CHARACTERIZATION OF AN EXPERIMENTAL VIDEODISC

FOR DIGITAL INFORMATION STORAGE

by

CHARLES BENJAMIN DIETERICH

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREES OF

BACHELOR OF SCIENCE

and

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June, 1978

Signature of Author Signature redacted
Department of Electrical Engineering and Computer Science,
May 17, 1978

Certified by Signature redacted
Thesis Supervisor (Academic)

Certified by Signature redacted
Company Supervisor (VI-A Cooperating Company)

Accepted by Signature redacted
Chairman, Departmental Committee on Graduate Students.

CHARACTERIZATION OF AN EXPERIMENTAL VIDEODISC FOR DIGITAL INFORMATION STORAGE

by

CHARLES BENJAMIN DIETERICH

Submitted to the Department of Electrical Engineering and Computer Science on May 17, 1978 in partial fulfillment of the requirements for the degrees of Bachelor of Science and Master of Science

ABSTRACT

The RCA VideoDisc system can permanently store up to two hours of television programming on a vinyl disc. This thesis describes experiments which were performed to characterize the utility of the VideoDisc system as a storage medium for digital information. For all studies in this report, a developmental version of the VideoDisc that stored one half hour of television programming per side was used. The methods and results of these experiments are presented as well as necessary background material concerning the operation of the VideoDisc system.

The work reported includes the design and implementation of a testing waveform used as an input to the system, detection methods used on the output signal, and the formation of statistics ot characterize the system's performance.

Experimental results include error rate and correlation studies as well as the characterization of error mechanisms which affect the retrieval of data. As a result of these studies, the information capacity of a one half hour VideoDisc as a read-only memory is estimated to be in excess of four billion bits.

Name and title of thesis supervisor:

Jeffrey H. Shapiro, Associate Professor of
Electrical Engineering and
Computer Science.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENTS

I would like to express my thanks to those who advised me on my thesis work. Istvan Gorog of RCA Labs. proposed the project and served as my primary supervisor. Jim Gibson, Jon Clemens, and Art Firester also served as "guardian angels" for the project. Dave Jose and Mike Ross were very helpful in providing information about the system's circuitry and standards. Most of all, I would like to thank Dick Palmer, who was always glad to listen to my troubles and who answered so many of my day-to-day questions.

Back at M.I.T., I am grateful to Professor Shapiro for monitoring my progress and for his much needed advice in the preparation of the thesis itself.

INTRODUCTION

This thesis deals with experiments performed at the RCA David Sarnoff Research Center in Princeton, New Jersey during the summer and autumn of 1977 as part of the Electrical Engineering and Computer Science Department co-op program. The goal of these experiments was to characterize RCA's experimental VideoDisc system as a storage/retrieval system for digital data.

The VideoDisc system was developed by RCA for consumer use. In these tests* the system uses a coated vinyl disc which employs an extremely fine phonograph-like groove on its surface to record one half hour of television programming. The video signal is reproduced using a sapphire stylus which rides in the groove. The recording system was designed to store picture information in video format. The video signal has been modified for efficient recording on the disc, and the player has been designed to use the qualities of this signal to eliminate noise and other distortions in the detection process.

The experiments described in this thesis were not intended to explore changes in recording format (groove depth, modulation methods, bandwidth, etc.) but rather to indicate a reasonable method of storing digital information on the disc using the current format, and to give some indication of how well such a storage method would perform.

* As of June 1978, new materials were being used for the disc and stylus and the recording time had been increased.

Preliminary calculations for the system give an incredible storage capacity. Specifically, assuming a bandwidth of 3MHz, with two signal samples per Hertz of bandwidth and up to 2^5 distinct levels implies that a 30 minute recording might hold:

$$(3x10^6 Hz)x(2\frac{samples}{Hz})x(5\frac{bits}{sample})x(60\frac{sec}{min})x(30\frac{min}{\frac{1}{2}hour})=54x10^9 bits$$

These calculations are overly optimistic because they neglect various requirements of the VideoDisc system, such as synchronization, and details of the noise processes encountered in detection of the data. The experiments performed for this thesis were designed to determine how to change the capacity calculation to accurately reflect the characteristics of the VideoDisc system.

To understand the experimental results, video signals and the VideoDisc system must be understood. For this reason, the thesis has been divided into four chapters. The first chapter provides the necessary background in video signals and the VideoDisc. Chapter two describes the test signals which were recorded on the test disc, and the equipment constructed to detect them. Chapter three explains the actual experiments performed with the test equipment, and some of the results obtained. Finally, these results and their implications are discussed in chapter four.

1. VIDEO SYSTEMS AND THE VIDEODISC

1.1 Video Systems

In order to describe the operation of the VideoDisc, several facets of video signals must be understood; this section provides a review of these facets.

1.1.1 Monochrome (Black and White) Video Signals

The VideoDisc signal format is a variation of the standard (N.T.S.C.) video signal used in broadcasting[1*]. The NTSC signal is designed to transmit one frame of a moving picture thirty times a second. The frame is divided up into two interlaced fields. Each field contains information about the entire picture, but with only half the resolution of the frame. Picture information consists of an array of the brightness level of every point in the picture (figure 1). These brightness levels are read out in the same way as words are read from a printed page (see figure 1). Each horizontal line has a sequence of words (brightness points) read out from left to right, each page (frame) has 525 horizontal lines of information read from top to bottom. The interlacing of fields causes the 263 odd numbered lines to be read out before the 262 even numbered lines.

The NTSC signal is intended for asynchronous reception. Synchronization information must be transmitted

---

1* National Television System Committee standards. All references are listed at the end of the thesis.

in the video signal itself. A new frame is transmitted every 33.3 milliseconds, so one horizontal line is transmitted every 63.5 microseconds. Ten microseconds of this period is reserved for the horizontal synchronizing pulse (sync). This pulse makes use of the fact that negative brightness cannot exist. The electronic representation of the video waveform assigns a voltage to a reference white level and another to represent no light (blanking). These are given the designations 100 IRE and 0 IRE respectively[2] (the Institute of Radio Engineers standard unit for video signals can be thought of as the percentage of full brightness). The IRE scale is linear with respect to voltage levels. In practice 0 IRE often equals 0.0 volts and 100 IRE equals 0.7 volts but the voltage assignment is arbitrary. The horizontal sync pulse uses a voltage level of -0.3 volts, or -40 IRE (less than no light). A 5 microsecond pulse of -40 IRE is embedded in a 10 microsecond blanking interval (see figure 2). The leading edge of sync indicates the start of a new horizontal line; the 8 microseconds that follow provide time for the video display flyback.

Vertical sync also uses -40 IRE to identify the beginning of each field. This pulse is significant in the VideoDisc system only because it takes up 7% of the time in each field; neither the player, nor the digital data storage system make use of it,and it is fed through the system to the video display without modification. Important details of the video system are reviewed in the following table:

	Level	Time	Frequency
Frame	-40 - 100 IRE	33.3msec.	30 Hz.
Field	same	16.7msec.	60 Hz.
Horizontal line	same	63.5usec.	15.75KHz.
Horizontal blanking	0 IRE	(10usec. including sync)	
Horizontal sync	-40 IRE	5 usec.	15.75KHz.
Visible portion of horizontal line	(0 - 100 IRE)	52 usec.	

1.1.2 Color Video Signals

Color video signals differ from monochrome signals in that three quantities must be specified for each point in the picture. In addition to the luminance (brightness), two chrominance quantities (hue and saturation) must also be specified. The brightness of a scene can be determined by the human eye with much higher resolution than the color or saturation. To provide four hundred brightness array points on each horizontal line, 4 MHz. signal bandwidth is required ($2 \frac{\text{points}}{\text{cycle}} \times 4\text{x}10^{6}\text{Hz.} \times 52\text{x}10^{-6}\text{sec.}$). Chrominance signals only require one eighth of this resolution, and therefore need only .5MHz. bandwidth. The two chrominance signals are modulated onto a subcarrier at 3.58MHz* The hue signal determines the phase of the subcarrier and the saturation determines the subcarrier amplitude (a grey area, with zero color saturation, has zero amplitude subcarrier). This subcarrier is directly added to the baseband video signal (see figure 3). To determine the hue a reference phase color subcarrier (3.58MHz.) burst is also included in the signal during what is called the horizontal period's "back porch" (see figures 2,3). While the proper saturation of a colored area is often a subjective decision, the hue of objects in a picture is much more critical. For this reason the phase of the reference must be detectable to within four or five degrees.(5 nanoseconds resolution).

1.2 VideoDisc Format

The VideoDisc has a modified NTSC color signal recorded on it. The three modifications are (see figure 4):

1) The bandwidth of the luminance channel is limited to 3 MHz., instead of just over 4 MHz.
2) The chrominance signals are moved from a 3.58MHz. subcarrier to a 1.53MHz subcarrier by a simple heterodyning process. The frequency of the color burst is also moved to 1.53MHz in this process.
3) The high frequency portion of the luninance signal

---

*The exact frequency is 3,579,545 Hz. For convenience, in this thesis we will round off this and many other frequencies. For exact values refer to the appropriate standards.

is pre-emphasized before recording to compensate for the characteristics of the detection system's frequency modulation detector.

1.3 VideoDisc System Configuration

The VideoDisc system, shown in figure 5, includes recording apparatus, replication processes, the VideoDisc player and a television set. The recorder modifies the NTSC color signal as described in section 1.2 and frequency modulates this signal onto a 5 MHz. carrier. This FM signal controls the intensity of an electron beam which in turn controls the groove depth on a master disc. This disc is replicated by a process similar to the phonograph replication process. The replicated disc is coated with a thin layer of metal and a layer of insulating styrene. Detection of groove depth is done with a thin metal strip deposited on the trailing edge of a sapphire stylus. The capacitance between this strip and the bottom of the groove is the parameter which represents the groove depth.[3] A capacitance to voltage converter recreates the 1-9 MHz. frequency modulated signal.

The FM signal is then demodulated using a zero-crossing type frequency to voltage converter. This

3. [illegible]

produces a replica of the modified NTSC signal. Here one major problem with disc recording is corrected. The VideoDisc must be centered very precisely to maintain timebase stability. A centering deviation of about 7 mils (0.18 mm) leads to a timebase excursion of about 50 microseconds.[4] To use the color subcarrier, the timebase stability must be on the order of a few degrees of phase at 3.58MHz. (a few nanoseconds).

There are two feedback systems which reduce the instability. The first, called the arm stretcher, physically moves the stylus along the groove; it modulates the effective rotational velocity, compensating for most of the time variation. To use the arm stretcher, the magnitude of the time variation must be known. The 1.53MHz. burst provides an excellent measure of timebase excursion. The tracking voltage in a phase locked loop locked to the 1.53MHz. burst integrates the velocity variation. This voltage controls the distance the arm stretcher is extended. This arm stretcher loop stabilizes the timebase for the entire video signal to within 150 nsec or so.

To further stabilize the timebase, another closed loop system is used (shown in figure 6). In heterodyning the NTSC subcarrier a 5.11MHz. local oscillator is employed. In reconstructing the video signal, the 1.53MHz. chrominance signal is heterodyned up to about 3.58MHz. by a 5.11MHz. voltage controlled oscillator. The heterodyned 3.58MHz. burst signal is phase locked to a 3.58MHz. crystal oscillator, using the 5.11MHz voltage controlled oscillator to compensate for the burst's phase variations. Unlike the arm stretcher, this correction only changes the chrominance signal phase, and does not affect absolute time reference. It does, however, provide a method for recreating a 1.53 MHz. signal which tracks any disc timebase variation to within a few nanoseconds. This final factor is instrumental in the implementation of non-self-clocking waveforms for digital data storage.

2. TESTING METHOD

The approach used to characterize the VideoDisc as a data storage/retrieval system involved four steps:

1) Defining what portions of the VideoDisc system would be modeled as the communication channel.
2) Designing a set of test signals for transmission over this channel.
3) Designing and building equipment to send (record) and receive (playback) these test signals, and to derive relevant characteristics from the received signals.
4) Performing experiments with the equipment to characterize and evaluate the characteristics of the channel.

