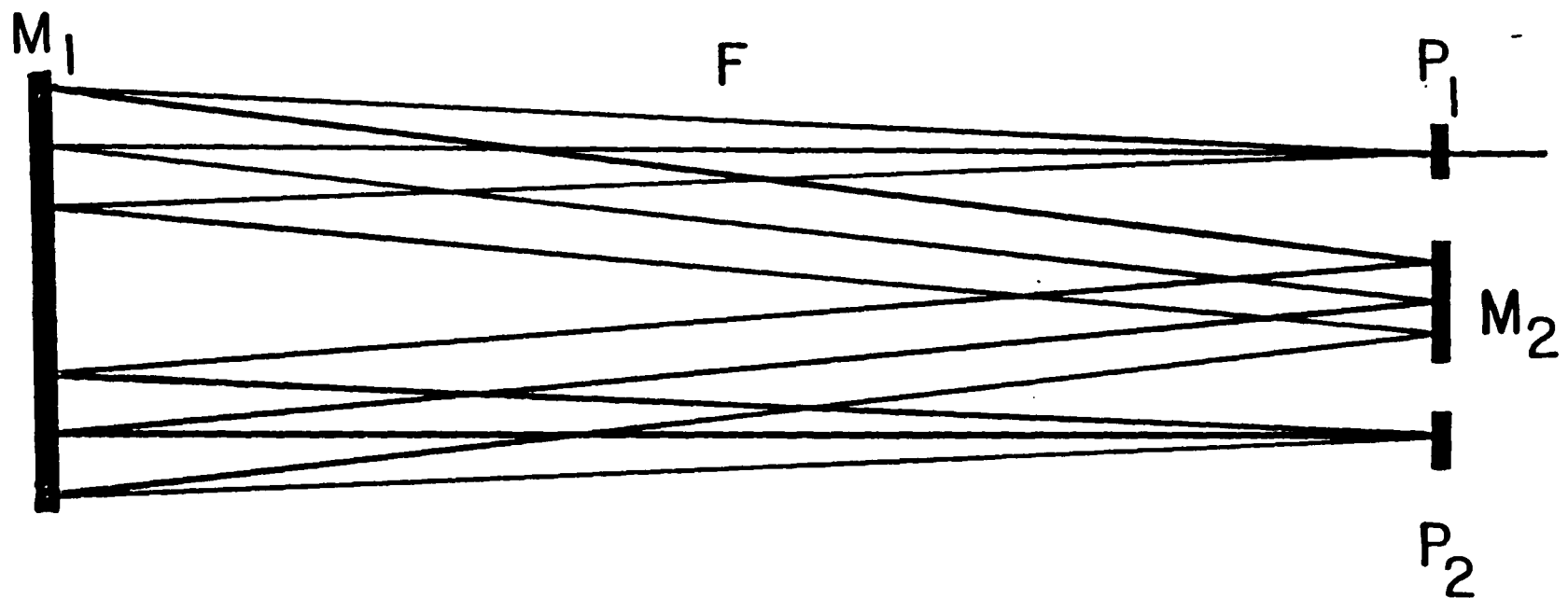


Figure 5.3-7 Reflective transform processor, folded mirror or reflective filter mode

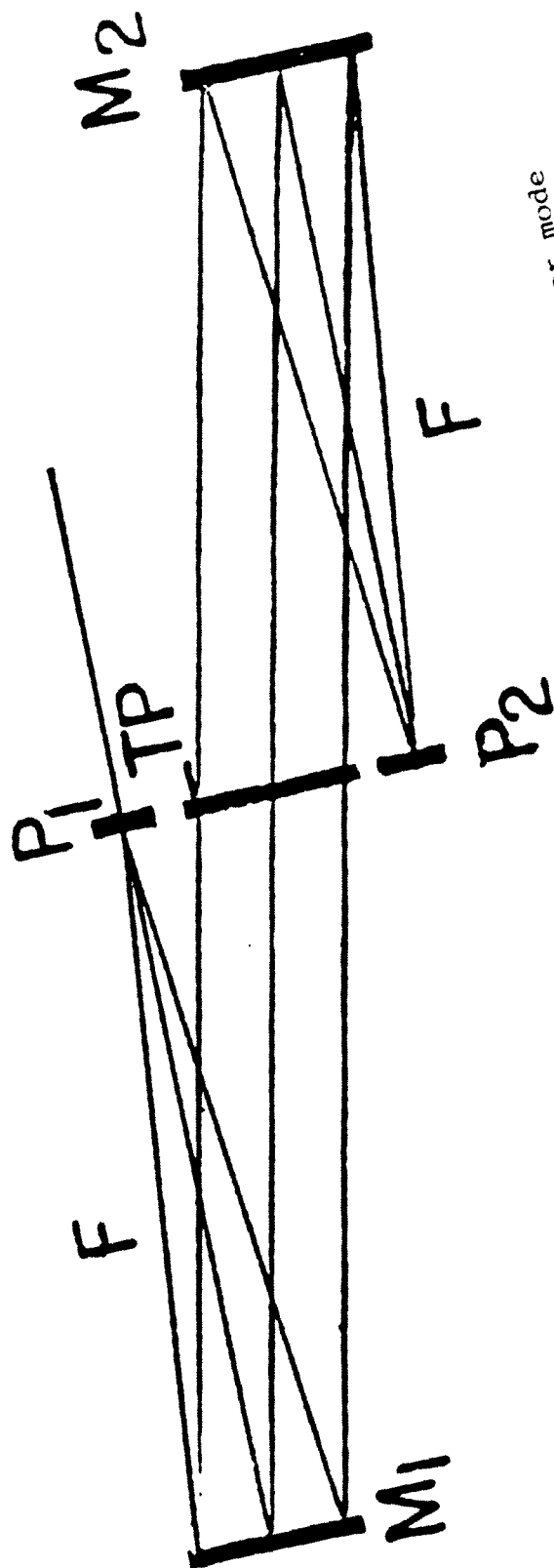


Figure 5.3-8 Reflective transform processor transmissive filter mode

the reflective transform plane arrangement and, indeed, this was the system used to perform the experiments.

For other coherent transform processing applications, such as matched filtering, the transmissive filter plane system might be favored due to input-output constraints on the physical system. Even in this application the reflective transform arrangement could be used with possibly higher diffraction efficiency if a blazed phase hologram replaced at the transform domain as a matching filter were used. This is due to the higher efficiency of this metal-coated reflection hologram [150].

Initial testing of this architecture was conducted after constructing the reflective transform system described below.

A paraboloidal mirror with diameter  $D = 7.6\text{cm}$ , and focal length  $f = 47\text{cm}$  was used. The ratio of the focal length/diameter  $= f/D$ , and is called the  $f$  number. For this system a large  $f$  number allows for paraxial ( $>15^\circ$  diffraction angles) operation which is ample for the low spatial frequency image content of the various input objects.

The illumination for the coherent system was a collimated He-Ne  $.63\text{ }\mu\text{m}$ ,  $.5\text{ mw}$ , randomly polarized laser beam. For the partially coherent illumination

system we used a broadband Hg-Xe 150 Watt (Hanovia Canard #901C) spatially filtered arc source.

To test the system for both the coherent and partially spatially coherent illumination, a USAF 1951 resolution transparency was used as the input object. The intensity of the collimated input light which was measured after apodization (so that the energy across this input area would be sensed) was found to be  $6.25\mu\text{w}$  at the input plane and  $4.2\mu\text{w}$  at the output plane. The inputs for both coherent and partially spatially coherent illumination were adjusted by attenuation, to produce the same readings.

Fig. 5.3-9a is a photographic image of the coherently illuminated test target taken at the output of the reflective transform system. The resolution of the coherently illuminated system had an output that was measured to be 37 lp/mm. Fig. 5.3-9b is a photographic image of the partially spatially coherent illuminated test target taken at the output of the same reflective transform system. The retransformed image of this broadband source case was measured to have a resolution of 45 lp/mm. This represented better resolution than could be obtained by the lens transform system of the same cost. The cost of a corrected refractive system was determined



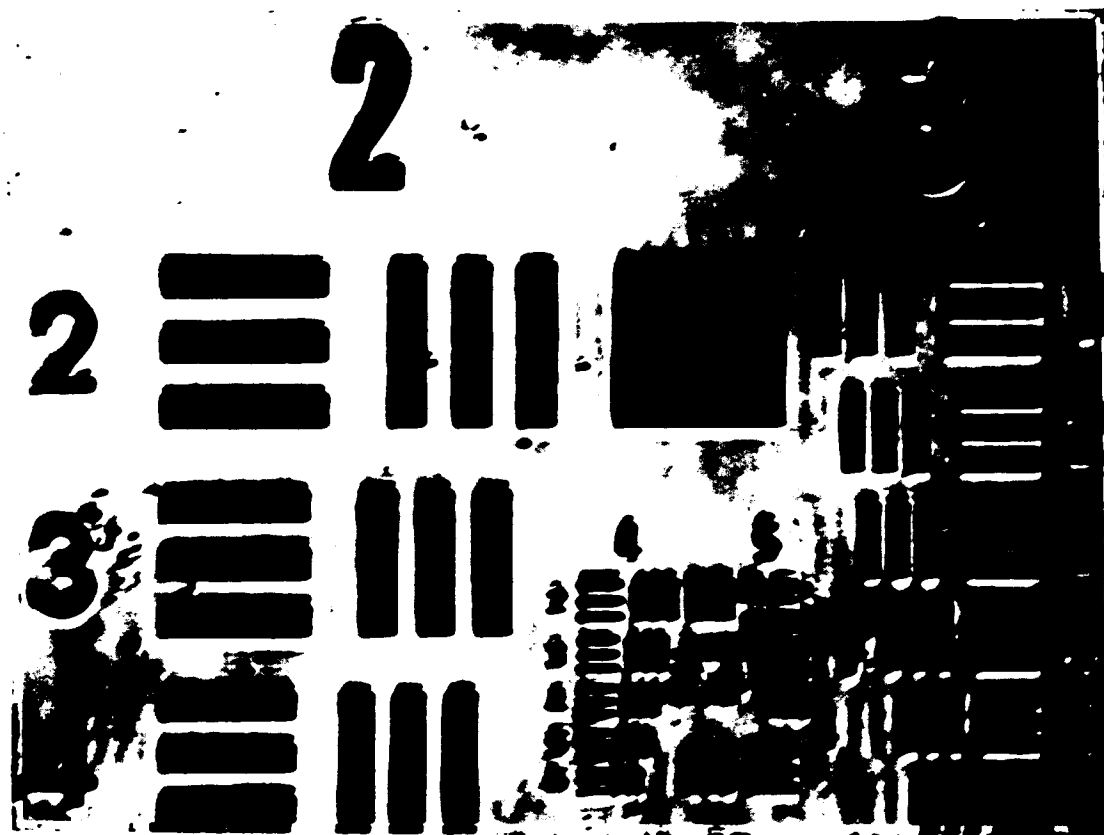


Figure 5.3-9a Photograph of reflective transform processor output plane  
coherent target illumination



Figure 5.3-9b Photograph of reflective transform processor output plane  
partially coherent target illumination

to be over ten times as expensive to construct.

The partially coherent illuminated image was seen to be free of dust noise and has good contrast.

In order to test the filtering properties of both cases of illumination, a simple wedge shaped first surface mirror replaced the all-pass mirror so as to serve as a preferential reflective binary filter. The filtering was accomplished by adjusting the mirror's vertical position so that only the upper sideband of the vertically diffracted spatial frequencies were passed. Fig. 5.3-10 is a simplified diagram of the test reflective transform filtering system. Figs. 5.3-11 and 5.3-12 are photographs of the output of the reflective filtering system when the mirror position only allows the high spatial frequencies to pass. Fig. 5.3-11 shows the edge enhanced output image for the coherently illuminated case and Fig. 5.3-12 is the output for the partially spatially coherent polychromatic broadband case. It was noted that the partially coherent system had the ability to perform spatial filtering operations on the transformed or pointspread function and produce the desired modification system with greater clarity. In addition, the telecentric single mounting alignment of 1 mirror for the forward and inverse transform optic allowed for a more