The first three of these steps will be dealt with in this chapter.

2.1 The Channel

The input and output points of the VideoDisc channel are not well defined. In its most general form, the channel has,as an input,a voltage which modulates the recorder electron beam which,in turn,modulates groove depth on the master disc. The output is a voltage produced by the capacitance to voltage converter in the player.

At the other extreme, the channel input could be constrained to be a 4 MHz. bandwidth video-like signal, with horizontal and vertical sync and color burst pulses included. The voltage waveforms in the visible portion of the horizontal period, which carry the data to be communicated, would be constrained to lie between 0 IRE and 100 IRE. Signal components which looked like chrominance signals would be heterodyned down to 1.53MHz. from 3.58MHz. The bandwidth would be limited to 3 MHz. and pre-emphasis filtered. The received voltage would only be available after frequency demodulation, chrominance remodulation, arm stretcher timebase correction and several other video processing stages.

Neither of these channel definitions were suitable. The first was too general and the second too constrained. Instead a definition in between these two was chosen. The desirable characteristics, such as use of the arm stretcher, the 1.53MHz oscillator which tracks any variations in the timebase, and the use of the existing frequency modulator and demodulator were retained from the more restricted channel description. Useless or complicating restrictions such as the chrominance remodulation, vertical sync, video pre-emphasis, and other video processing stages were removed.

The channel, as tested for this thesis, consists of:

1) A frequency modulator which accepts voltage levels between -50 IRE and +120 IRE with a bandwidth of 3MHz.

2) The VideoDisc master production equipment and all stages of replication.

3) The stylus, capacitance to voltage converter, FM signal demodulator, arm stretcher and phase locked loop (1.53 - 3.58 - 5.11MHz.) circuitry.

Input signals are restricted to include horizontal sync and 1.53MHz. burst. The data signals must be between 0 IRE and 100 IRE and occur in the visible portion of the horizontal period. Output signals comprise the frequency demodulator output and the demodulator's anomaly detector (the anomaly detector, or defect gate, is turned on whenever the interval between adjacent zero crossings corresponds to a voltage level of more than about 180 IRE or less than -60 IRE). Also,timing signals such as the 1.53MHz. signal which is phase locked to the color burst recorded on the disc, and horizontal sync pulse are available as outputs.

2.2 Test Signals

To reproduce quality video signals, the VideoDisc system must meet certain performance standards. Two of the most stringent standards which the system must maintain are the phase linearity and signal-to-noise ratio standards. The phase linearity standard requires that the brightness value for each point in the brightness array be kept separate from adjacent brightness points in their video signal representation. This implies that time orthogonal signaling methods (such as bit-by-bit signals[5]) can be used on the channel, even at signaling rates close to the sampling limit of twice the signal bandwidth. A signal-to-noise ratio in excess of 40dB is required to keep the noise from being visible when the video is displayed.[6] The channel's high signal-to-noise ratio implies that a multi-level signaling scheme might be usable. N bits of information would be encoded onto a pulse, causing its amplitude to be one of 2^N levels. The receiver would sample this pulse to determine which level was transmitted.

The test signals are designed to probe the issues of pulse duration (signaling rate) and the number and structure of levels in a multi-level signaling system. The pulse shape is not a variable in these tests--a square pulse signal, bandlimited to 3 MHz. is used throughout.

Preliminary investigation into the channel's characteristics indicated several factors for concideration. Noise on the channel seemed to be primarily due to two sources. The first source appears to be Gaussian distributed, and arises from the inherent roughness of the vinyl surface and the coatings. This creates variations in the capacitance seen by the stylus and it is demodulated along with the desired video signal causing zero crossing jitter. The second noise source is due to vinyl defects and dust or other substances in the groove. These create anomalies, completely eliminating the recorded signal for anywhere from a few hundred nanoseconds to several microseconds. Neither of these noise processes are completely independent of the signal (brightness) level. A signal near 100 IRE may have a higher probability of anomaly and higher Gaussian noise than a signal near 0 IRE. A problem equivalent to studying the performance of the channel for digital data storage is to study the effect of these two types of noise on square pulse signals of various amplitudes and durations.

2.2.1 Two Level Signals

The two level signals are the primary test signals used in the system. They provide performance information as a function of signal amplitude (distance between levels), signal offset (base IRE level),and pulse duration (clock rate). Using the two-level signal set we can simulate the performance of a more general multi-level signal set by choosing the amplitude separation between the two levels to be a separation found in a multi-level signal. For example, if adjacent levels are separated by 12 IRE, eight levels could be contained in the interval between 0 IRE and 100 IRE.

The aim of the two level signals is to encode a known binary data sequence onto the visible portion of the video format using square pulses of various amplitude and offset levels. Figure 7 shows the general two level signal waveform before the 3 MHz. bandlimiting filter. The data sequence is identical for every horizontal line. For each test signal, particular values of delta, A_o, and T are chosen. The pulse amplitude, delta, assumes values of 4, 8, 12 and 16 IRE. The offset, A_o, is either 0, 32, 64 or 80 IRE. The pulse duration, T, is chosen such that the clock frequency is directly related to the 1.53 MHz. burst frequency. Taking T^{-1} to be twice 1.53MHz. or 3.06 MHz, yields 195 full cycles per horizontal period (exact value). Of these 195 cycles, 160 are in the visible portion of the video format. Values of T corresponding to 3.06, 1.53, .76, and .38 MHz. data rates (or 1, 2, 4, and 8 cycles per clock pulse) were used.

The binary data sequence encoded in these signals is a maximal length, or pseudorandom, sequence. These sequences are easily generated and are deterministic.[7] When the signal is played back and detected, the received data sequence can be compared with the original pseudorandom sequence to produce an error sequence. Pseudorandom sequences accurately simulate the random nature of data sequences. Therefore, the error sequence characterizes the errors which an actual data storage system would make.

2.2.2 Four Level Signals

While the 64 different two level signals characterize the channel in many ways, they provide no information about intersymbol interference. To examine this problem, which multi-level signal sets are quite sensitive to, 32 waveforms which accentuate this sensitivity are produced (figure 8). These waveforms substitute a pulse of amplitude much greater than delta for every other occurence of a one or zero. For ones in the data sequence, the higher level pulse has amplitude delta + 32 IRE. For zeroes in the data sequence the high level pulse is 32 IRE below the normal zero level (A_0- 32 IRE). These signals serve one other function in addition to evaluating intersymbol interference. The high level pulses can be regarded as a separate signal set, with 'delta'= 68,72,76 and 80 IRE. This would provide performance information on very large signals. All four data rates were used with the four level signals, but only two offsets were recorded.

2.2.3 Test Sequencing

To put all 96 test signals on one VideoDisc and to be able to determine which is which on playback, some form of automatic test sequencing and identification is required. The VideoDisc can hold thirty minutes of video format signals, recorded at radii between 5.75 inches and 3.3 inches. The characteristics of the channel may vary as a function of disc radius. To evaluate this relationship each of the 96 tests should be recorded several times on one disc. Each test lasts two seconds, the automatic sequencing method permits all 96 tests to be recorded in a little over three minutes. Each test signal is recorded at least nine times on a single VideoDisc.

The format for the test signal progression is shown in figure 9. Each two second test period begins with a fixed 16 H (where 'H' is the horizontal period) sequence of levels, each of which is constant for the entire visible portion of a horizontal period. This sequence is used in synchronizing the two second test periods. The sequence of values chosen has an autocorrelation function similar to that of a Barker code.[8]

A Barker code is a sequence $(C_N(n))$ which assumes values in the binary set (+1,-1) and has an autocorrelation function $R_{cc}(k)$ which satisfies:

$$\sum_{n=0}^{N-k} C_N(n) \times C_N(n+k) = \begin{cases} \pm 1, & \text{for } k \neq 0 \\ N & \text{for } k = 0 \end{cases}$$

The synchronizing sequence length desired (N=16) was longer than the longest known Barker code. The code employed was designed to be similar to a Barker code in that it its autocorrelation function contains an N unit high pulse at k=0 and does not take on large positive values for $k \neq 0$.

The autocorrelation function's positive pulse is designed to signal the start of the parameter data sequence, which takes up the next eight horizontal lines. The eight bits of parameter data are encoded one bit per H . They specify what test parameters are used in the next test period*. The decoder will store this sequence, recording it with the statistics gathered from the test period. The test parameter sequence is followed by 32,744 lines of actual test signal waveforms. The initial 204 lines allow the decoder's automatic level alignment equipment to find the test signal's average level. This average level will be used to set the signal detection threshold.

2.2.4 Test Signal Review

As a review, we will now list the important features of the test signals:

The test signals last for 32,768 Horizontal periods.

The initial 128H are used for test identification

* ~~Clearly,~~ only 96 of the 2^8 possible test parameter sequences are used.

and alignment, the remaining 32,640 horizontal periods in a particular test are identical waveforms used for statistical sampling.

Every horizontal period begins with a -40 IRE sync pulse and 1.53MHz. burst signal.

The visible portion of the horizontal period, that follows sync and burst, contains the test waveform, which lasts for 160 cycles of 3.06MHz. or about 52 usec.

The waveform in the visible portion is controlled by a pseudorandom data sequence. The clock rate is either 3.06MHz., 1.53MHz., 0.76MHz., or 0.38MHz.

For all signals with a particular clock rate, every horizontal period contains an encoding of the same data sequence, only the offset and level separation (delta) between ONE and ZERO levels change.

Four level signals differ from two level test signals in that ONEs are represented by two different pulse sizes, one of which is 32 IRE larger than the other. ZEROes also are represented by two different level pulses one of which is 32 IRE farther away from the ONE levels. These pulses are called high level pulses because of their large, 64 + delta IRE, separation from each other.

2.3 Testing Equipment

Three major pieces of equipment are required to perform experiments on the VideoDisc channel. The first piece, the encoder, produces the test signal as specified in the previous section. The second device, the decoder, takes the signal which has been reproduced by the VideoDisc player, and converts it into a binary data stream. The decoder also performs all synchronization and timing functions for the test system. The error registers convert the binary data stream into a set of statistics which can be stored in a computer and analyzed further.

The test setup block diagram is shown in figure 10. The VideoDisc recorder feeds the encoder block a 1.53MHz. sine wave. From this timing signal the encoder creates the test signals, including the video format of the test signal (sync and burst) and the pseudorandom data sequence S(n)*. The encoder also counts the 32,768 horizontal lines which make up one two second test period, inserting the test synchronizing sequence and the test parameter sequence at the proper times.

Just as the encoder encodes the pseudorandom data onto the video waveform, the decoder must take the re-

---

*The index n denotes the time interval $nT \leq t < (n+1)T$

created video waveform from the VideoDisc player, along with horizontal and color subcarrier timing signals, and from it produce an estimate of the transmitted data sequence. this estimate, $\hat{S}(n)$, can be compared to what was actually transmitted by using another pseudorandom sequence generator to recreate the binary sequence, S(n). An error sequence, E(n), is produced to indicate when $\hat{S}(n) \neq S(n)$, ($E(n) = (\hat{S}(n)$ exclusive-OR $S(n)$). The pseudorandom sequence generator in the decoder also produces a binary sequence HL(n) which takes on the value ONE when a high level pulse was transmitted. Another sequence, D(n), gives the state of the defect gate in time interval n.

The characteristics of E(n) and D(n) and their relationships to S(n) and HL(n) are measured statistically in the error registers. These four sequences make up the inputs to the error register block. The error register's configuration allows a wide range of statistical experiments to be performed with the sequences. Correlations and cross-correlations as well as other effects produced in the channel,are measured statistically and recorded at the end of every two second test period.

Some understanding of each of these three pieces of test equipment is required to interpret experimental results. The next three sections of this chapter will explain their operation in greater depth. Circuitry details will be omitted except when they are critical to the analysis of system performance or when the implementation of a functional block is not straightforward.

2.3.1 Encoder

There are four functions which are performed in the encoder (figure 11). The first is timing, i.e. generating the horizontal period, the test period and the progression of the signal's parameters. The second is the generation of the test synchronizing sequence and parameter data sequence to indicate the beginning of, and the parameters used in,a test period. The third is the generation of the pseudorandom data sequence, S(n), and the high level flag, HL(n). The fourth takes the digital signals which have been produced by the other three sections and generates an analog waveform from them.

The three blocks at the top of figure 11 perform the horizontal period timing, the test period timing and parameter sequencing. The horizontal timing block has, as outputs,pulses which indicate the location of sync and burst as well as the four data clocks (3.06MHz., 1.53MHz., 0.76MHz. and 0.38MHz.). The clock frequency parameters from the parameter sequencing block determine which one of these clock rates is used in the pseudorandom sequence generator. The pseudorandom sequence generator produces a 31 bit long repeating sequence, containing

16 bits in which S(n)=1 and 15 bits with S(n)=0. The circuit uses five flip-flops and one exclusive-OR gate[9]. From S(n), HL(n) is created in a straightforward manner.

The test synchronizing sequence, C(h), and parameter sequence, $G_p(h)$, are generated at the start of each test period (the index h is incremented at the horizontal rate, 15.75 kHz.). The video former uses the test parameters to set delta and A_o. Which circuits in the digital to analog converter receive the data sequences S(n) and HL(n) is determined by the signal type, delta and offset parameters. The entire system works automatically, inserting the test synchronizing sequence and parameter sequence at the proper intervals. The only control (not shown) is a reset button. This continuous video signal is bandlimited to 3½ MHz. and fed into the frequency modulator in the VideoDisc recorder.

2.3.2 Decoder

In theory, all the decoder must do is make some evaluation of the received waveform, judging whether the transmitted data in the time period $nT \leq t < (n+1)T$ was a ONE or a ZERO, thus creating a detected data sequence, $\hat{S}(n)$. This sequence need only be compared with the true data sequence, S(n), to produce the error sequence, E(n). In practice much more is required of the decoder. Four synchronizing systems are needed to determine: the value of T, the value of n, the location of n x T, and the proper way to judge the received signal.

Assuming the synchronization systems exist and provide this information, detection proceeds by the following method. The received waveform, r(t), can be modeled as the transmitted waveform, X(t), plus some noise process, n(t). X(t) can be represented* in the form:

$$X(t) = \sum_{n} B_n \times (u(t-nT) - u(t-(n+1)T))$$

where u(t) is the unit step function and B_n equals A_o+ delta when S(n)=1 and $B_n=A_o$ when S(n)=0. To produce an estimate of the data sequence, S(n), the most likely value of B_n given r(t) must be determined. The decoder uses a correlation detector to perform this operation. For square pulse signals, the correlation detector performs a gated integration:

$$K(n)=\int_{nT}^{(n+1)T} r(t)\, dt$$

Expanding r(t) we have:

$$K(n)=\int_{nT}^{(n+1)T} X(t)\, dt + \int_{nT}^{(n+1)T} n(t)\, dt$$

$$= T \times B_n + N_n$$

Where N_n is defined by the second equation. It is assumed

* Clearly, this form does not hold outside the visible portion of the horizontal line.

that N_n is approximately Gaussian distributed and zero mean. Therefore, if $T \times B_n > T \times (A_o + \frac{delta}{2})$ then B_n is more likely to have been A_o+ delta than A_o implying that $\hat{S}(n)=1$ is the maximum likelihood estimate of S(n) (and visa-versa for $\hat{S}(n)=0$).

The quantity $A_o + \frac{delta}{2}$ is called the detector threshold. In view of the variation of the parameters A_o and delta, sixteen different values of the threshold are used for the various different tests. Instead of worrying about maintaining all of these thresholds, the system finds the threshold automatically. This number is found by averaging the data level over several horizontal periods. Because S(n) is ZERO almost as often as it is ONE, and because N_n is zero mean, $\overline{r(t)}$ is very close to $A_o + \frac{delta}{2}$, the correct value for threshold. The average of r(t) is made over the visible portion of the video signal (the interval which contains the data), so a visible portion low-pass filter is used. This is a simple (resistor-capacitor) one pole filter, but with a variable value for R; during the visible portion of the signal, R x C = 5H, during sync and burst $R \times C = \infty$ By design, the four level test signals also have an average level which is the optimum threshold, so the sequence $\hat{S}(n)$ can also be derived from the four level signals using the detector described above. An estimate of HL(n) is not produced.

The floating threshold is one of the four synchronization systems used in the decoder. For this signal detection scheme to function properly, two other forms of synchronization are required. First, the integration limits must be aligned to the beginning and end of the transmitted square pulse. This is accomplished by adding a variable, wideband delay to the demodualted video output, as was shown in figure 10. The delay is varied until the phase difference observed on an oscilloscope is zero and there are minimum errors. The second synchronization is the horizontal period synchronization process, needed to define the visible portion of the horizontal period as well as choosing the proper starting point for the recreated pseudorandom sequence, S(n). Fortunately, the VideoDisc player also requires a horizontal timing pulse, so the timing pulse for the decoder is taken directly from the player. This signal is aligned to the demodulated video using another variable delay line. This conceptually simple method of producing horizontal synchronization caused a few problems when experiments were performed, as will be mentioned in the next chapter.

The fourth synchronization system produces a pulse at the start of each two second test period by scanning the received signal for the test synchronizing sequence. To detect this signal another correlation detector (which integrates over one horizontal period and had a fixed threshold) generates a binary series, G(h), which indicates the average signal level during horizontal period number h. A shift register and resistive summing network produce the correlation function between the received sequence G(h) and C(h) as described in section 2.2.3. R_{GC} takes on a large positive value when the received sequence is aligned with the test synchronizing sequence (even allowing for one or two detection errors). This positive pulse occurs at 16 H into the two second test period. It indicates that the next eight values of G(h) will corespond to the test parameter sequence, $G_p(h)$. An eight bit shift register stores these values of G(h) for output to the computer. If R_{GC} also had a large pulse 32,768 horizontal periods earlier, then the system has probably been functioning properly. If this was not the case then a locked groove or a skip has occured and the statistics taken in the previous test are probably incorrect.

The block diagram of the decoder system is shown in figure 12. The data sequence detector comprises the two blocks in the upper right hand side. Detection of the test synchronizing sequence and test parameters is performed in the three blocks at the lower right. The defect gate signal, d(t), is a continuous analog signal. Circuitry at the right converts d(t) into a binary series, D(n), using a gated comparator and a flip-flop. The test parameters and lock/skip flag are output directly to the computer interface, whereas the four sequences: E(n), S(n), HL(n), and D(n) are fed to the error registers.

2.3.3 Error Registers

The previous pieces of equipment are designed to be aligned and used as they are. The error registers, on the other hand, have no set configuration. The gates and counters are designed to be arrangeable in many different ways so that many different statistical quantities can be measured. Each new configuration constitutes a new experiment. Twenty-nine experimental configurations were used in gathering information about channel operation for this thesis.

The error registers comprise six modulo 10^5 TTL counters which serve as event counters, and an event patchboard, which includes gates, shift registers and counters. This patchboard accepts as inputs the sequences S(n), E(n), D(n), and HL(n). The event patchboard can be used to create event indicator functions from the detector output sequences. An example of this is:

$$Y(n) = E(n) \text{ and } E(n-1) \text{ and } D(n-1)$$

This function (or event) is ONE whenever two errors occur in sequence and a defect occurs at the same time as the first error. Every occurence of this event in a two second test period increments the event counter.

At the end of the test period, the counter's value is transmitted to a computer file and the counter is reset to zero.

The error registers are shown in figure 13. Experiments can investigate coincident occurences of two conditions (using AND gates), sequential occurences of a condition (using the shift registers) or occurences of a condition during a specific time period (using the presettable down counters). Two simple and useful configurations are:

Y(n)= E(n) (errors)

Y(n)= E(n) and HL(n) (high level errors)

In one experiment, the existence of very long bursts of errors was being investigated. The measured event occurs at the start of every burst of errors; also two events can not occur within 89 bit of each other. Essentially, the experiment classifies all bursts of errors (or bursts of bursts of errors) that last less than 89 bits as one event. The circuitry wired on the patchboard is a hardware implementation of the flowchart or PL/1 routine in figure 14. With E(n) as an input, this routine counts how many disjoint segments of the sequence E(n) contain an error in the first position of the 89 bit segment.

There are six event counters, so up to six experiments can be performed at one time. Counters can also be put in tandem to count to higher than 10,000 (the carry signal from one counter being used as the event for another counter). The patch boards are able to generate hundreds of statistical quantities, only a few of which were used in the thesis research. Only the configurations which produced interesting and useful statistics will be outlined in the discussion of the actual experiments.

3. EXPERIMENTS

A total of 29 different experiments were performed with the foregoing equipment over the period of about two months. These tests were of two different types. The first type gave statistics of events which served to characterize the channel in a mathematically concise manner. The second type investigated situations which were not explained easily using simple mathematical characterizations. This chapter is organized into two sections. The first discusses the characterization experiments, while the second will deal with methods of investigating other factors in the channel.

3.1 Characterization

As stated in chapter two, the noise processes which distort the test waveform are of two main types, additive Gaussian-like noise and anomalous noise. The Gaussian noise is more likely to cause errors in the lower energy test waveforms (smaller values for delta and T). The anomalous noise (defect gate detected noise), by contrast, affects all test waveforms of a given duration equally. Gaussian noise is always present, while anomalous noise is bursty, only affecting a small portion of the signal.

To aid in the characterization of the channel, we can conceptually lump all the modulators, sync systems, and processing into one block called an error generator. This error generator, shown in figure 15, generates an error sequence, E(n), and a defect sequence, D(n). Within the scope of this thesis, characterization of the error generator is equivalent to characterizing the channel. The characteristics of a well designed generator model can be used to design an error correction system for an actual data storage/retrieval system.

The simplest generator model would make E(n) a Bernoulli process and make D(n) independent of E(n). A Bernoulli process is totally characterized by the per increment probability of being ONE*, i.e. Prob(E(n)=1). This is simply the probability of error or error rate, which the error registers can measure by setting Y(n)= E(n). Figure 16 shows this probability as a function of clock rate and delta (probability is plotted on a $\log_{10}$ scale, clock rate on a $\log_2$ scale). This graph also includes Prob(D(n)=1), the probability of defects, and Prob((E(n)=1) and (HL(n)=1)), high level signal error probability. For error rates greater than 10^{-3} the error curves are similar to those derived theoretically using the noise power spectrum measured on the disc. These theoretical error rates are derived in appendix 1 and shown in figure 17.

This first model for the noise process can be used

---

* In a Bernoulli process Prob(E(n)) is independent of E(m) for all m≠n.

to indicate the disc's data storage capacity. Channels which are disturbed by Gaussian noise alone are well understood and a large number of formulas exist for evaluating signal performance on such a channel.[10] Using the assumption that all errors were caused by Gaussian noise, one can estimate what noise level caused the error rate. This noise level determines the maximum data rate of a signal set constrained to lie between 0 IRE and 100 IRE. The error probabilities in figure 16 can be used to compute a form of channel capacity in this way. A partial table of the maximum data rates so derived is shown in the following table:

	Capacity (Mb/s)				
Clock rate	4IRE	8IRE	12IRE	16IRE	High Level
3.06MHz.	7.6_8	7.6_8	6.1_8	8.0_8	5.0_4
1.53	5.2_{16}	4.4_8	4.1_8	4.1_8	
0.76	3.4_{32}			2.3_{16}	
0.38	1.9_{64}				

These values are the maximum information storage capacity of the VideoDisc in Megabits per second for signals using the test system's waveshapes, clock rates and detection methods. The number does not include capacity lost to sync and burst intervals (which would decrease the capacity by 18%). Each value has a subscript which indicates how many different levels the waveform assumes in the optimum storage system. As an estimate of actual performance, the 12 IRE signal's calculated capacity is probably the most reliable. It proposes a multi-level system with eight levels and an adjacent level separation of 14 IRE. The delta= 12 IRE signal is a reasonable simulation of this signal.

Below error probabilities of 10^{-3}, factors other than Gaussian noise begin to dominate E(n). The high level error rate, for example, should always be less than 10^{-12} if Gaussian noise were the only factor influencing E(n). In this range the Bernoulli model is no longer accurate. For these signals a new error generator model is required.