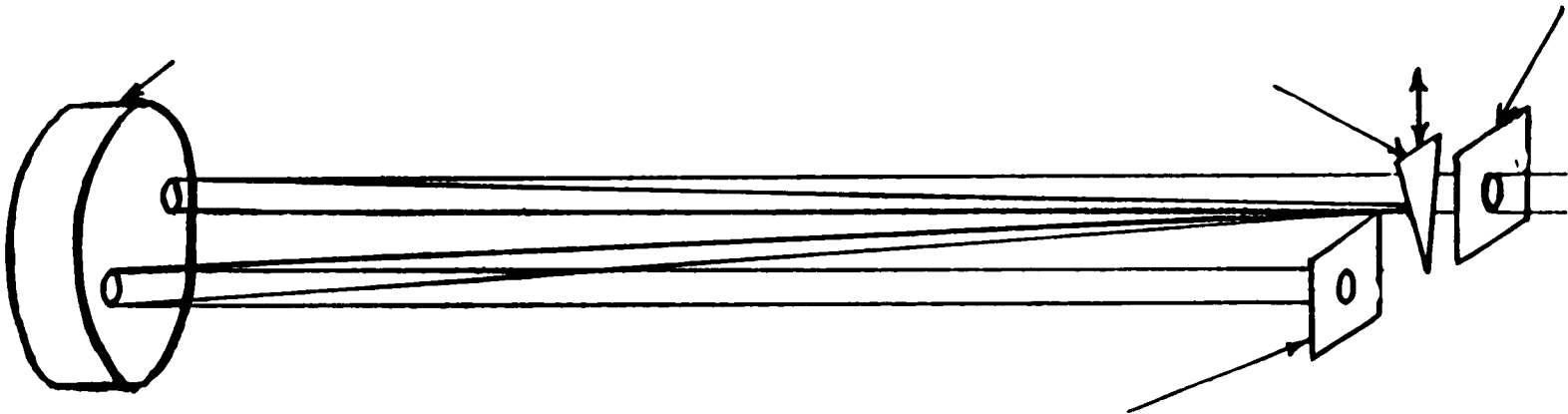


Figure 5.3-10 Simplified diagram of test reflective transform filtering system

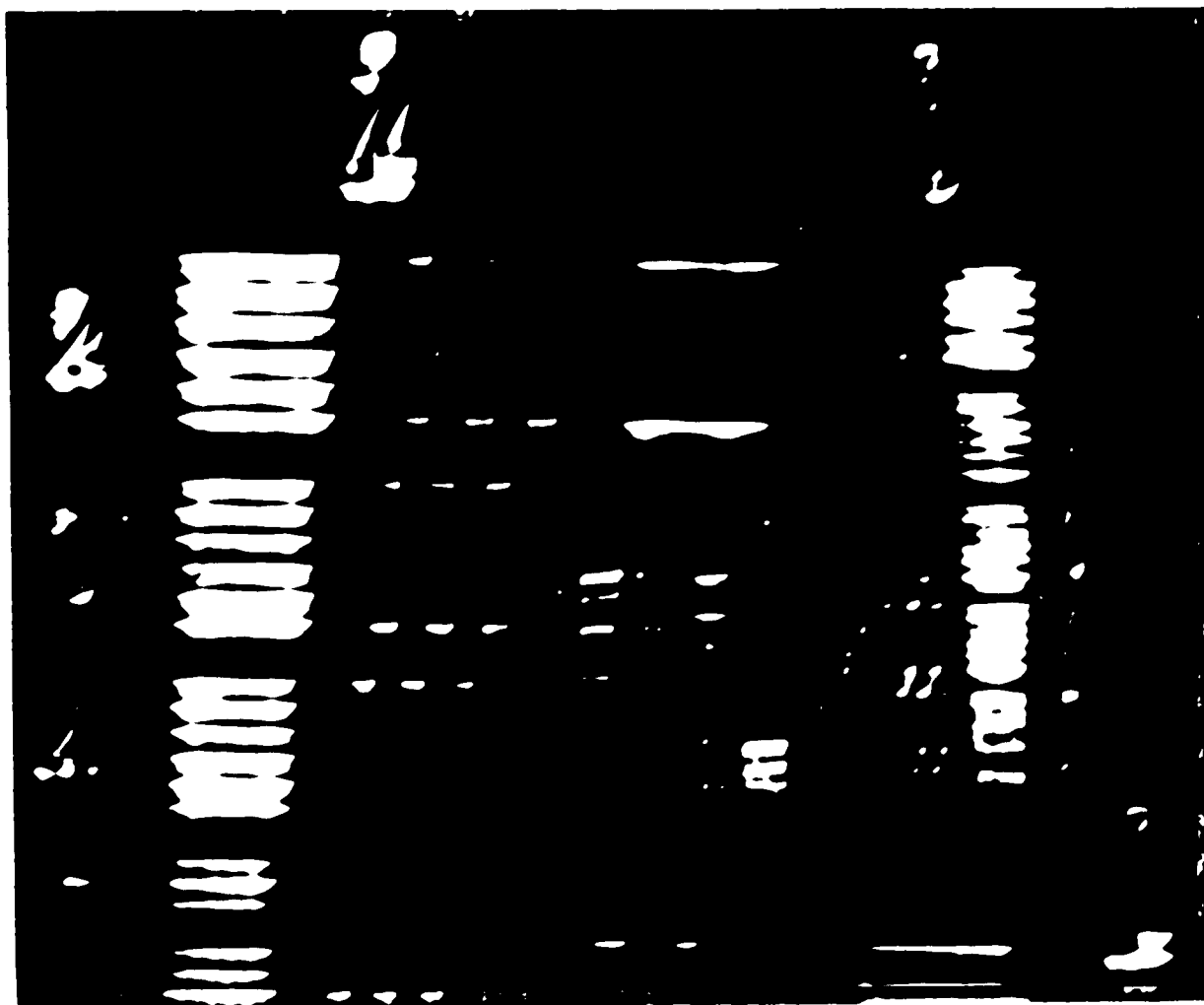


Figure 5.3-11 Edge enhanced output--vertical high pass, coherent case

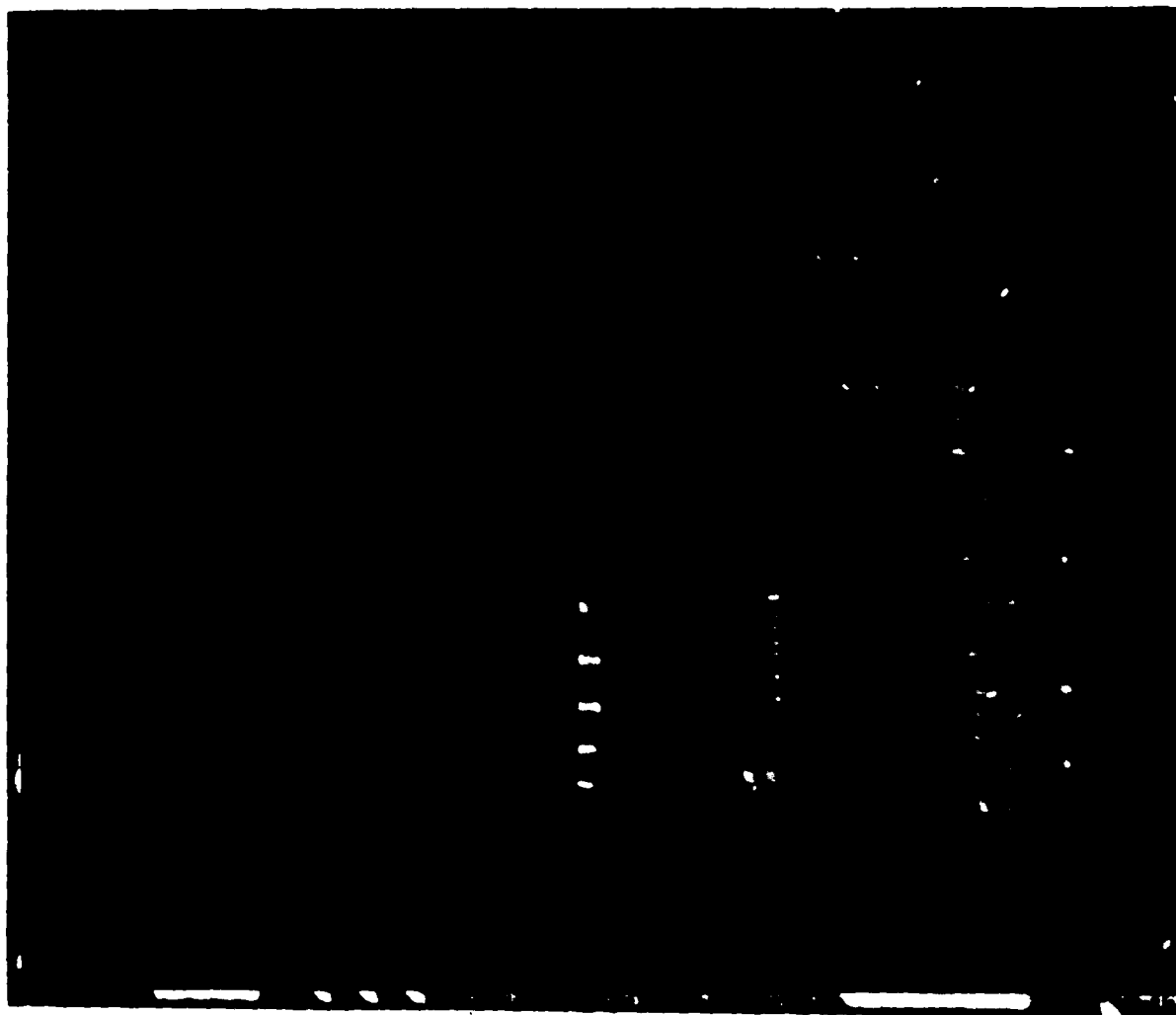


Figure 5.3-12 Edge enhanced output--vertical high pass, partially coherent case

vibrationally stable system.

The outcome of the series of experiments then led to the construction of a sequential monochrome input partially spatially coherent, polychromatic preprocessing system.

#### 5.4 Time Sequential Monochrome Input Partially Coherent

##### Polychromatic Hybrid Optical-Digital Encoder

The 16mm vibration isolated transport of the previous section was mounted so that the film plane, Gimbal mounted reflective transform filter and vidicon camera were coplanar as shown in Fig. 5.4-1. The same arc source was used in the sequential system. The diameter of the collimating optics in this system and reflective transform optics were made twice as large as the experimental system. This allowed there to be a larger separation between the input and output positions transverse to the optical axis. A 6" paraboloidal mirror with a 48" focal length  $f/8$  was used as the transform and inverse transform optic. A 6" astronomical lens  $f = 36"$  was employed as a collimating lens for the input illumination. The 16mm input plane of the film transport received a more isoplanic (constant) input irradiance due to the smaller angular size of the 16" frame and the smaller angular source subtendence produced by the larger collimating lens. Figs. 5.4-2 and 5.4-3 show the reconstructed video output of the reflective transform hybrid encoder for the coherent and partially



Figure 5.4-1 Time sequential reflective transform preprocessor





Figure 5.4-2 Sequential reflective system, coherent case

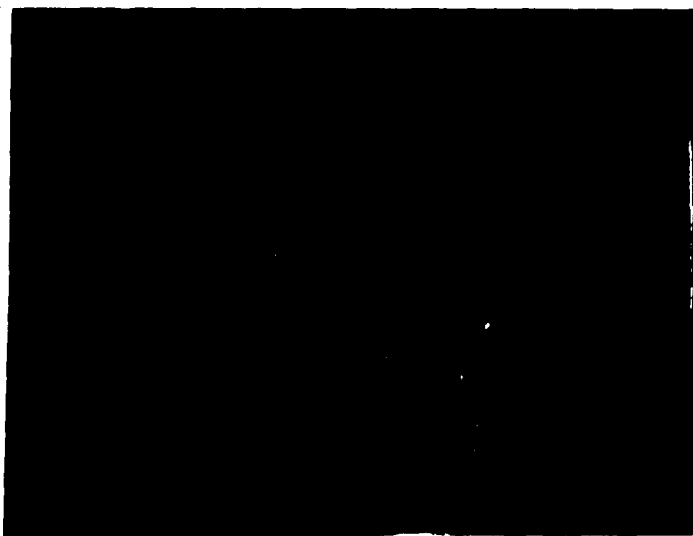


Figure 5.4-3 Sequential reflective system partially coherent case

spatially coherent broadband sources, respectively.

The input to both of these systems was a time sequential real time image of a TV test target. It was noted that in the partially coherent phase the output is free of all coherent artifacts.

Subjective results for real-time simulation of a hybrid optical-digital ADM encoded image system with time sequential phase-coded input was given in Table 5.4-1 for encoding with and without optical preprocessing and plotted in Fig. 5.4-4.