The next model which might be used keeps D(n) independent of E(n), but E(n) is now related to E(n+m) for small m. This generator can be characterized by the correlation function:

$$R_{EE}(m) = \text{Prob}(\ E(n)=E(n+m)=1\ )$$

The values of this function for T= 1/0.76MHz and delta= 16 IRE are plotted in figure 18.(this particular test waveform was chosen for illustration because it has a low error rate and a moderately high clock rate). The exceedingly high correlation of errors for this waveform is evident. If the generator were a Bernoulli process then $R_{EE}(1)$ would be $R_{EE}(0)^2$ (less than 10^{-6}). This implies that almost all of the errors occur in bursts.

The next logical step would bring the defect gate, D(n), into play. The defect generator correlation function, $R_{DD}(m)$, is plotted in figure 19. These two generators are cross-correlated, as shown by the graph of $R_{DE}(m)$ in figure 20.

R_{DE}= Prob(D(n)=E(n+m)=1)

Clock rates of 0.76MHz. and 0.38MHz. are plotted here, with R_{DE} plotted as a percentage of $R_{DD}(0)$. The delay from the video filter and delay lines are evident in the time lag of the cross-correlation peak.

All of these results create a confusing picture of the error generator. If we define an error burst as a period in which Prob(E(n)=1) = $\frac{1}{2}$, and assume that the error rate takes on some constant low value at all other times, and define a defect burst as a period during which D(n)=1, then we can deduce several characteristics. The first concerns the distribution of error burst lengths. Using only the correlation function at m=6, $R_{EE}(6)$, it can be shown (see appendix 2) that at least 50% of all errors (for T= 1/ .76MHz., delta=16 IRE) are part of bursts of length nine or greater. The defect correlation function, on the other hand, guarantees that over 50% of the defects last less than four cycles of the 0.76MHz data clock. One of two conclusions can be drawn. The first says that defects affect the test signal's waveform for a period much longer than the actual defect. The second blames the high error correlation on some other, unknown, error mechanism, not related to defects.

Further characterizations (higher correlations, etc.) might have shed some light on the question. This route, however, would be very indirect. A more direct procedure would be to hypothesize generators which included specific mechanisms for the creation of errors. Experiments which explored critical characteristics of the generators could be used to eliminate false hypotheses. This is the method of experimentation used in the next section.

3.2 Investigative Experiments

While the characterization of the channel involved a wide variety of pulse amplitudes and clock rates, the investigative experiments concentrated on understanding details of channel operation for the two most promising signal waveforms. The first signal is the high level 3.06MHz. clock rate signal. It is the highest data rate signal which is not affected by Gaussian noise. The second signal is the delta=12 IRE, 3.06MHz. clock rate waveform. This signal has almost the same level separation as an eight level signal set (three bits per sample). Which was found to be the optimum number of levels for the Gaussian noise-Bernoulli error sequence model.

The 3.06MHz. high level signal is only affected by defect noise and the unknown noise source. Experimental results showed that the number of errors correlated with defects made up less than 25% of the total number of errors; this number did not have a large variance. The number of errors caused by the unknown noise was much larger, and it had a much higher deviation from its mean value. Observation of the signal on an oscilloscope suggested that the "unknown noise" problem could be due to the horizontal sync pulse misfiring. If the system was badly synchronized then the pseudorandom sequence would be misaligned for the horizontal period. Like Barker codes, pseudorandom sequences have an autocorrelation function which is approximately impulsive; misaligned sequences will have a 50% error rate. Therefore, if horizontal synchronization were the culprit, errors should occur in clumps of forty (there are 80 high level pulses per horizontal period).

An experiment was designed to test the validity of this model. The number of lines containing over 28 high level errors was measured, as was the total number of high level errors. The ratio of the second number to the first ranged from 43 to 40 with an average of 41. Very strongly implying that this was the cause of the unknown noise.

Several efforts were made to improve the horizontal sync pulse's stability, These included putting a faster comparator at the timing circuit input, taking the sync signal directly from the FM demodulator output and using a phase locked loop to generate an averaged sync pulse. None of these techniques solved the problem. No matter what was tried, between 50 and 500 horizontal lines in each two second test generated a sync signal which was more than 160nsec. away from the proper location. As the problem could not be overcome using the test system, an experiment in which the number of errors not caused by sync could be extracted and estimated was used.

The next experiment measured the number of 89 bit long disjoint segments in the error sequence which started with an error (see section 2.3.3 and figure 14). A line with bad sync would have a 160 bit segment which contained frequent errors, and would therefore take up two segments. Every burst of errors caused by a defect would also start off a new segment, except when it occured immediately after another error or was coincident with a badly synchronized line (which would be rare). A plot of the number of high level errors versus the number of segments is shown in figure 21. Only eight data points were taken, but these eight points cluster around a line with a slope of 21 high level errors per segment and an X intercept of about 250 segments in the two second test period. As two segments would occur in every badly synchronized line, the slope of 21 again indicates that

42 errors occur per badly synchronized line and 250 or so errors are caused by other sources, which produce errors in much shorter bursts.

To find out if these other errors were caused by defects, a very broad trap was set, counting all high level errors which occured within seven time increments after a defect. Three hundred to four hundred defect correlated high level errors were observed in each test period, making defects a likely cause for almost all of the remaining high level errors.

If defects could be considered the major source of errors, more study of their characteristics was desirable. Using a setup similar to the 89 bit error block test, a measure of defect lengths was obtained. Figure 22 is a plot of the probability that the defect gate stays on longer than a certain number of microseconds (measured as length in clock pulses). The ratio of defective bits to defects, or average defect length, was 2.25 microseconds.

These tests revealed several characteristics of the channel. Near the outside of the disc (radius near 5 inches) defects were twice as likely to occur when the signal offset was near 100 IRE as when the offset was 0 IRE. At smaller radii this effect became more pronounced, the ratio being four or five to one near 3.5".

Determination that defects were the source of most errors and rough characterization of that source was the extent of investigation done on the high level 3.06MHz. clock rate signals.

The other waveform, delta=12 IRE and T= 1/ 3.06MHz., was studied in a different way. Because most errors were caused by Gaussian noise for this level separation, correlation functions would not yield interesting data ($R_{EE}(1)$ was measured and found to be very close to the error rate squared). This left only three measurable quantities: variation with disc radius, variation with offset and intersymbol interference. Moving from the outside to the inside of the disc increased the error probability about 40%. Moving from 0 IRE to 80 IRE did not significantly change the error probability. The error probability for the delta=12 IRE waveform was much higher with a four level test signal than with a two level test signal. There seemed to be a lower limit to the error probability of .09 . The large pulses in the four level signal also affected the delta=16 IRE signals, with the lowest measured error probability being .05 . These figures imply that an eight level, 3.06MHz. square pulse signal may not perform as well as estimated previously. Because no signal effectively simulated equally spaced four level signals (delta=32 IRE), the performance of this signal set can only be guessed at. Theoretical error analysis shows that Gaussian noise should cause an error rate of 10^{-4}. Defect related errors would also occur at a rate near 10^{-4}. Intersymbol interference would be less severe (how much less is unknown), making this signal set the one which might yield the highest data storage capacity.

4 CONCLUSIONS

The results in this thesis are not as far-reaching as they might seem. A brief review of what the experiments have not shown may clarify this issue.

4.1 Limitations

Perhaps the most important limitation on the results is the fact that only one disc was tested. This statistical sample of one was known to meet several performance specifications, but it was not compared directly with other discs. It cannot be inferred that the error and defect probabilities found on the disc would be typical, better, or worse than those found on any other disc. Also, only one experimental VideoDisc player and stylus were used; these were known to be functional, but not necessarily typical.

If we assume that the disc, player and stylus are typical, then the results obtained from the particular encoder and decoder used in the experiments represent a lower bound on what can be done with a storage system. Many design variables were arbitrarily restricted, making this far from an exhaustive search for the optimum system. Other waveforms may have less intersymbol interference. Different filtering and pre-emphasis might reduce errors. Another sync system could probably lower the error probability for large amplitude signals. There are several other parameters which might improve the channel performance, but varying them was beyond the scope of this project.

4.2 Inferences

It is the lower bound aspect of the experiments which gives the most useful inferences. Results of the investigative experiments imply strongly that a 70 IRE separation two level, square pulse signal will have an error rate near 10^{-4}. The capacity[11] in bits per clock-period-containing-data is at least .994* . Using the defect gate signal to indicate when an error is likely might simplify the decoding hardware, but it could not increase capacity by more than .0055**. Thus a two level signal is capable of storing over 2.5 Megabits per second in the video format. Four or eight level signals may increase this value. If the problem of intersymbol interference is solved, up to 5 Megabits per second could be stored on the disc. It may be that the four level (0 IRE, 33 IRE, 66 IRE, 100 IRE) waveform would be the best choice, but no concrete evidence is available.

Before this project was begun a preliminary estimate set the disc storage capacity at 54 billion bits. The

---

* 5×10^{-4} was used as an overbound on P(E). The value given is one minus the entropy of P(E).

** For the erasure channel, C= 1- P(defect gate ON).

assumption that thirty-two levels could be used reliably was wrong. Instead of five bits of information per sample, only one or two can be stored reliably. The use of a 6 MHz. clock rate, possible in theory, was judged impractical; a 3.06 MHz clock was used instead. In addition, the estimate ignored issues of sync and time base stabilization, which further reduced the capacity by 20%, leaving a realizable digital data storage capacity of over 4.5 gigabits on a half-hour VideoDisc.

REFERENCES

1. Fink, Donald G., Television Standards And Practice Selected Papers from the Proceedings of The National Television System Committee and Its Panels, McGraw-Hill Book Company, Inc. New York (1943).

2. Standards on Television: Methods of Measurement of Television Signal Levels, Resolution, and Timing of Video Switching Systems, 1950. in Proceedings of the I.R.E. vol. 38, number 5. May, 1950. p.551.

3. Clemens, J.K., "Capacitive Pickup and the Buried Subcarrier Encoding System for the RCA VideoDisc", RCA Review, vol. 39, number 1, March 1978. p.33.

4. Rhodes, R.N., "The VideoDisc Player", RCA Review, vol. 39, number 1, March 1978. p. 198.

5. Wozencraft, John M. and Jacobs, Irwin Mark, Principles of Communication Engineering, John Wiley & Sons, Inc., New York (1965), p. 288-290.

6. Dean, Charles E., "Measurements of the Subjective Effects of Interference in Television Reception", Proceedings of the I.R.E. vol. 48 number 6. June, 1960.