Table 5.4-1  
Time Sequential Partially Coherent Polychromatic  
Hybrid Encoder

| Mbit/sec. | ADM with Optical Preprocessing vs. ADM<br>without Optical Preprocessing (mean Scores) |                                                                |                                                   |
|-----------|---------------------------------------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------------|
|           | 16mm B&W Test<br>Target Film<br>(Still)                                               | 16mm B&W Indus-<br>trial Training<br>Film<br>(Moderate Motion) | 16mm B&W Simu-<br>lated Tact.Sc.<br>(Slow Motion) |
| 22        | 1.0                                                                                   | 1.0                                                            | 1.0                                               |
| 14        | 1.0                                                                                   | 1.0                                                            | 1.0                                               |
| 11        | 1.7                                                                                   | 2.5                                                            | 1.9                                               |
| 8         | 3.1                                                                                   | 3.9                                                            | 3.2                                               |
| 5         | 4.2                                                                                   | 4.5                                                            | 4.2                                               |

The conditions for viewing the display were again adjusted so that they would be the same as the tests outlined

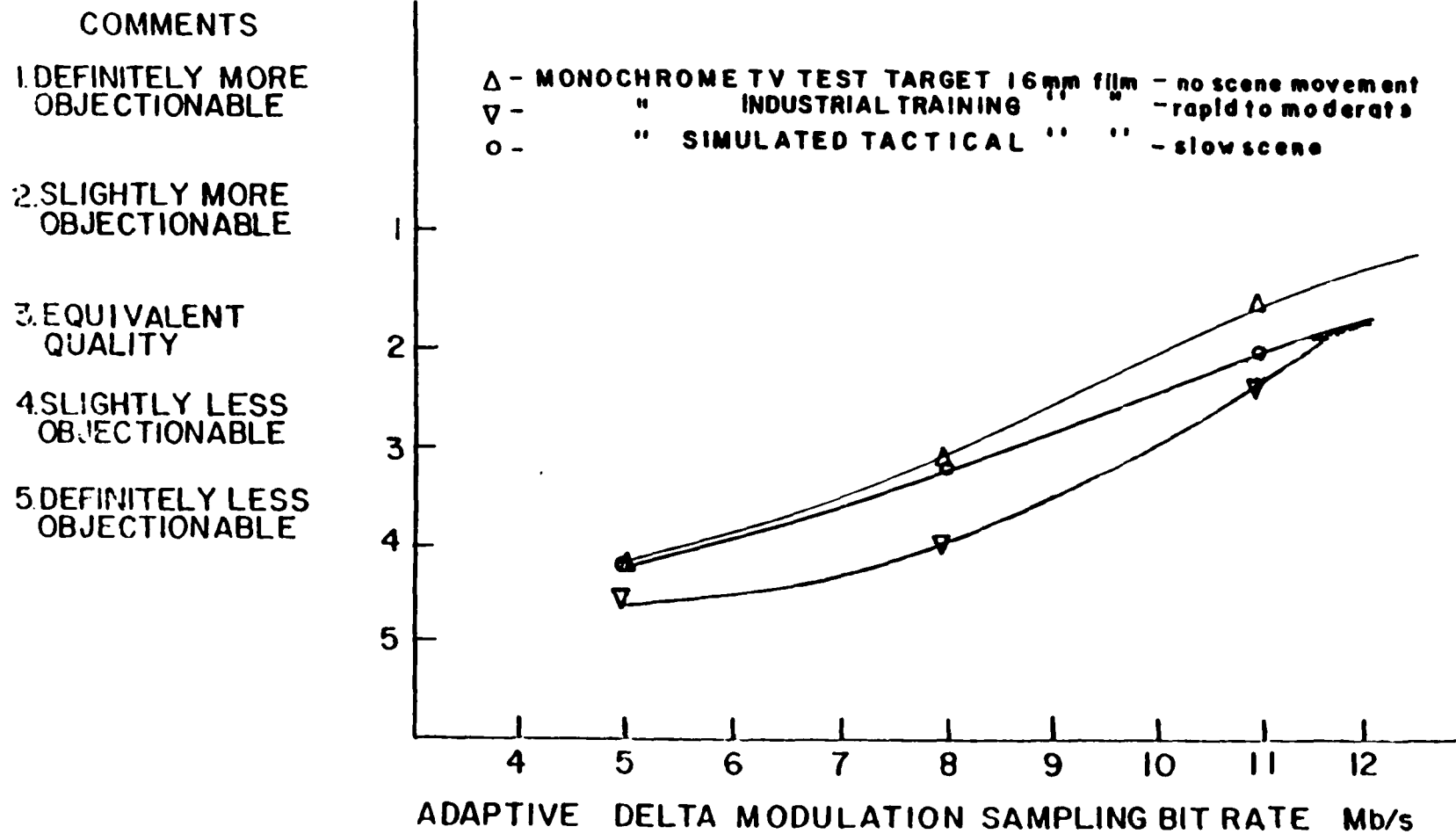


Figure 5.4-4 Time sequential partially coherent polychromatic hybrid encoder subjective noise quality with optical preprocessing vs. without optical preprocessing

previously. Various parameters, such as filter position and illumination levels were adjusted to obtain the best subjective effect for a particular bit rate.

The absence of coherent interference noise which was seen to have masked some of the low-pass filtering of the optical preprocessor may account for the difference between the results obtained for the coherent vs. partially coherent cases.

We see this difference in the mean response when viewing the reconstruction of the monochrome TV test target film input. This reconstruction that contained no movement elicited the same response at a sampling rate of 14 Mb/sec. for the coherent system vs. 11 Mb/sec. for the partially coherent system. As the edge busyness becomes clearly superthreshold, the preprocessed reconstruction is preferred. In the monochrome simulated tactical scene, a tank is seen to move slowly across a field. Since this movement is not close to the maximum temporal frequency response that the eye is peaked to, very little noise masking due to the slow motion occurs.

The results are therefore similar to that of the TV test target.

The monochrome industrial test film had a great deal of movement that masked the low-pass effects of the filter at low sampling rates where the edge busyness was clearly superthreshold.

The ADM sampling rate at which the optically pre-processed video reconstruction had a subjective quality judged to be better than the non-preprocessed video reconstruction sampled at the same rate were compared to equal quality non-preprocessed video reconstruction sampled at higher rates. In order to obtain the effective compression ratio for time sequential partially coherently illuminated monochrome inputs, eq. 4.2-1 again was employed. Table 5.4-2 shows the mean quality comment scores for the monochrome industrial training film and Fig. 5.4-5 is a plot of this table in the region where compression was achieved.

Table 5.4-2

Mean Subjective Quality Scores for Partially Coherent  
Time Sequential Real-Time Simulation  
Hybrid Optical-Digital Encoder

| Mbit/sec | Mean Score for Monochrome Industrial Training Film Partially Coherently Illuminated |                          |
|----------|-------------------------------------------------------------------------------------|--------------------------|
|          | ADM Output with Filtering                                                           | ADM Output w/o Filtering |
| 22       | 2.2                                                                                 | 1.6                      |
| 14       | 2.5                                                                                 | 2.4                      |
| 11       | 2.5                                                                                 | 2.7                      |
| 8        | 2.7                                                                                 | 3.1                      |
| 7        | 3.0                                                                                 | 3.7                      |
| 6        | 3.4                                                                                 | 4.1                      |
| 5        | 3.8                                                                                 | 5.0                      |

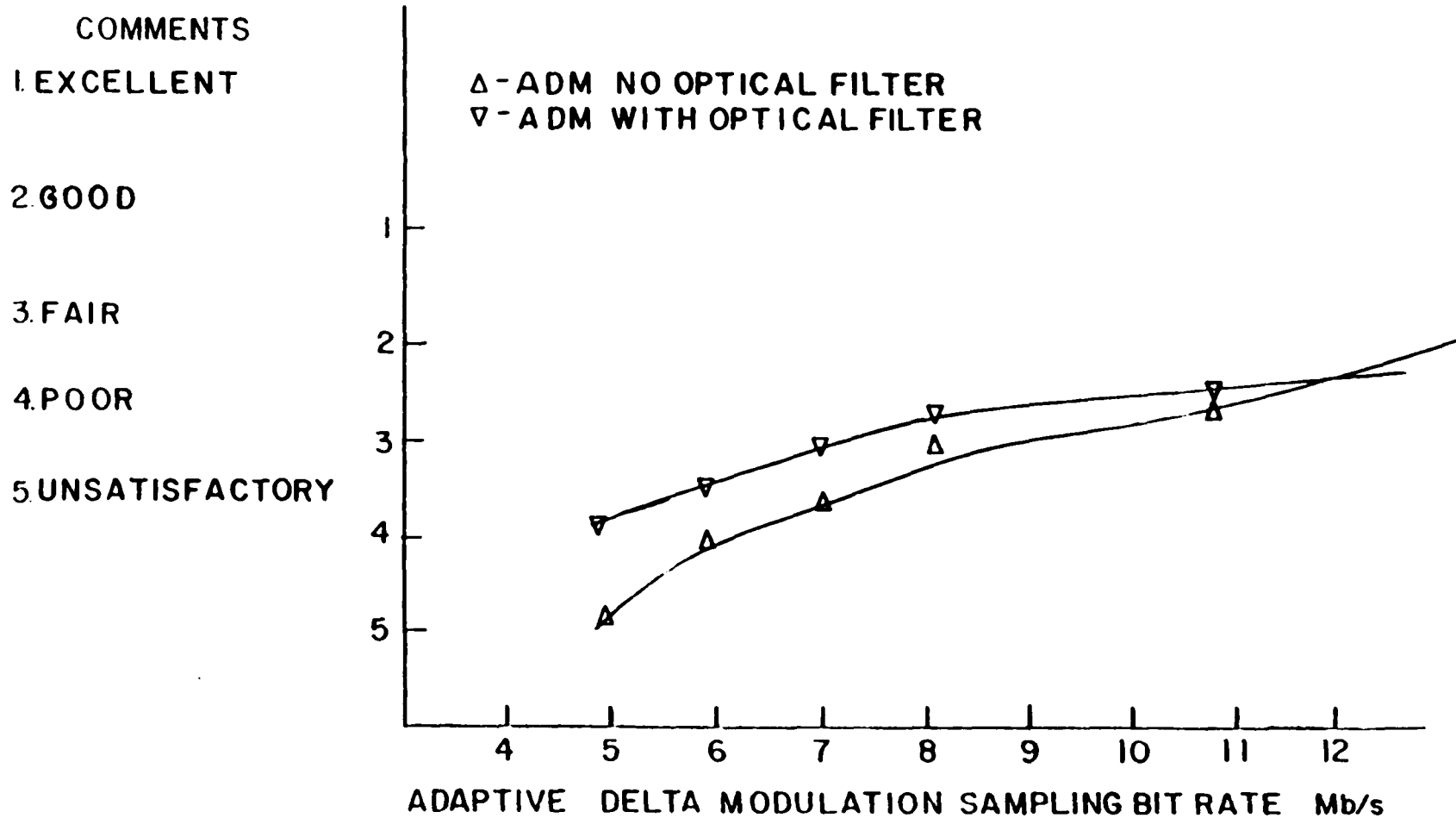


Figure 5.4-5 Subjective quality scores for partially coherent time-sequential with vs. w/o optical filtering

The above quality comments chosen were from a comment scale that ranged from "excellent" to "unsatisfactory" as shown below.

Comment Scale

1. Excellent
2. Good
3. Fair
4. Poor
5. Unsatisfactory.

The conclusions drawn from these results were

(1) that the overall quality of the simulated real time phase encoded input illuminated with partially coherent polychromatic light was improved by approximately 1/2 a comment point for both filtered and unfiltered reconstructions.

(2) The increase in quality appears to be the result of a combination of the reduced sensitivity of the observer to local noise in real time input and the reduced edge instability perceived on filtered edges in scenes with motion. Here the key perceptor for large area motion has a higher priority than the small area motion so less time and attention is spent fixed on these boundaries where the local noise is located.

(3) The effect of reducing the coherent noise is to improve the quality of the video reconstruction thereby

raising the quality score.

(4) Large edge error excursions are still perceived in scene material with motion and optical preprocessing of slow motion scene input counters the appearance of this error.

The effective compression of this system was measured at 1.67 for a good to fair image rating and 1.4 for a fair to poor image rating.

This represents an improvement in the effective compression achievable with coherent still input hybrid processing. These experiments show that real time simulation using sequential inputs with partially spatially coherent polychromatic illumination, uncovers the increase in compression that is possible with the hybrid optical-digital encoder when encoding moving monochrome input scenes.



CHAPTER VI  
POLYCHROMATIC PARTIALLY COHERENT HYBRID  
ENCODING FOR COLOR TRANSMISSION

The transmission of still and moving color video scenes is often required to be done in real-time. However, when a standard 4.5 MHz NTSC color video signal is sampled at the Nyquist rate and encoded using 4-6 quantization levels (PCM), the data can be as high as 48-64 Mb/sec. per color channel. This amounts to an overall bandwidth requirement close to 100 Mb/sec. for the transmission of broadcast quality color images. As in the transmission of monochrome image input, this high digital bandwidth is usually unacceptable for most applications. This is due to the fact that the already allocated channels were designed for analog rather than digital transmission. Even on new channel systems designed for digital transmission channel bandwidth is at a premium due to consumer demand.

A number of adaptive digital alternatives such as adapted delta modulation have been used to lower the data rate per color channel. Optical preprocessing of the color image before encoding would thus seem a logical extension to reduce this digital rate when encoding with ADM even further.

In this section we discuss the effects of bandwidth compression and the resultant image quality in several still

and moving or time sequential color image transmission systems. These systems use the partially spatially coherent polychromatic optical preprocessor as a front end to the ADM digital encoders. The preprocessor prepares each frame of the sequential color phase encoded input for reduced noise digital ADM encoding. The encoding and decoding of the digital signals are performed by three hard-wired real-time state of the art adaptive delta modulators.

#### 6.1 Still Color Input Hybrid Encoding

From the experiences gained in the monochrome hybrid encoding system that we built, and the psychovisual data on the reduced sensitivity of the observer to noise, we constructed a three-channel hybrid color encoder. The characteristics of the noise instability for color input when ADM digital encoding is used was then tested. In addition, the subjective noise effects of the color system for each channel allowed us to determine the appropriate preprocessing needed.

Using the same experimental arrangement as described in Chapter III, section 3.3-2, we replaced the monochrome camera with a color camera that produced three output video color channels. Figs. 6.1-1 shows the typical spectral sensitivity for each color camera channel.

Using one ADM encoder-decoder pair connected over a noiseless channel, we reconstructed one color channel at a time. The image input that was used was again a black

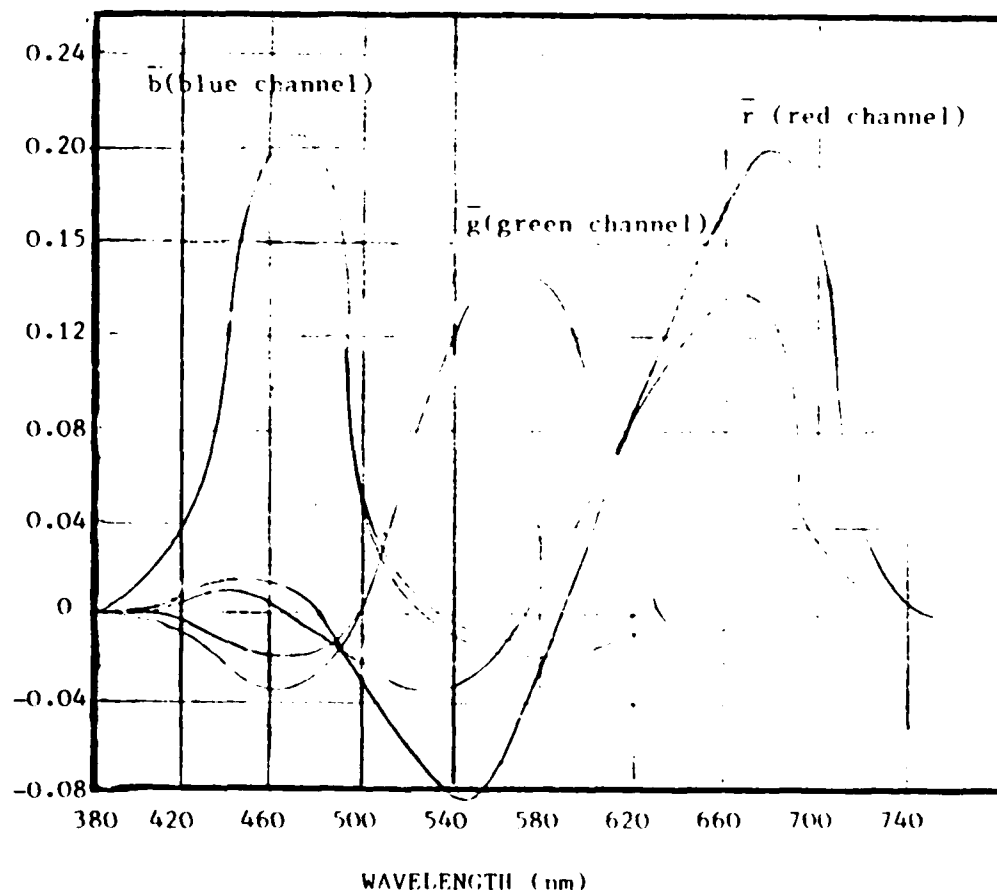


Figure 6.1-1 Spectral sensitivities in camera channels

bar on a white background. No optical preprocessing was used since we were interested in determining the effect of encoder noise alone on the subjective quality of the reconstructed output. Figs. 6.1-2a-d are color polaroid photographs of the reconstructed output as displayed on a color monitor. The red, green, and blue channels derived from the color camera output were each separately encoded at a rate of 5.2 Mbit/sec. The direction of the scan in Figs. 6.1-2a-c was transverse to the white to black and black to white vertical edges. Fig. 6.1-2d shows the output when the scan orientation was nearly parallel to the edge of the pulse. This was encoded using the red channel at a sampling rate of 16.5 Mb/sec. for the purpose of comparison. It was observed that the subjectively perceived edge busyness in the green channel reconstruction was more visible than in either the blue or red channel reconstructions. Based upon this result, we then constructed a three-channel transform domain encoder. Reasoning that less filtering would be needed on the blue and red channels than on the green channel, to achieve the same degree of subjective noise content, a savings in bandwidth appeared possible.

Since the green and red channels sampled at the same rate as the green channel, appeared to have less subjectively perceived edge noise, they could be encoded at a lower sample rate. By adjusting the apodization and



(a)



(b)



(c)

Figure 6.1-2 ADM scan transverse to wide bar pulse,  
response at 16.5 Mbit/sec, no optical  
preprocessing  
(a) Blue channel (b) Green channel  
(c) Red channel

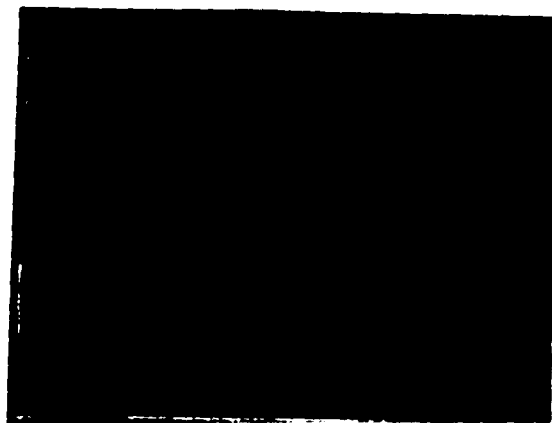


Figure 6.1-2d ADM scan parallel to wide bar pulse, at  
16.5 Mbit/sec, no optical preprocessing

central transform filter for each color in a different manner, each channel would achieve the lowest possible transmission rate. Fig. 6.1-3 is a schematic diagram of the divided transform filtering preprocessor.

A 200 Watt Hg-Xe arc lamp (Hanovia-Canard #901b) acted as a polychromatic partially spatially coherent light source. In order to increase the spatial coherence of this source, light from the arc is collected by lens  $L_1$  and focuses an image distribution of the arc intensity onto the spatial filtered plane (SFP). The position of the spatial filter (a 370 $\mu$ m pinhole) is adjusted so that a constant portion of the arc's spatial radiance distribution free of chromatic aberration is transmitted. This is done by viewing the light from the spatial filter on an alignment card beyond  $L_1$  and observing the distribution of the pinhole image. The light that is passed by the spatial filter is then collimated by a 6" diameter lens with a 30" focal length. The collimated light is passed through an absorbing filter  $f_1$  (Oriel IR absorbing filter Model G 776-7100) and  $f_2$  (Oriel UV absorbing filter Model G 772-3900). The filtered collimated light then transilluminates a monochrome 35mm USAF 1951 input test transparency placed in the signal plane S. The partial coherence of the light is determined by the angular subtendence to the pinhole source.

For a mean waveleangth  $\bar{\lambda} = 400\text{nm}$  and using Hopkin's

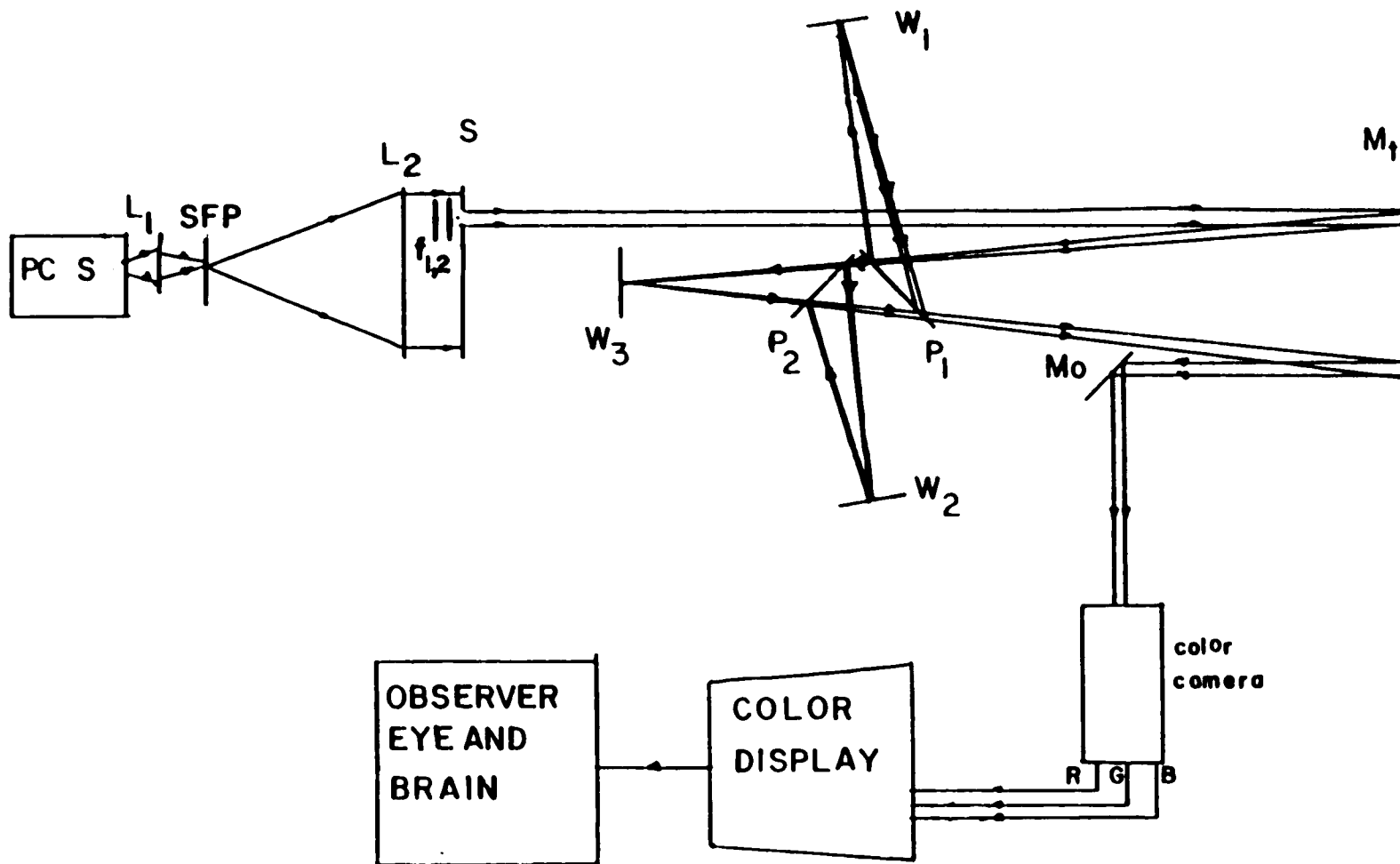


Figure 6.1-3 Divided transform plane filtering preprocessor



formula [151] given by  $d = .16\bar{\lambda}/\alpha$  where  $\alpha$  = the angular source size. For the system described this gives a coherence diameter of .33mm assuming a partial coherence in this area of  $\gamma_{12} = .88$  [158].

For our input 35mm slide, this represents approximately 1/100 of the horizontal dimension. For a video screen resolution containing approximately 480 resolvable spots, the source is nearly coherent over approximately 4 pixels. The region of interest, where the high contrast transitions exist, appears then to be illuminated by a spatially coherent source. The diffracted spectra leaving the input transparency are incident onto an off-axis position on the 6" diameter f/8 transform mirror labeled  $M_t$ . After reflection, the polychromatic converting beam is separated by the use of two dichroic mirrors  $P_1$  and  $P_2$ . The red, green, and blue chromatic converging bands are independently reflected to three separate transform filtering mirrors. Each mirror filter is equipped with its own variable diaphragm and is mounted on a 3-axis Gimbal mount with horizontal and vertical translation stages.  $W_1$ ,  $W_2$  and  $W_3$  represent the positions of each one of these mirror filtering stations. The spectra that are passed are reflected back to the dichroic mirrors and recombined. The recombined filtered spectra then propagate to the paraboloidal mirror  $M_t$  but are now imaged to a position conjugate to the position of the input

on  $M_t$ . Upon reflection, the spectra are retransformed, and the combined color spectra are then reflected onto color camera vidicons by output mirror  $M_0$ . Note that the input transform and output transform planes are not coplanar. This allows for the physical separation of the components. Though this introduces an additional phase factor, it is known [152] that the lateral scale of the Fraunhofer or Fourier transform pattern for plane wave illumination of the input transparency is only a function of the local length of the lens and not the distance of the input from the first transform lens. The additional phase that is introduced due to the shift in the input plane position is compensated for by a foreshortening of the distance to the output plane.

In order to determine the resolution of each color channel of the optical system without optical filtering the reflective filter profiles were replaced by plane mirrors in each transform filtering station, and the apodizing diaphragms were opened to their maximum. The RGB color outputs of the camera were then directly connected to the color display monitor and viewed after optimal alignment.

Each color was aligned separately by successively blocking the transform spectra of the remaining 2-color components.

The resolution of each color optical channel was

determined using the smallest resolvable group in the resolution target that appeared on the color monitor display. Table 6.1-1 lists the results of the resolution for each color channel. The retransformed color images were then placed in registration by allowing two retransformed color images to pass simultaneously and register the third to the first two that were now in registration.