7. Gallager, Robert G., Information Theory and Reliable Communication, John Wiley and Sons, Inc. New York (1968). p.232.

8. Van Trees, Harry L., Detection, Estimation, and Modulation Theory, Part III, John Wiley and Sons, Inc. (1971) p. 316.

9. Peterson, W.W. Error Correcting Codes, M.I.T. Press, Cambridge, (1961), p.147-148.

10. Wozencraft and Jacobs, op. cit. section 5.4 esp. p. 318.

11. Gallager, op. cit., p.92.

12. Abramowitz, M and Stegun, I.A., Handbook of Mathematical Functions, National Bureau of Standards (1964) p.244

13. Hewlett-Packard, HP-25 Applications Programs (1976) p.108

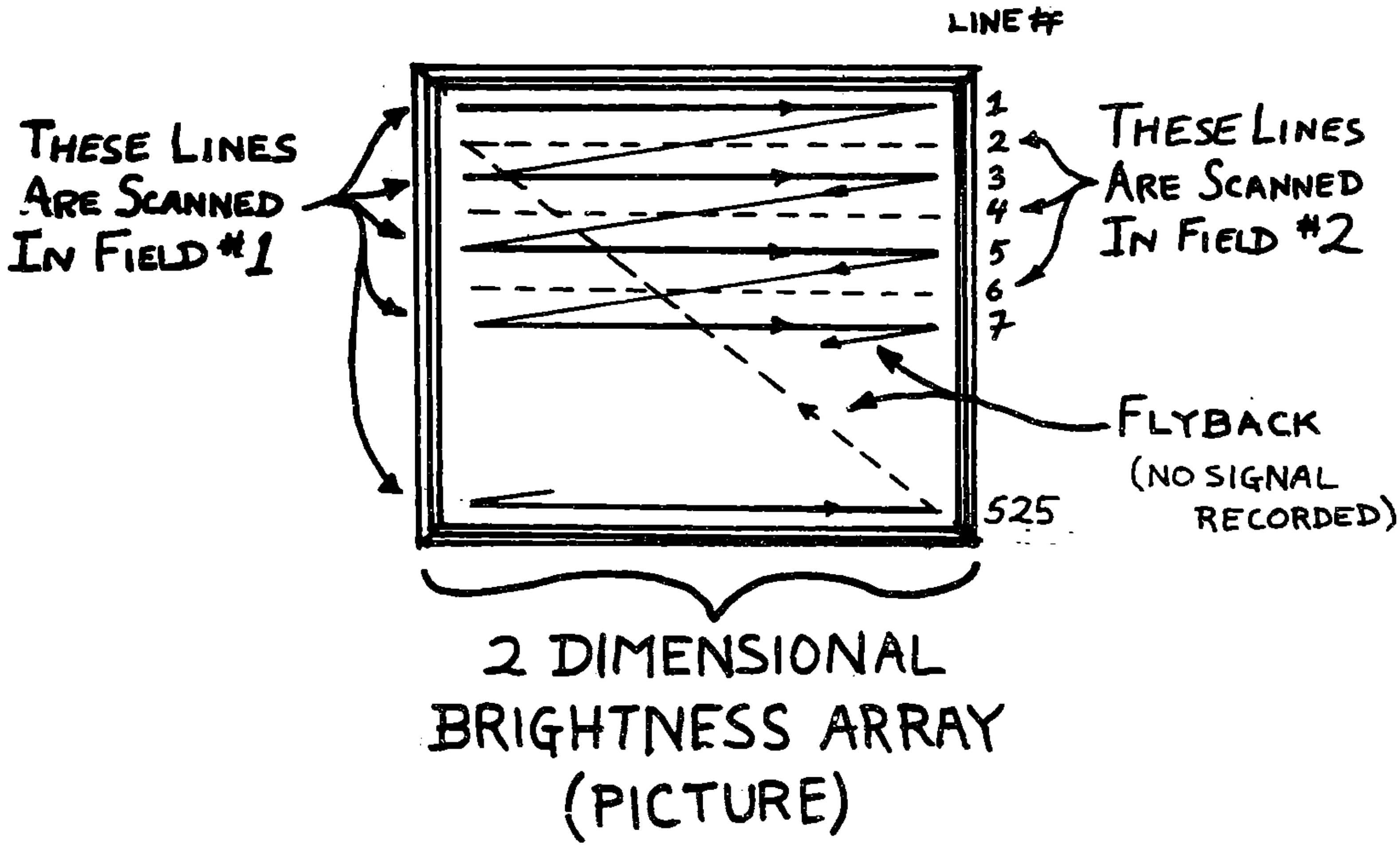


FIGURE 1: BRIGHTNESS ARRAY AND SCANNING METHOD

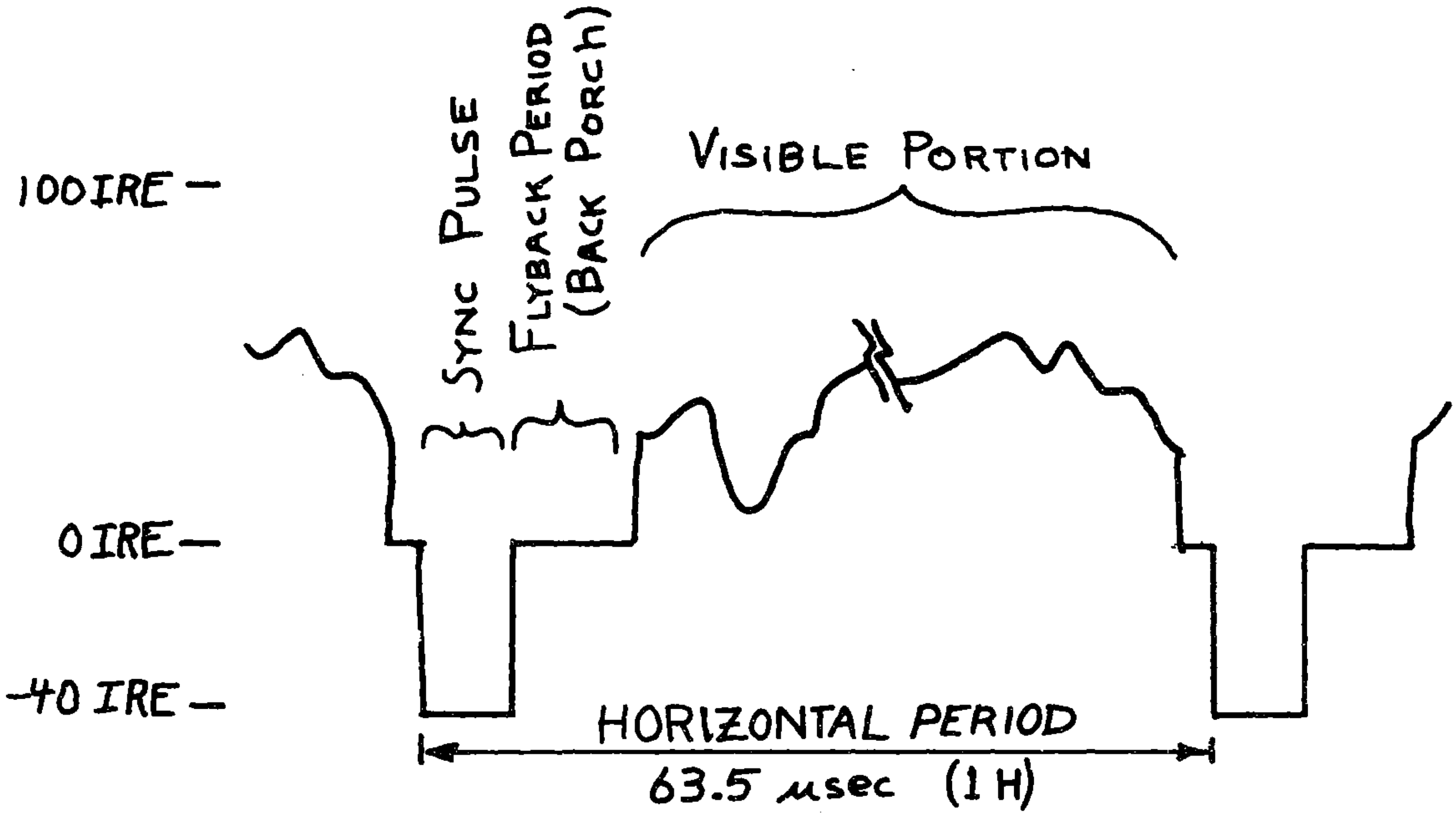
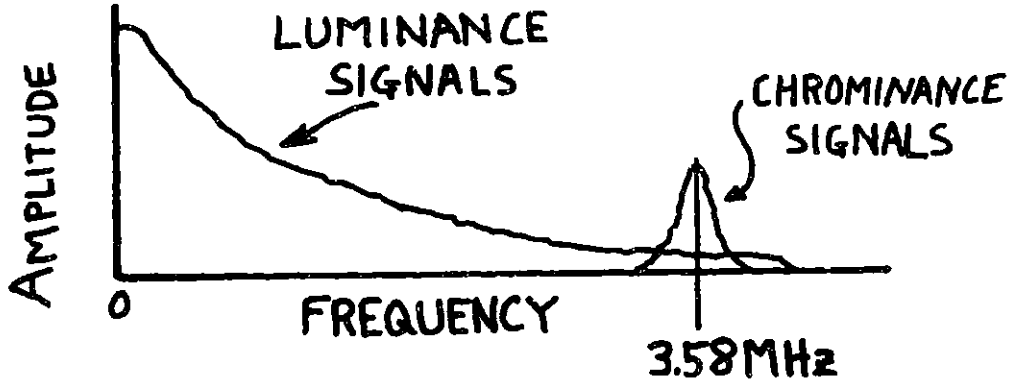
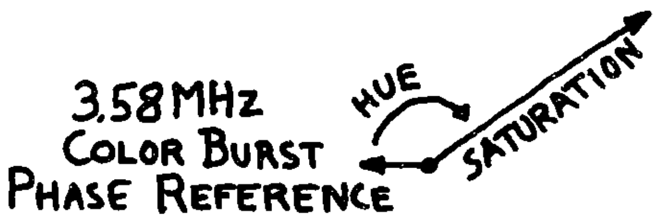


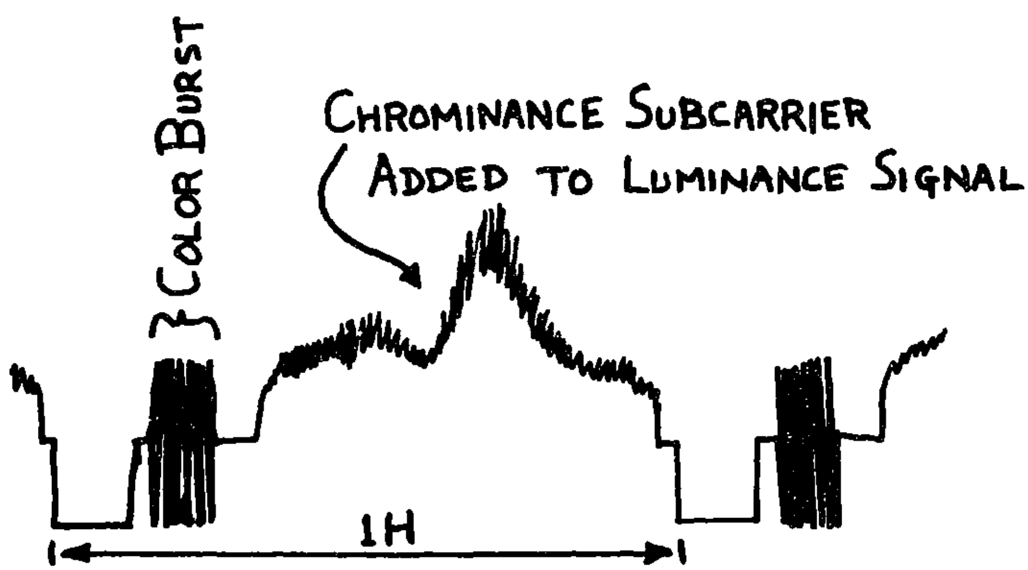
Figure 2: Monochrome Video Signal



FREQUENCY SPECTRUM OF N.T.S.C. COLOR SIGNALS



SUBCARRIER PHASOR DIAGRAM SHOWING ENCODING OF THE TWO CHROMINANCE SIGNALS



WAVEFORM FOR COLOR VIDEO SIGNAL

FIGURE 3: COLOR VIDEO SIGNALS

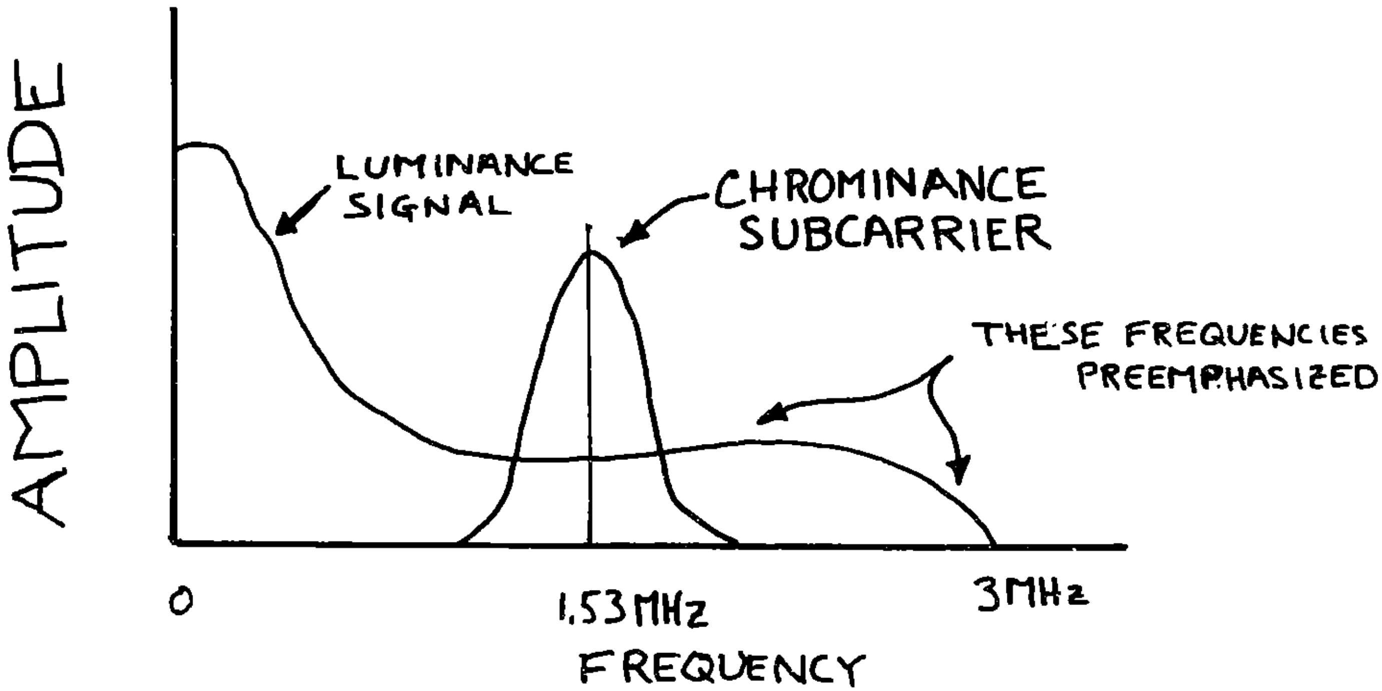


Figure 4: VIDEODISC FREQUENCY SPECTRUM

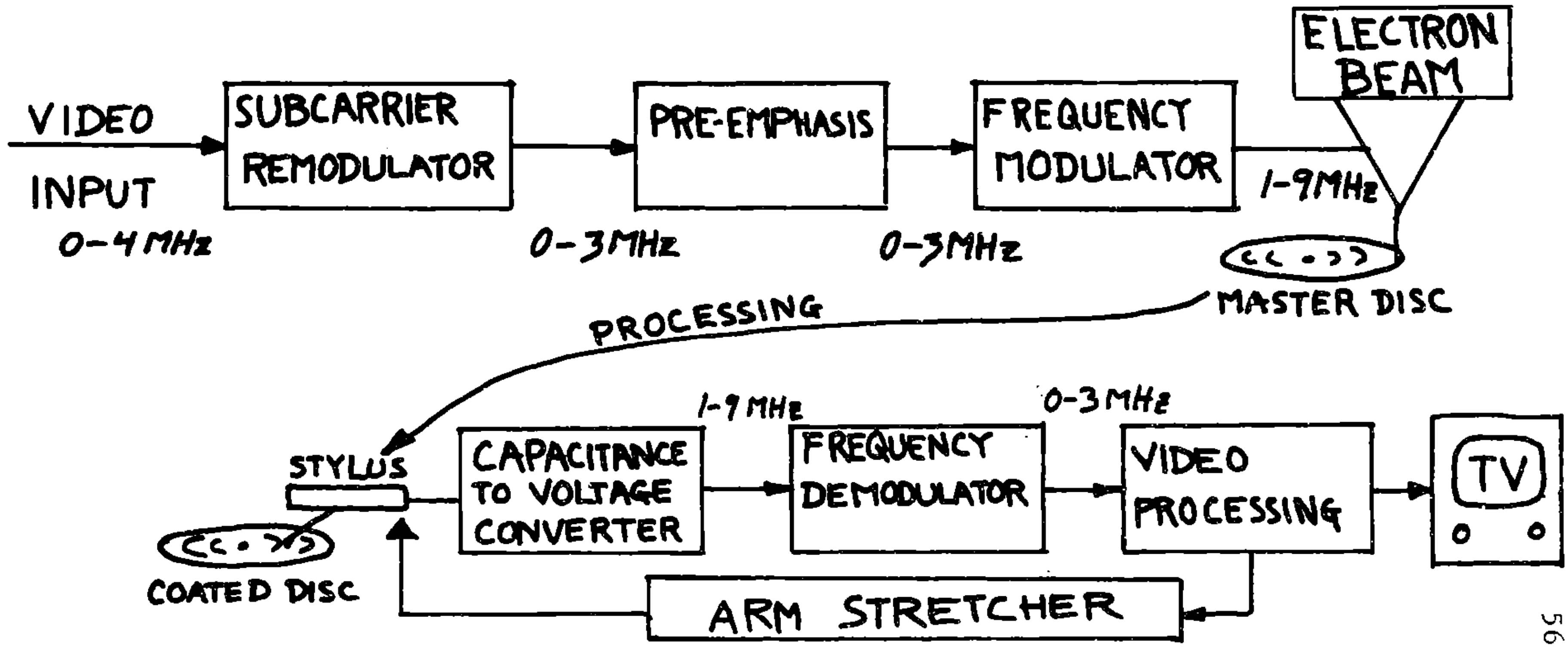


FIGURE 5. VIDEODISC SYSTEM

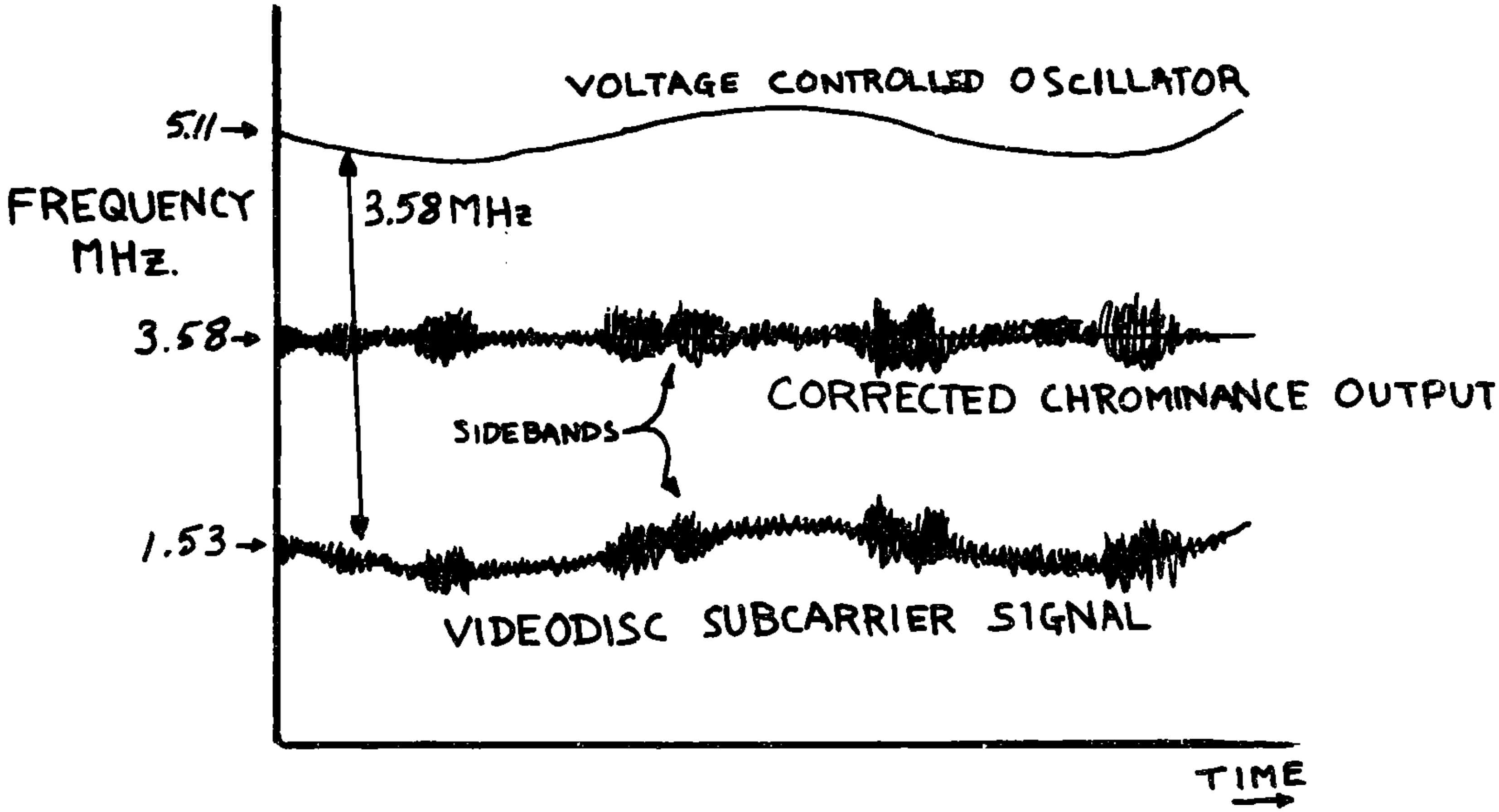


Figure 6: Chrominance subcarrier frequency correction scheme showing 5.11MHz voltage controlled oscillator tracking frequency changes in the VideoDisc subcarrier (exaggerated scale).