Due to loss of light, and the camera spectral sensitivity, upon recombination of the spectrum the relative intensity of each color channel when combined did not produce a white output on the color monitor. This problem was alleviated by including a series of Cibachrome color compensating gels to adjust the sources' spectral distribution. The percentage of magenta, yellow, and cyan used to produce a white reconstructed output was determined experimentally. In addition, the video output was recorded on a color VHS recorder. The relatively poor resolution of the system was traced to the ghost images produced by the second surface reflections from the back of the 2mm dichroic mirrors. In order to correct for this, two dichroic coatings deposited on membrane pellicles were used. It is well known that pellicles do not have second surface reflections. These pellicles replaced the dichroic mirrors. Figs. 6.1-4a and b are photographs of a divided transform system with the dichroic pellicles in place. The resolution for each color and the combined

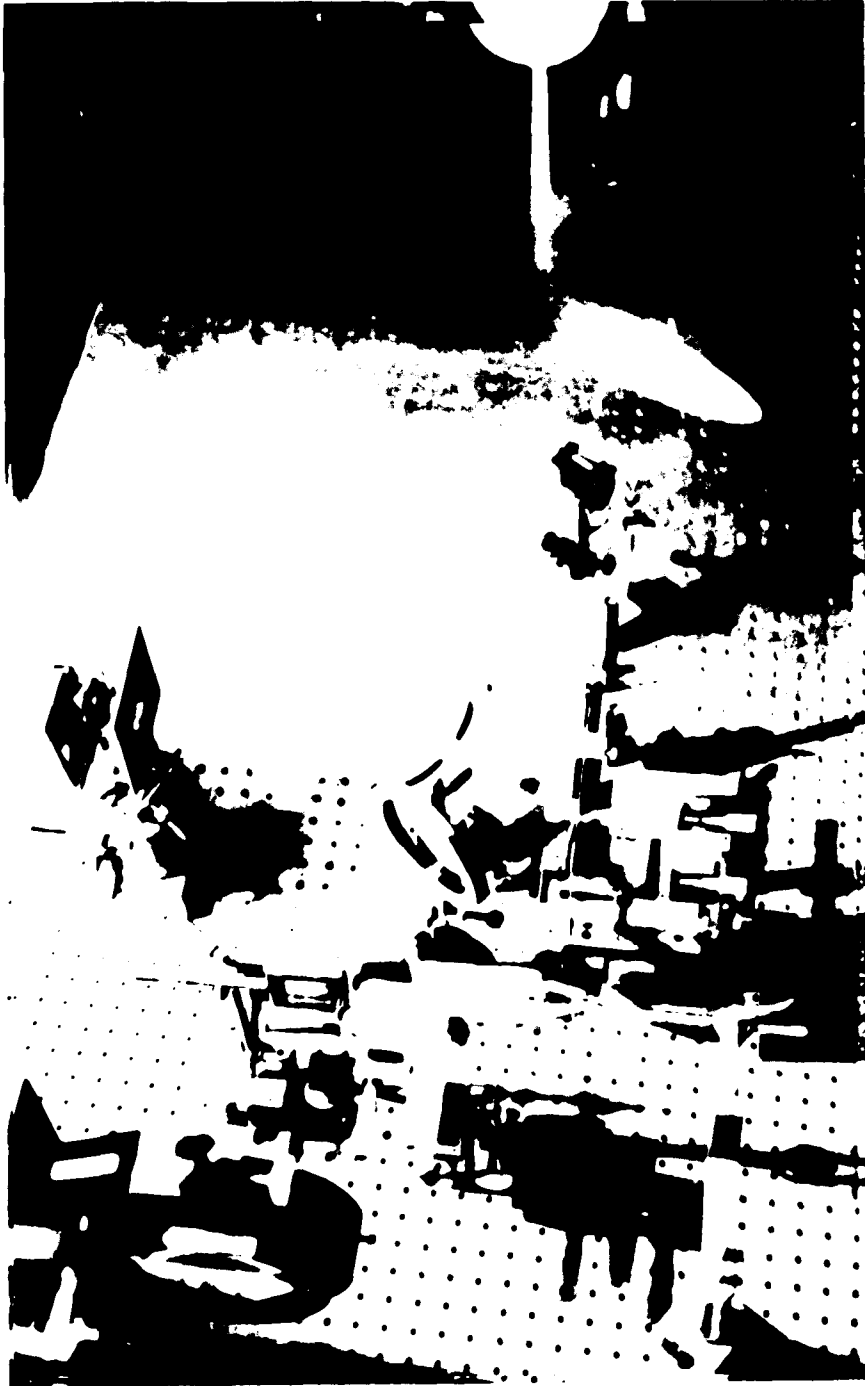


Figure 6.1-4a Photograph of divided transform plane filtering preprocessor with dichroic pellicle beam splitters

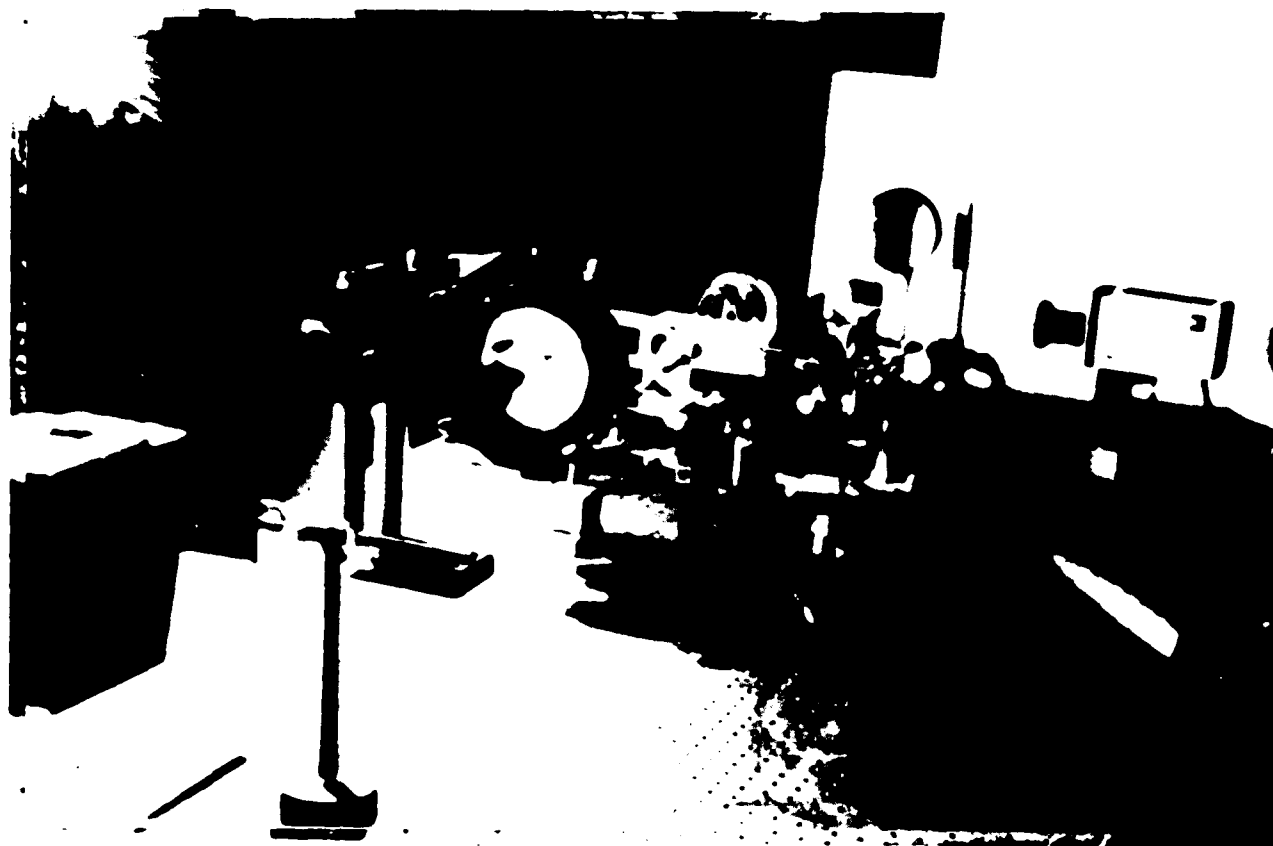


Figure 6.1-4b Photograph of divided transform plane filtering preprocessor,  
another view

output are shown in Table 6.1-2.

Although the ghost problem was solved, the resolution of the higher spatial frequencies was still poor and remained a problem. It was discovered that the dimensional flatness of the reflective transform mirror filter substrate was an extremely important parameter in the resolution of the retransformed image. Table 6.1-3 gives the resolution obtained with different mirror substrate thicknesses. As the thickness was increased, phase irregularities due to surface deformation introduced by the support mounts, decreased.

The pellicles did not produce second surface images. Unfortunately, they were found to be extremely sensitive to ambient temperature, humidity, and air current fluctuations, producing phase and registration errors in the retransformed output image.

These above problems could be countered through the use of thick substrate dichroic reflectors that would separate the first and second surface reflections. This is the method that is usually used in 45° variable attenuating beam splitters.

Upon additional testing and investigation it was determined that the results of the foregoing experiments associated with the decrease in resolution and increase in system complexity of the preprocessor did not warrant further investigation for our purposes.

Table 6.1-1

Divided Transform Plane Preprocessor: Target Resolution  
 with 2mm Dichroic Mirrors from Color Monitor  
 No ADM

| Red                             | Green                           | Blue                            |
|---------------------------------|---------------------------------|---------------------------------|
| 4.00 Lp/mm<br>(Group 2, elem.1) | 5.04 Lp/mm<br>(Group 2, elem.3) | 6.35 Lp/mm<br>(Group 2, elem.5) |

Table 6.1-2

Divided Transfer Plane Preprocessor Target at Resolution  
 with Dichroic Pellicles at Color Monitor  
 No ADM

| Red                          | Green                        | Blue                         | Combined                     |
|------------------------------|------------------------------|------------------------------|------------------------------|
| 6.35 Lp/mm<br>(Grp.2 elem.5) | 8.00 Lp/mm<br>(Grp.3 elem.1) | 11.3 Lp/mm<br>(Grp.3 elem.4) | 7.13 Lp/mm<br>(Grp.1 elem.6) |

Table 6.1-3

Resolution per Channel Obtained with Different Transform  
 First Surface Mirror Substrate Thicknesses

|                                   | .15 mm                       | 1.2mm                        | 5mm                        |
|-----------------------------------|------------------------------|------------------------------|----------------------------|
| Resolution<br>no Beam<br>Splitter | 7.13 Lp/mm<br>(Grp.2 elem.6) | 12.7 Lp/mm<br>(Grp.3 elem.5) | 25 Lp/mm<br>(Grp.4 elem.5) |

The above described system may be of advantage in other multi-channel transform operation applications where the data does not need a reasonably high resolution, as in matched filtering output detection. This type of system would serve to indicate whether a particular chromatic spatial frequency band were present or absent. In one application three monochrome high resolution CCD arrays could be placed in a position of the transform stations and act as multiplexed chromatic channel transform sensors.

#### 6.2 Polychromatic Partially Coherent Single Transform Plane Optical Hybrid Encoder for Still and Sequential Input Color Images

As previously stated, straight PCM encoding of RGB video signals must operate on the order of 100 Mb/sec. for broadcast quality image. This represents roughly 30 Mb/sec. per channel.

Using ADM good color reproductions can be achieved at sampling rates of 10 Mb/sec. per channel for parallel encoded RGB signals. Below this rate the effects of edge busyness produce unwanted image degradation. This edge busyness instability can be reduced by our optical analog color preprocessing system and allow for bandwidth reduction when sampling rates fall below 10Mb/sec.

To perform two-dimensional color transform filtering



without having to resort to an expensive 3-color coherent laser transforming system, our new polychromatic transform filtering system offers an appealing alternative over the conventional transform arrangement.

Let us now take a look at the main features of the single plane color transform preprocessor hybrid encoder. Fig. 6.2-1 is a schematic diagram of the single plane transform polychromatic partially spatially coherent hybrid encoder-decoder system.

The source is a 200 Watt Hanovia-Canrad Hg-Xe arc lamp that is spatially filtered with a  $370\mu\text{m}$  pinhole. It is then collimated by a 6" diameter f/5 lens and is incident on the input plane. At the input plane, either a still 35mm phase encoded transparency or a 16mm phase encoded film held by sequential transport pin registered carrier, is placed. The diffractive spectra from the phase encoded input object is then incident on a 6" diameter f/8 paraboloidal transform mirror. The focus spectra are then incident to the absorption filter weighting profile and reflected back by a plane first surface mirror. This filter mirror has a 1/4" substrate for dimensional stability in order to avoid phase errors due to mirror deformation. The filtered spectra again pass through the absorption filter after reflection and are then incident on the transform mirror at a position conjugate to the input mirror position.