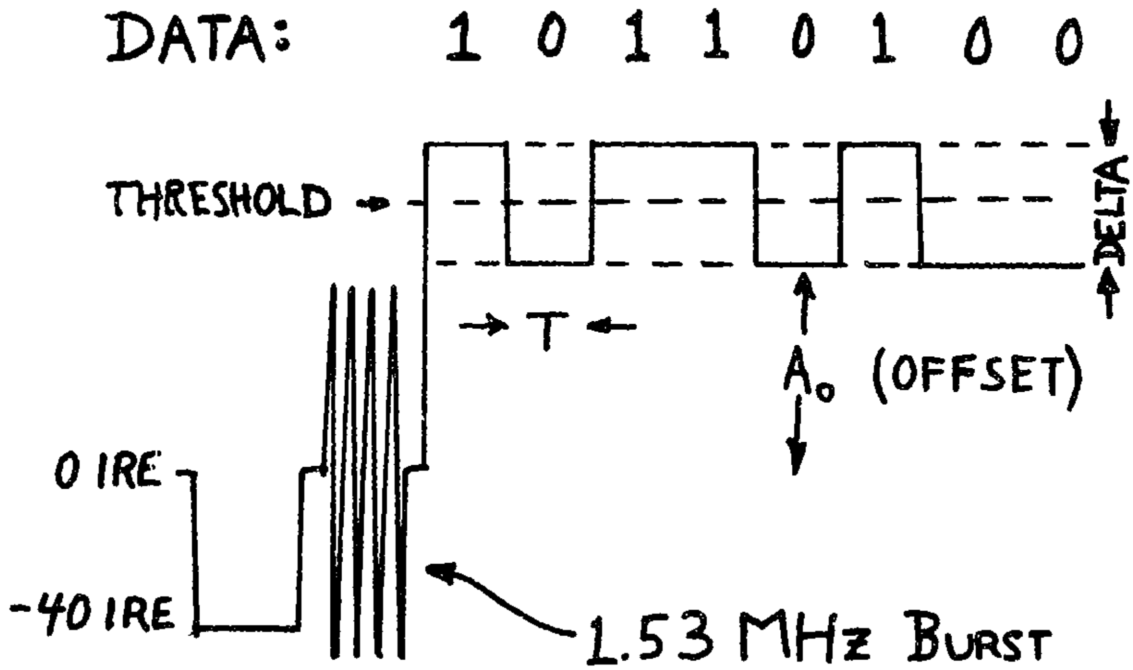


FIGURE 7: TWO LEVEL TEST SIGNAL

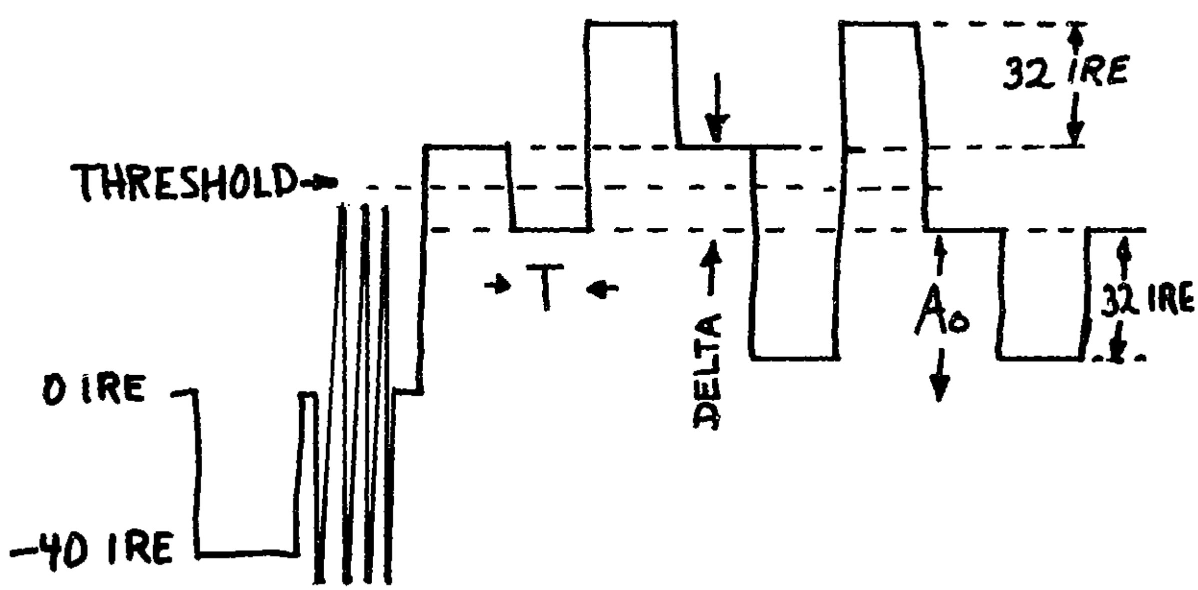
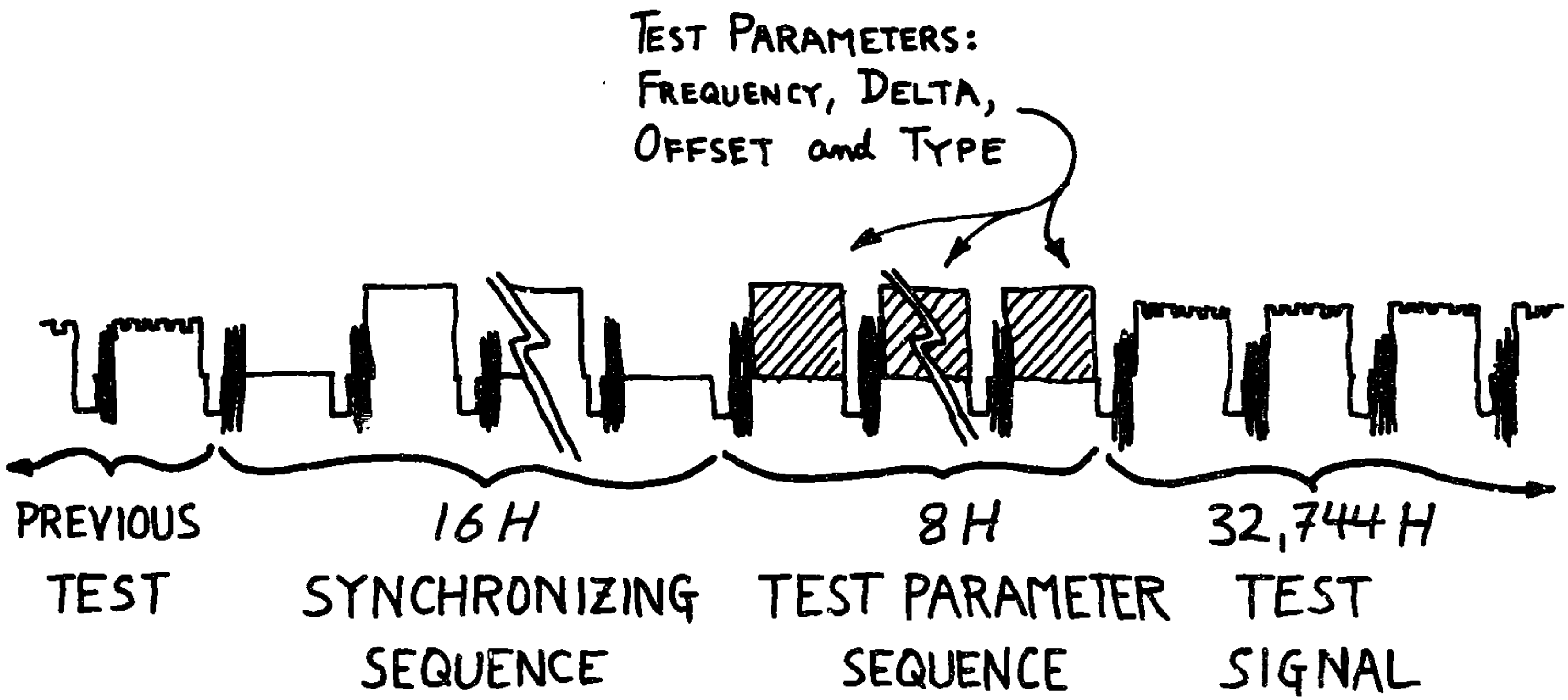