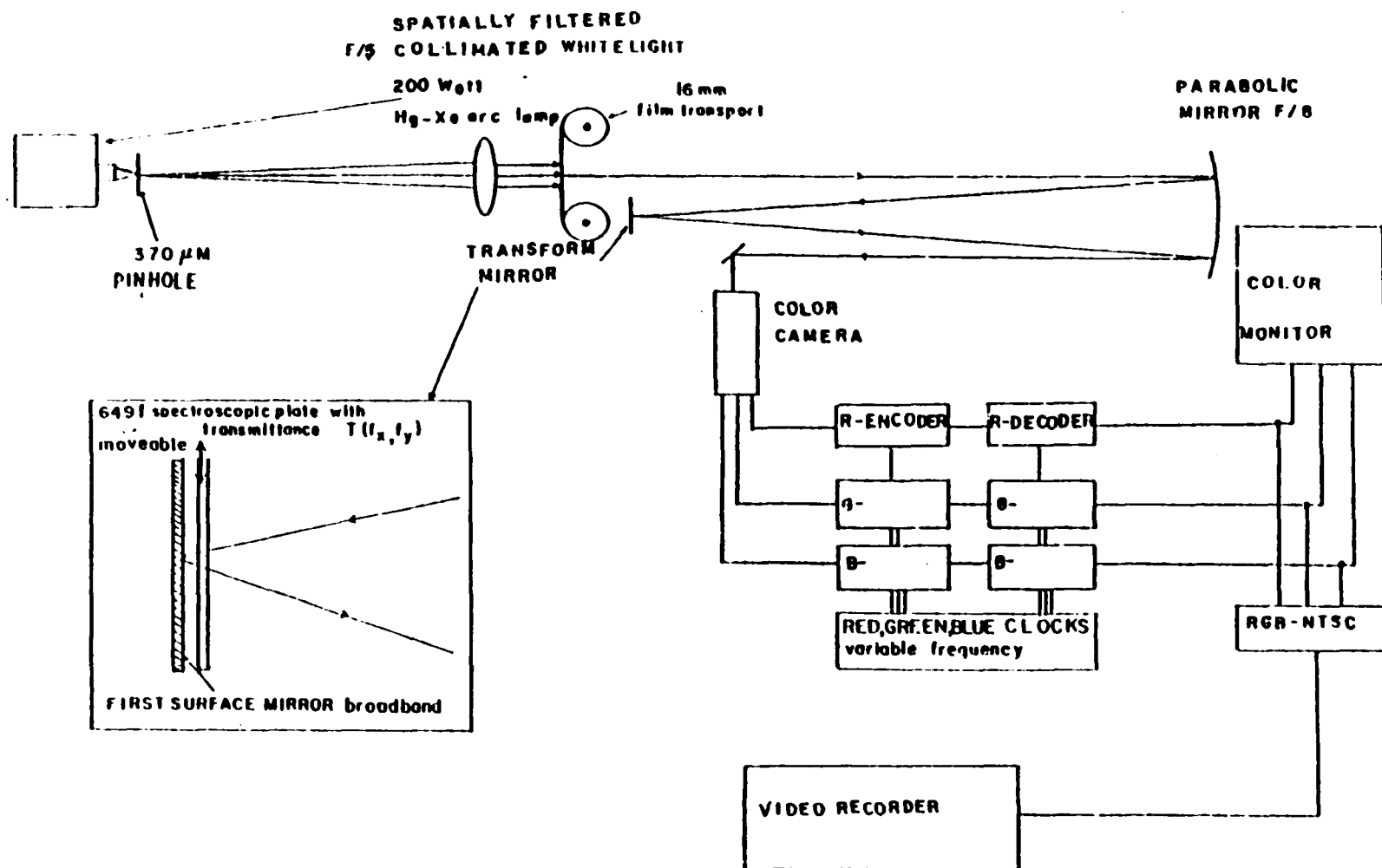
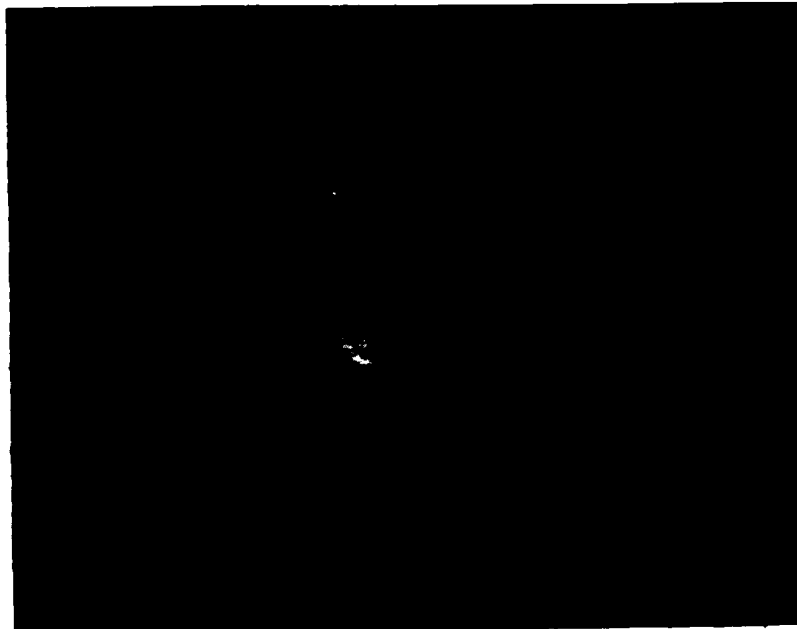


Figure 6.2-1 Schematic diagram of single plane transform polychromatic partially spatially coherent hybrid codec system

The retransformed spectra are then reflected onto the vidicons of a Hatachi color camera. In this arrangement the electronic color balance of the camera controls were used to achieve the proper mixture of color components needed to produce a white output in place of the correction gels. The output of the red, green and blue channels are fed in parallel to three separate high-speed Schilling adapted delta modulators. Each ADM encoder has a variably adjustable sampling rate driven by synchronous red, green and blue clocks. This potential would allow us to take advantage of lower clock rates producing lower sampling rates for the blue and red channels. This is due to the subjective difference in edge noise perceived in the reconstructed image for these colors as outlined previously. The three ADM encoded bit streams are fed in parallel over three noiseless coaxial cables and decoded with three separate ADM decoders. The output of these decoders is then input into a color monitor where it is displayed. In addition, an RGB to NTSC converter is used so that the output could be recorded on a video recorder. Figs. 6.2-2a and b are photographs of this three channel hybrid color system. The RGB signals are changed to NTSC format since that is the standard in this country for analog transmission. Fig. 6.2-3 shows the matrix equations used in transforming the RGB components into the luminance  $Y_t$ , and two-chrominance difference signals  $C_1$  and  $C_2$ .



(a)



(b)

Figure 6.2-2 Photographs of hybrid 3-channel color system

- (a) Sequential input reflective transform color preprocessor
- (b) R.G.B. parallel channel ADM electronics, R.G.B. to N.T.S.C. converter display monitors and video recorder

$$\begin{bmatrix} Y_t \\ C_1 \\ C_2 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

*PAL System 1 (true luminance)*

$$Y_t = 0.222R + 0.707G + 0.071B$$

$$C_1 = 0.493(B - Y_t)$$

$$C_2 = 0.877(R - Y_t)$$

*NTSC*

$$Y_t = 0.299R + 0.587G + 0.114B$$

$$C_1 = 0.736(R - Y_t) - 0.268(B - Y_t)$$

$$C_2 = 0.478(R - Y_t) + 0.413(B - Y_t)$$

Figure 6.2-3 Matrix equation for R.G.B. to  $Y_t$ ,  $C_1$ ,  $C_2$   
 (a) Matrix  
 (b) European P.A.L. and American N.T.S.C. color systems

Fig. 6.2-3b shows the European and American, PAL and NTSC, composite video color standard matrix element components. These are used to produce the I and Q channels shown in Fig. 6.2-4. The IYQ signals are ordinarily used to the 4.5MHz analog video signals.

We optically preprocess the color input image and then digitally ADM encode, and transmit the RGB components in parallel. Another possible approach would be to investigate preprocessing of ADM encoded images and then transmit the I, Y, and Q components as is shown in Fig. 6.2-5. By time multiplexing these three channels using a different number of levels for each channel type, one could reduce the bandwidth necessary to transmit the encoded video image. Work along these lines has been done by Davidovici [157] where the RGB components were converted to IYQ signals each of which was ADM encoded and multiplexed before transmission.

Figure 6.2-5 shows a schematic diagram of such a sequential multiplex DPCM encoder for transmission of  $Y_t$ ,  $C_1$  and  $C_2$ .

#### 6.2-1 Single Plane Polychromatic Partially Spatially Coherent Transform Filter Operation

The single plane transform preprocessing filter operates on the polychromatic transform (or spatial frequency power spectrum) as a superposition

$$I = \frac{R - Y_t}{1.14} \cos 33^\circ - \frac{B - Y_t}{2.03} \sin 33^\circ = 0.736(R - Y_t) - 0.268(B - Y_t)$$

$$Q = \frac{R - Y_t}{1.14} \sin 33^\circ + \frac{B - Y_t}{2.03} \cos 33^\circ = 0.478(R - Y_t) + 0.413(B - Y_t)$$

Figure 6.2-4 Conversion formulas for I and Q components from R, B,  $Y_t$ , N.T.S.C. format

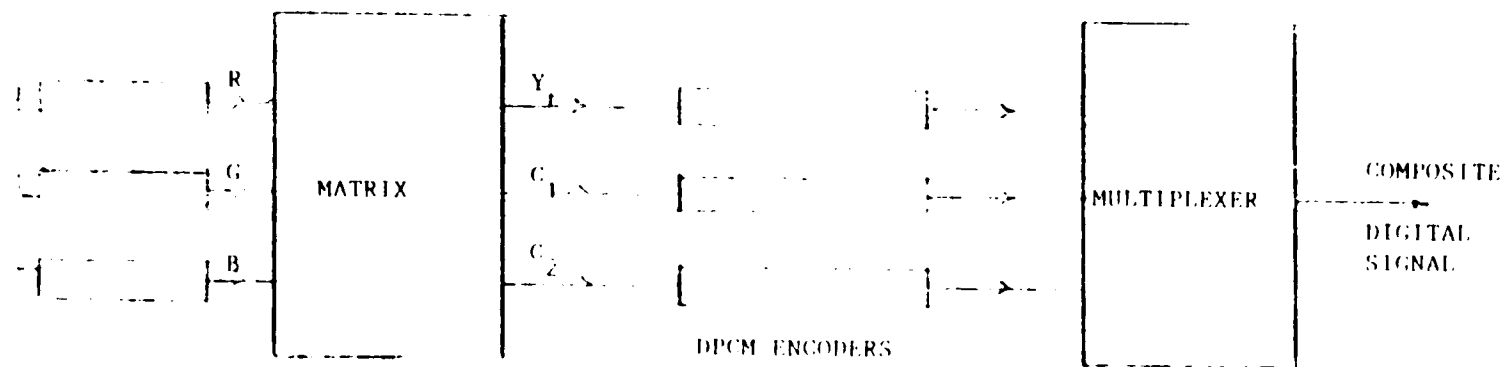


Figure 6.2-5 Principle of separate DPCM encoding



of weighting functions for the various coherence separable polychromatic fields [160].

The physical filter absorption profile,  $T(x_t, y_t)$  is positioned so that the weighted transmittance of the filter lies centered on the linear region of amplitude absorption. The polychromatic transform spectra passed through the filter twice, once before being incident on the plane first surface transform mirror and once after reflection from this mirror. Therefore the effective intensity weighting filter is  $T^2(x_t, y_t)$  and produces a total effective amplitude transmittance of  $T(x_t, y_t)$ .

Due to the wavelength dependence of the diffracted spectra, there is a scaling in the lateral magnification of the physical positions  $x_t, y_t$  in the transform domain that increases as the spatial frequency increases. It is also scaled with the wavelength since the inverse spatial frequencies are generally given as  $\xi = x_t / \lambda f$ ,  $\eta = y_t / \lambda f$ . Since  $f$  is constant in the reflective transform system for all wavelengths, the scaling of position with  $\lambda$  in the transform domain will produce a slightly different spatial frequency weighting filter for each  $\lambda$ . Since the physical filter amplitude absorption is a gradually changing function, rather than a sharp binary cutoff, the resulting change in the filter weighting function and accompanying edge preprocessing

modification with  $\lambda$  is also gradual. The longer wavelengths thus see a slightly different filter profile than the shorter wavelength. This works out to advantage since the edges of the blue image component that create diffracted spectra closer lying to the axis than either the red or green spectra. Therefore they experience less of a difference in the differential absorption of the positive and negative phase shifted components. Due to this the blue edges, that are perceived as containing less subjective noise instability upon reconstruction, need less filtering.

The wavelength dependence of the diffracted spectra carrier angle due to the phase encoded gradients produce an accompanying dispersion, as the collimated polychromatic illumination transits the phase relief. The change in propagation direction that occurs may be understood by examining Fig. 6.2-6. In this figure we assume a piecewise linear phase gradient prism model. The angle of incidence of the collimated illumination  $\theta_1$  is seen to be equal to  $\alpha$ , the edge phase gradient encoded relief angle. This angle, in turn, is seen to be related to the relief encoded illumination angle. This relief encoded illumination angle acts as an angular carrier on which the diffracted spectra

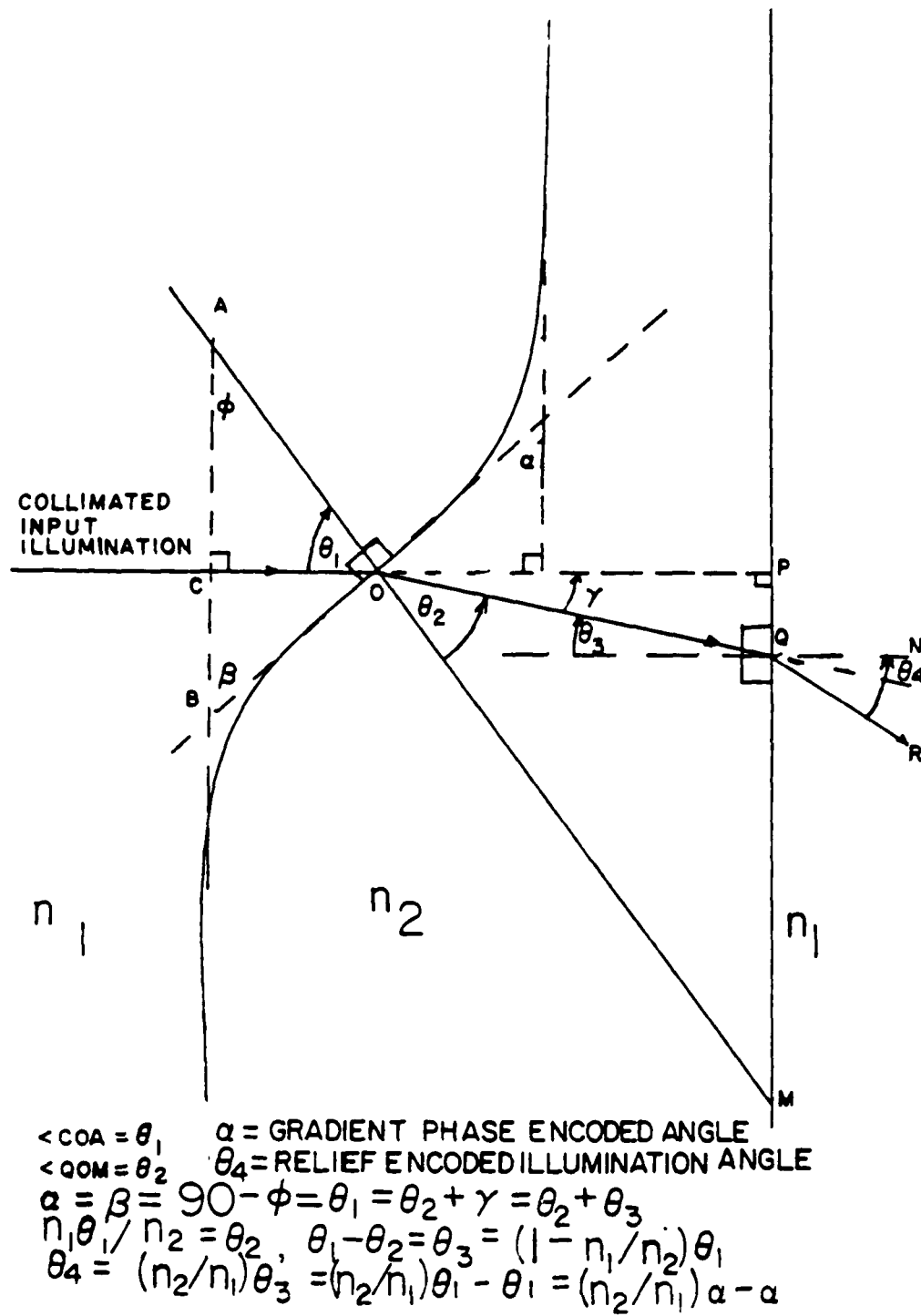


Figure 6.2-6 Input illumination, relief angle and carrier encoding angle geometry

center.

For an F/8 maximum cone angle,  $\theta_{4\max.} = .125$  radians ( $n_1=1$ ,  $n_2 = n_2(\lambda)$ ). Although the index of refraction of tanned gelatin containing bleached and exposed silver crystals is a complex matrix, one can get a rough idea of the dispersion of this kind of composite matrix by examining the dispersion of similar composite matrices. The dispersion in composite lead salt glasses is close to the measured value of the index of tanned silver containing gelatin and is approximately  $n \approx 1.6$  [159]. These types of matrix indices are generally modelled as a polynomial of the form

$$n^2 = A + BL + CL^2 + D^2 + E\lambda^4$$

where A, B, C, D, E, F are constants and

$$\text{and } L = 1/(\lambda^2 - F)$$

or

$$n = G + H/(\lambda - I)$$

where  $\lambda$  is expressed in Angstrom units with

$$G \approx 1.58 \leftrightarrow 1.55$$

$$I \quad 1000 \leftrightarrow 500$$

$$H \quad 100 \leftrightarrow 50$$

This typically produces a change of index of 1-2% over the visible spectrum, so that, for the Blue

$$\theta_{4\max_{\lambda b}} = 1.61\alpha - \alpha$$

following from the relations as seen in Fig. 6.2-6.

Assuming the maximum angle of .125 radians = .61 $\alpha$ ,

then  $\alpha_{\lambda b \max} = .205$  radians for the blue. For the red,

$$\theta_{4\max_{\lambda r}} = 1.59\alpha - \alpha$$

Again assuming the maximum angle of .125 rad. = .59 $\alpha$

then  $\alpha_{\lambda r \max} = .2124$  radians. This represents a

maximum change in  $\alpha$  of 7 mill rad. If we assume

$\sin \theta = \tan \theta = \theta$  then  $\Delta x_{\max}/f = .007$ . Therefore,

the dispersion near the axis will be negligible.

The dispersion at larger angles will compensate for

the scaling due to the diffraction at those edges

where the face angles are large enough to produce

appreciable encoder carriers.

## 6.2-2 Three Parallel Channel ADM Encoding for RGB

### Color Channels

After the optical preprocessing of the color phase

encoded input, the retransformed image is scanned

by the color camera. The three color signals (R.G.B)

each enter a separate ADM encoder. The advantage

of three separate encoders is that each channel may

be driven at a different clock rate while still being

able to produce noise content in a reconstructed image that is judged to be equal because of the difference in perception of a blue channel component over the green or red channel component. There are other advantages provided by color encoding due to the edge error position averaging. Since most edge signal information that produces large errors in the reconstructed edge is at high contrast black to white edges, all three color channels are generally present at these edges. The concomitant edge busyness of each separate color channel masks the edge position error in the same fashion as the dither effect. This dither effect discovered by Roberts [153] reduces the contour noise in PCM encoded pictures.

To evaluate the difference in the subjective quality of a single B & W channel and compare it to the subjective quality of a three color ADM reproduction at various clock rates we introduce a still color test slide into the input of the test system. To obtain a monochrome output, we disconnected the red and blue channels to the display monitor and reduced the chrominance until a black and white image was seen. Several different color input scenes of varying complexity were used as inputs. The subjective quality measured the

comments received when comparing the relative quality of the monochrome image to the color image. Table 6.2-1 shows the results which are plotted in Fig. 6.2-7. The R, G and B channels were encoded using the same clock rates and thus sampling frequencies. Figs. 6.2-8a and b are photographs taken from the color monitor of the color and monochrome images. Although noise was still visible in the picture, the time varying nature of the color image and thus the subjective edge noise quality was judged to be better than the monochrome image when the sampling rates per channel were 8 Mb/sec.

#### 6.2-3. Partially Coherent Polychromatic Hybrid Optical-Digital Encoding of Color Sequential Inputs

In order to determine a meaningful subjective quality for the optical-digital hybrid encoder, for real-time images, the subjective quality of color input scenes was simulated using sequential phase encoded color input film. The phase encoded test inputs were classified as to the degree of motion in the scene. The classifications were: little movement, moderate movement, and rapid movement. Table 6.2-2 shows the results of simulated real time quality obtained when the input had little to moderate movement at various sampling rates. The sampling rates used for each channel were set equal.

Table 6.2-1

Polychromatic Encoder Subjective Noise Scores w/o Optical  
Filtering: Monochrome vs. Color Display Noise Content

| Mb/sec | Beach Scene | Woman's Legs | Suited Man |
|--------|-------------|--------------|------------|
| 22     | 3           | 3            | 3          |
| 14     | 3           | 3            | 3          |
| 10     | 2.5         | 2.2          | 2.4        |
| 8      | 2.1         | 1.8          | 1.9        |
| 5      | 1.9         | 1.5          | 1.6        |



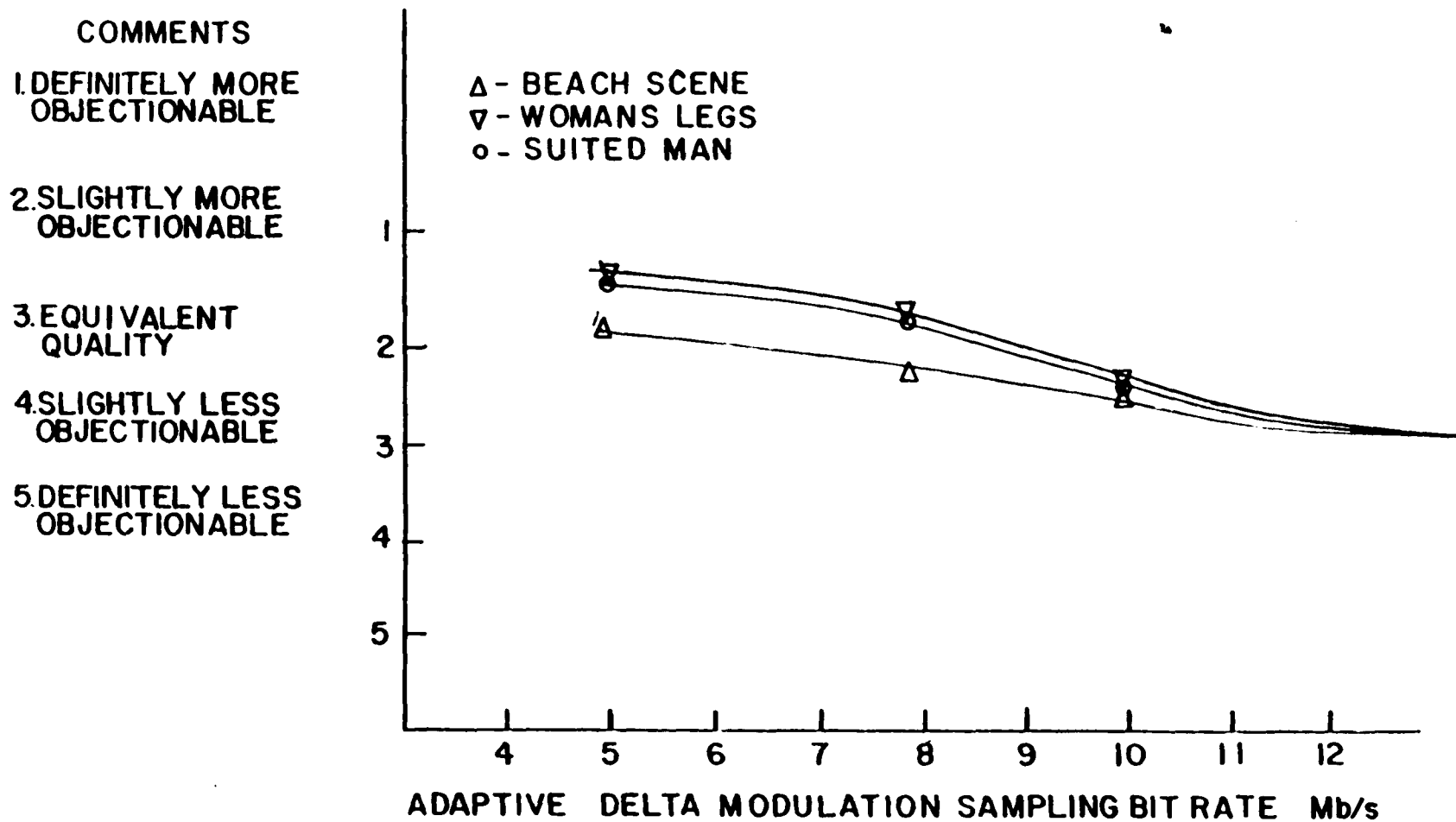


Fig. 6.2-7 Monochrome vs. Color Display Noise Content



(a)



(b)

Figure 6.2-8 Still monochrome and color displays,  
8 Mb/sec with optical filtering  
(a) color display  
(b) monochrome display

TABLE 6.2- 2  
 Mean Subjective Scores for Partially Coherent  
 Polychromate Hybrid Encoder

| Mb/sec | ADM with Optical Filter vs.<br>ADM w/o Optical Filter     |
|--------|-----------------------------------------------------------|
|        | Head & Shoulder Scene with Little to Moderate<br>Movement |
| 22     | 1.0                                                       |
| 15     | 1.0                                                       |
| 14     | 1.9                                                       |
| 11     | 2.5                                                       |
| 9      | 3.1                                                       |
| 8      | 3.5                                                       |
| 7      | 3.7                                                       |
| 6      | 4.1                                                       |
| 5      | 4.5                                                       |

Fig. 6.2-9 is a plot of these results.

We discover that the vertical scanning of the images allowed for less edge noise to be perceived since, as a rule of thumb, there are more high contrast vertical edges in natural portrait scenes than horizontal edges. The filter and input illumination intensities were adjusted to produce the most objectively pleasing output. At high sampling rates above 8 MHz, the reconstruction without encoding is preferred, due to modification of the phase encoded color edges. As the sampling rate per channel dropped below 8 MHz per sec./channel, the optically encoded image is preferred. Figs. 6.2-10a and b is a photograph of the color monitor when the input film seen contained moderate movement. Fig. 6.2-10a is with optical filtering and Fig. 6.2-10b is without optical filtering when the sampling rate was 5 Mb/sec. per channel.

We also tested the 3-color hybrid system at very low sampling rates (below 5 Mb/sec. per channel). In order to determine the difference in the subjective quality of color versus monochrome reconstructed moving scenes with rapid movement. The input scene was a hand moving across textiles of different colors. The real-time subjective quality at very low sample rates elicited poor but usable response for both

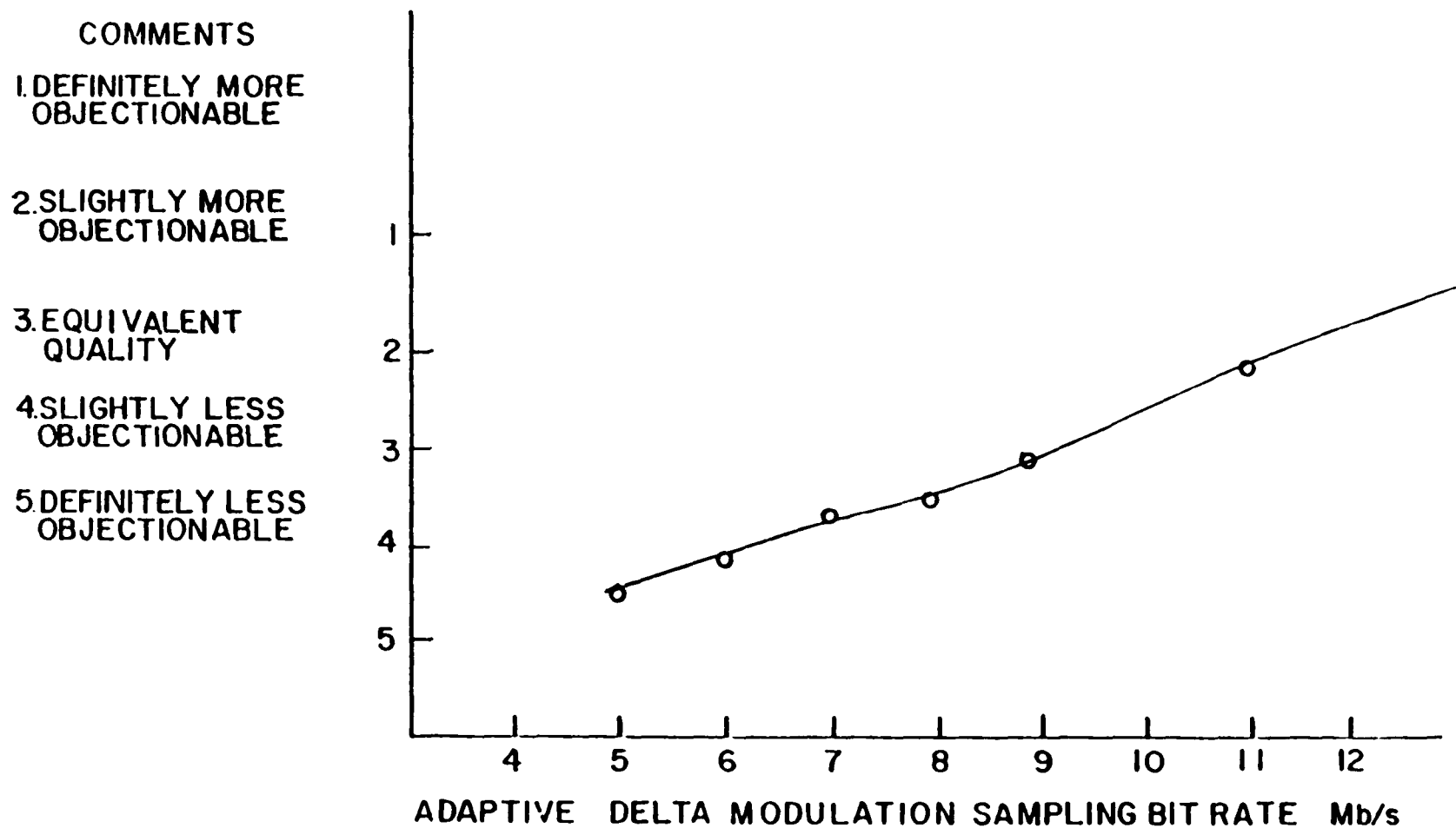


Fig. 6.2-9 Subjective Noise Quality with Filtering vs. no Filtering for Color Input with Little to Moderate Motion.



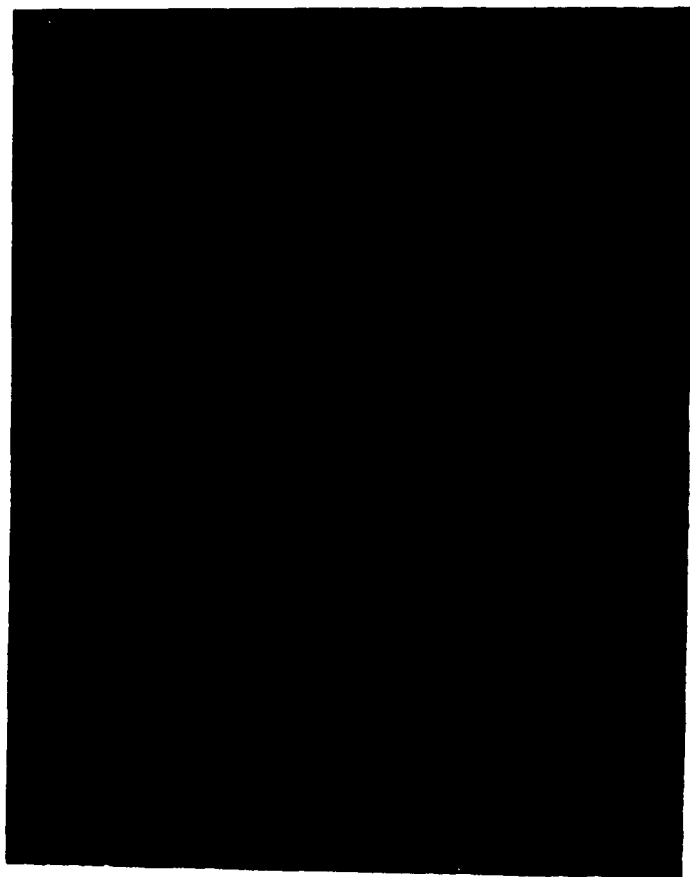
Fig. 6.2-10 Time sequential color input monitor display of ADM reconstruction containing moderate scene movement at 5 Mbit/sec vertically scanned  
(a) with optical preprocessing  
(b) w/o optical preprocessing

color and monochrome operations when filtering was performed as opposed to poor and unusable responses without filtering. In addition, the color video image was perceived as being less noisy than the monochrome image. Fig. 6.2-11a and b are photographs of the color monitor output of preprocessed images that were both vertically scanned. The sampling rate was 3.5 Mb/sec/channel. The reader is again cautioned against using these still images as a measure of the system quality.

The flesh tones in the encoded images at these low sampling rates in constant areas did not appear to degrade. It was noted that for scenes with rapid movement the same edge busyness (the same sampling rate) did not produce as distracting an effect, which was the reason behind being able to reduce the encoding rates to such a low level.

The signal dependent edge noise subjectively perceived thus changes with the degree of scene motion and spatial frequency content.

In Chapter VII we discuss how this frequency dependent time varying content might be sensed to further reduce the bandwidth. This work was felt to be beyond the scope of the present thesis.



(a)



(b)

Figure 6.2-11 Color monitor output ADM encoded at 3.5 Mb/sec optically preprocessed

(a) Color display

(b) Monochrome display



## CHAPTER VII

### FUTURE INVESTIGATIONS

The purpose of this thesis has been to study new methods of hybrid optical-digital encoding in order to reduce the effective overall bandwidth required to transmit still and moving, monochrome and color scenes.

As such, the demonstration experiments presented above were designed to show that the concept described in the theory does work, rather than to optimize the hybrid encoder. Several modifications to the present system might be desirable if a true prototype system were to be developed.

The experience gained in doing these experiments has generated a number of ways in which an additional reduction in the overall bandwidth could be achieved.

#### 7.1 Improvement of the Present System

The edge noise, which is signal dependent, has been seen to increase with the complexity of the input scene since more high contrast edges are encountered upon scanning the image. When the scene is less complex, perceived quality increases, so less filtering of the image is required. One improvement to the preprocessor would be to use an adaptive transform filtering arrangement. By using a beam splitter on the transformed spectra before

filtering, one could sense the distribution of spatial frequency and thus change the filtering to be done. This sensing of the transform domain could be accomplished with a high resolution CID photo diode array or transform sector detector [85]. The energy in the high frequency components could be sensed and the position of the filter could be modified to obtain the optimal filtering and thus improve the image quality [154,161].

Another improvement that could be afforded by the use of a transform plane sensor would be the increase in subjective quality in moving scenes. One could sense the time variant nature of the high frequency components as well as the time varying nature of the DC components. Taking the difference of these two readings, one would be able to sense the degree of motion of boundaries in the image and thus clock rates could be rapidly varied for the different degrees of scene motion. For scenes with a great deal of motion i.e. those where subjectively perceived edge noise is less could have their sampling rates lowered thus saving bandwidth.

An improvement to the spatial filter could be made by employing a thin film coating to produce the transform mirror filter profile instead of using a photographic emulsion in front of the mirror. This thin filter reflective transform mirror filter could replace the tandem plane mirror-filter arrangement and produce

a filter that would be less grainy than the photographic emulsion, thus introducing less noise into the system. In addition, a greater dynamic range in the reflection profile can also be achieved allowing for greater spatial frequency and range response. Production of the thin film reflective filter could be accomplished by evaporating aluminum or Inconil onto a dimensionally stable glass substrate. The thickness variation in a metal coating, and thus the degree of reflection, could be produced by evaporation onto the substrate inclined at an angle to give the desired profile.

The Fourier transform domain lies not on a plane, but on a curb surface. Because of this, it may be advantageous to form this special filter on a curved substrate which conforms to the contour of this surface.

It was intuitively felt that since the weighting filter has a slowly varying transmittance function, its failure to lie on the curve transform surface will not significantly alter the filter operation. However, Further theoretical analysis of this situation will be useful.

#### 7.1-1 Photo Refractive Input Plane

One of the drawbacks to the present system is the necessity to use complex non real-time wet chemical processing to produce the phase-encoded relief input. Using a photo refractive spatial

light modulator, monochrome phase encoded input could be introduced into the optical preprocessor at real time video rates. For color input scenes, the use of line sequential multiplex color transmission of each color component RGB could allow for real-time color encoding. This could be accomplished by placing a color filter wheel synchronized to the transmission system between the color illuminated transparency and spatial light modulator [155, 156].

## CHAPTER VIII

### SUMMARY AND CONCLUSIONS

The basic objective of the work reported was to design, build and operate a hybrid optical-digital processor for bandwidth reduction of ADM encoded scenes at low rates.

A hybrid optical-digital encoder was designed and successfully used for this purpose in both coherent and polychromatic, partially coherent modes of operation. Simulated real-time operations of the polychromatically coherent hybrid optical-digital ADM encoder was the first such operation of a phase-encoded processor encoder system, was found to be the preferred method since the reflective architecture reduces noise resulting from optical system noise.

To minimize the noise associated with image filtering systems, a reflective transform architecture was developed that compensates for resolution and noise. This reflective transform preprocessor developed was the first to incorporate this polychromatic conditioning filter, which allows for simultaneous preprocessing to be achieved at low cost.

Having minimized the sources of optical noise, operating the system in the partially coherent mode at the same time, utilizing sequential input to

real-time viewing conditions, the effective compressions in bandwidth based on a subjective quality of the reconstructed images with vs. without preprocessing, were determined for low sampling rates.

Subjective data was obtained for various pictures with varying degrees of movement and scene complexity. These subjective comments were found to be generally in reasonable agreement with the results of other authors in terms of the increased visibility of the edge noise component, and reduced image quality at low sampling rates.

Color as well as monochrome subjective evaluations of the edge noise characteristics uncovered asymmetry in the monochrome reconstruction and a dither averaging of the color noise components which masked the edge noise. The objective of this characterization was to produce an optical preprocessing filter which was matched to the encoder noise characteristics. The program was successful with monochrome as well as color ADM encoded images. In obtaining for the first time a reduction in edge noise that discriminated between error-causing and non-error-causing transitions through phase encoding the input, asymmetric transform filter achieved compression that differed from simple binary symmetric or defocusing techniques. Analysis of the experimental results showed that this type of optical preprocessing of images to be transmitted using ADM achieved compression at low sampling rates when the edge bysyness

became the dominant perceptual noise mechanism. At these rates the viewers preferred an image that was freer of this time varying, distracting class of noise.

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