FIGURE 8: FOUR LEVEL TEST SIGNAL

Figure 9: AUTOMATIC TEST SEQUENCING



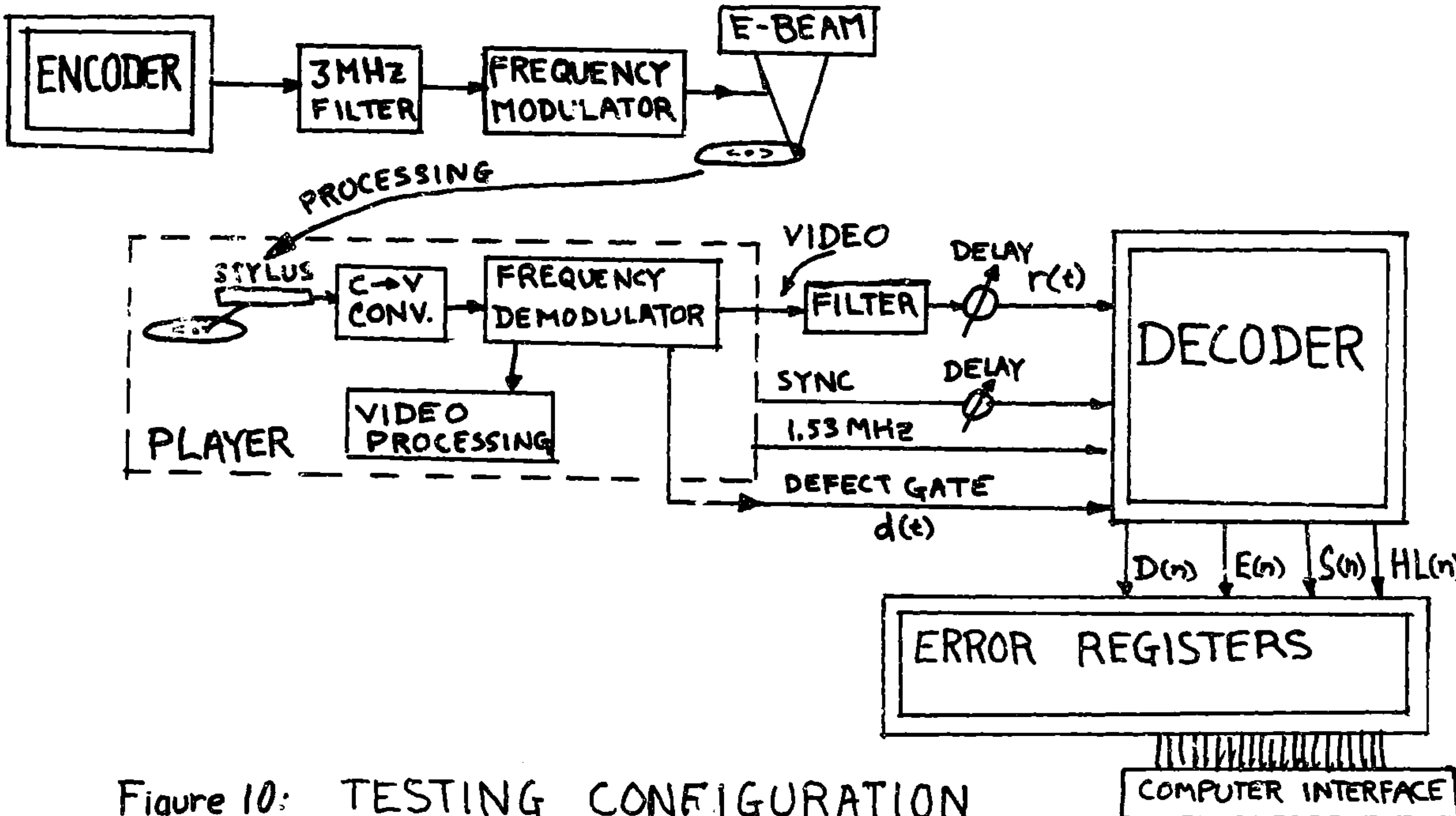


Figure 10: TESTING CONFIGURATION

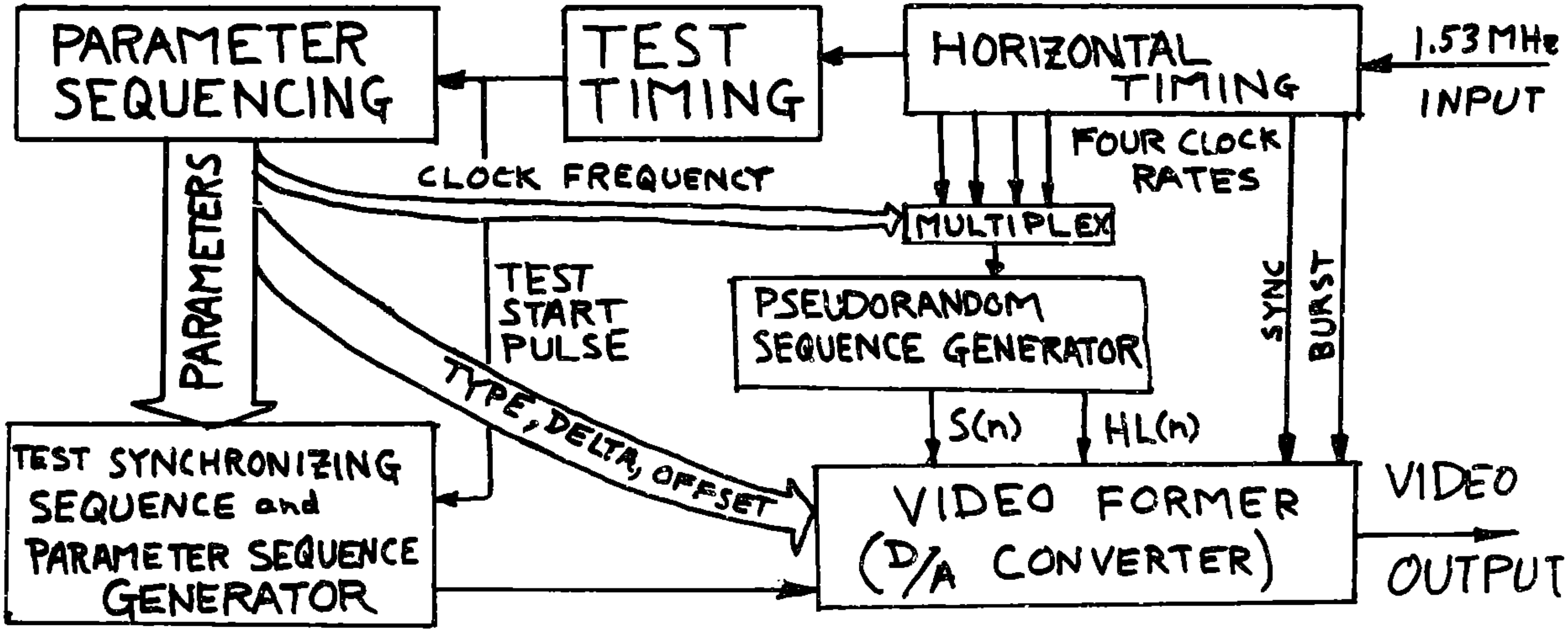


Figure 11: Encoder Block Diagram

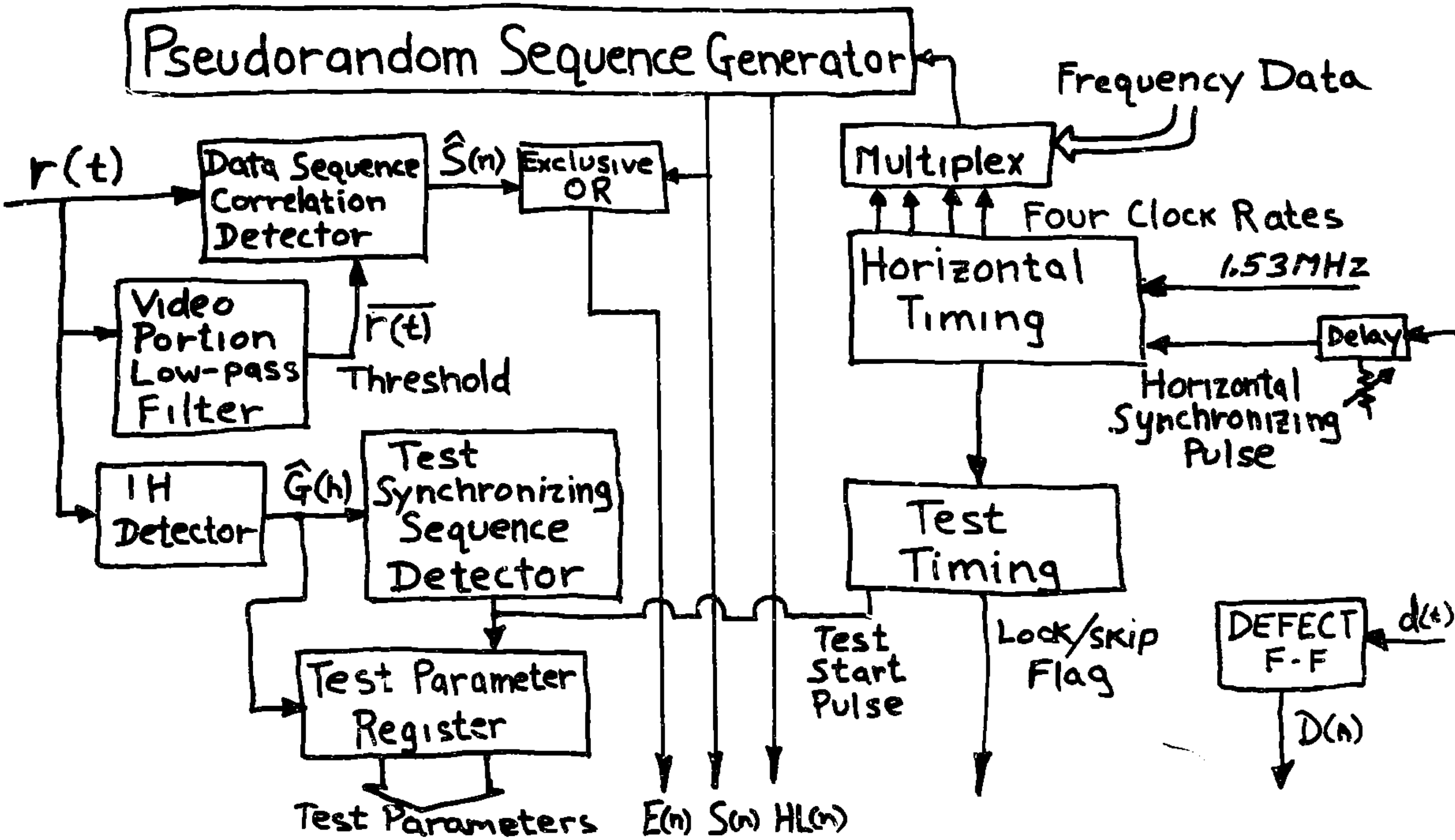


FIGURE 12: DECODER BLOCK DIAGRAM

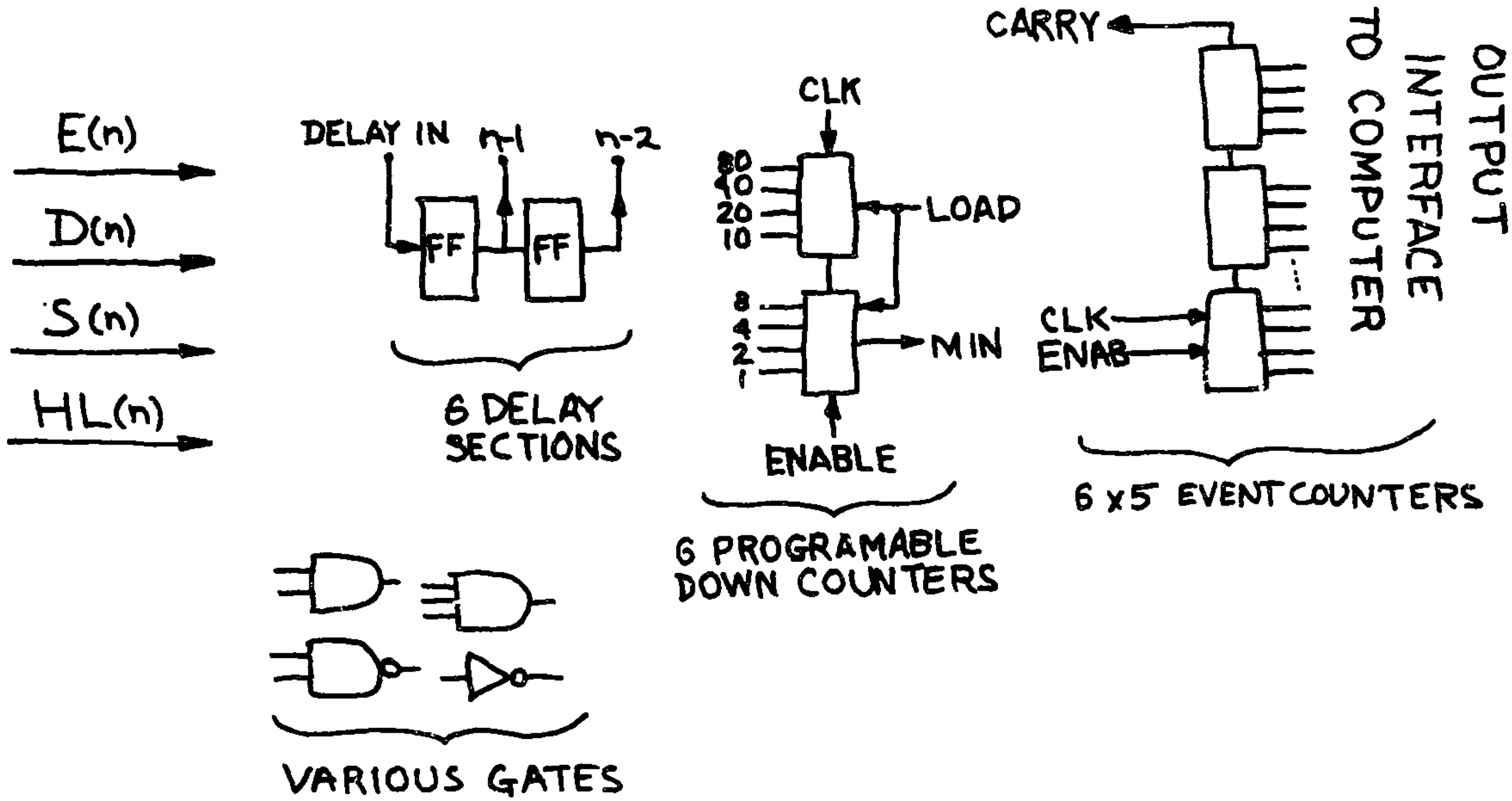


FIGURE 13: ERROR REGISTERS

```
PROCEDURE 89BIT_ERROR_CLUMPS;
COUNTER =0;
  DO N=1 to 32640x195; /* 195 bits per line at 3.06.*/
     IF COUNTER=0 THEN
        DO;  IF E(N)=1 THEN DO;
                             COUNTER=89;
                             EVENTS=EVENTS+1;
                             END;
        END;
        ELSE COUNTER=COUNTER-1;
  END;
OUTPUT EVENTS;
END;
```

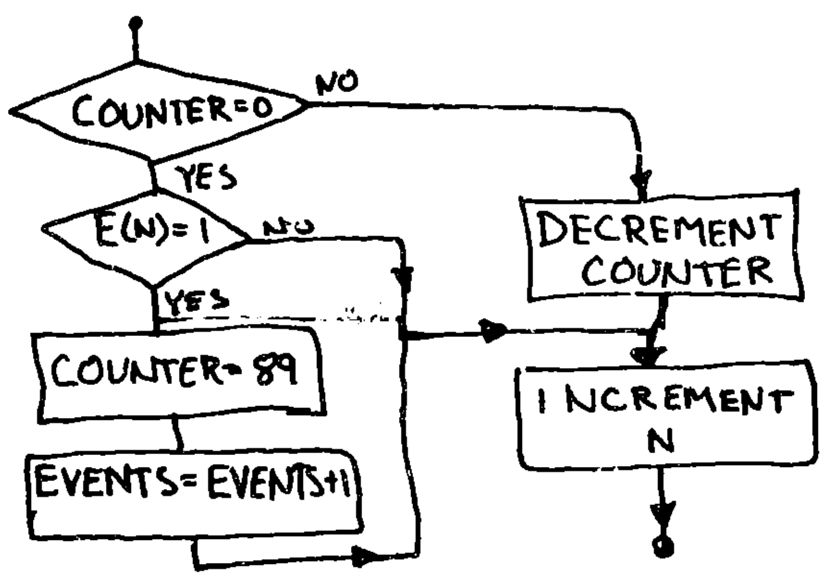


Figure 14: EXPERIMENT ALGORITHM

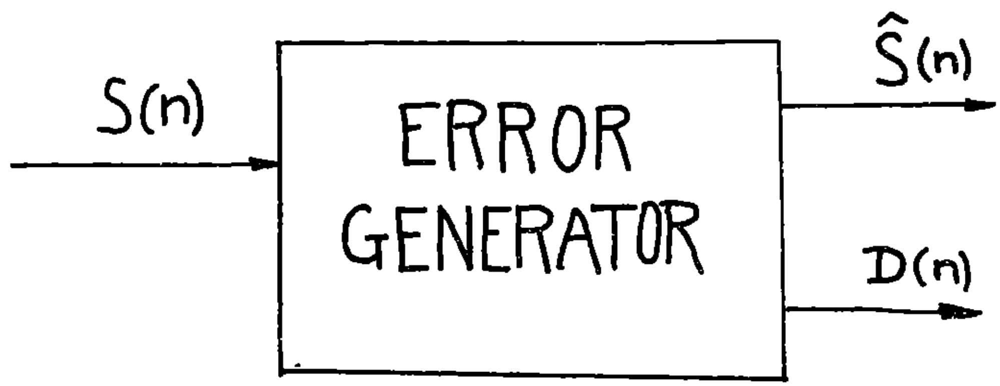


Figure 15: Error Generator. Model of encoder, VideoDisc, channel and correlation detector as a single unit.

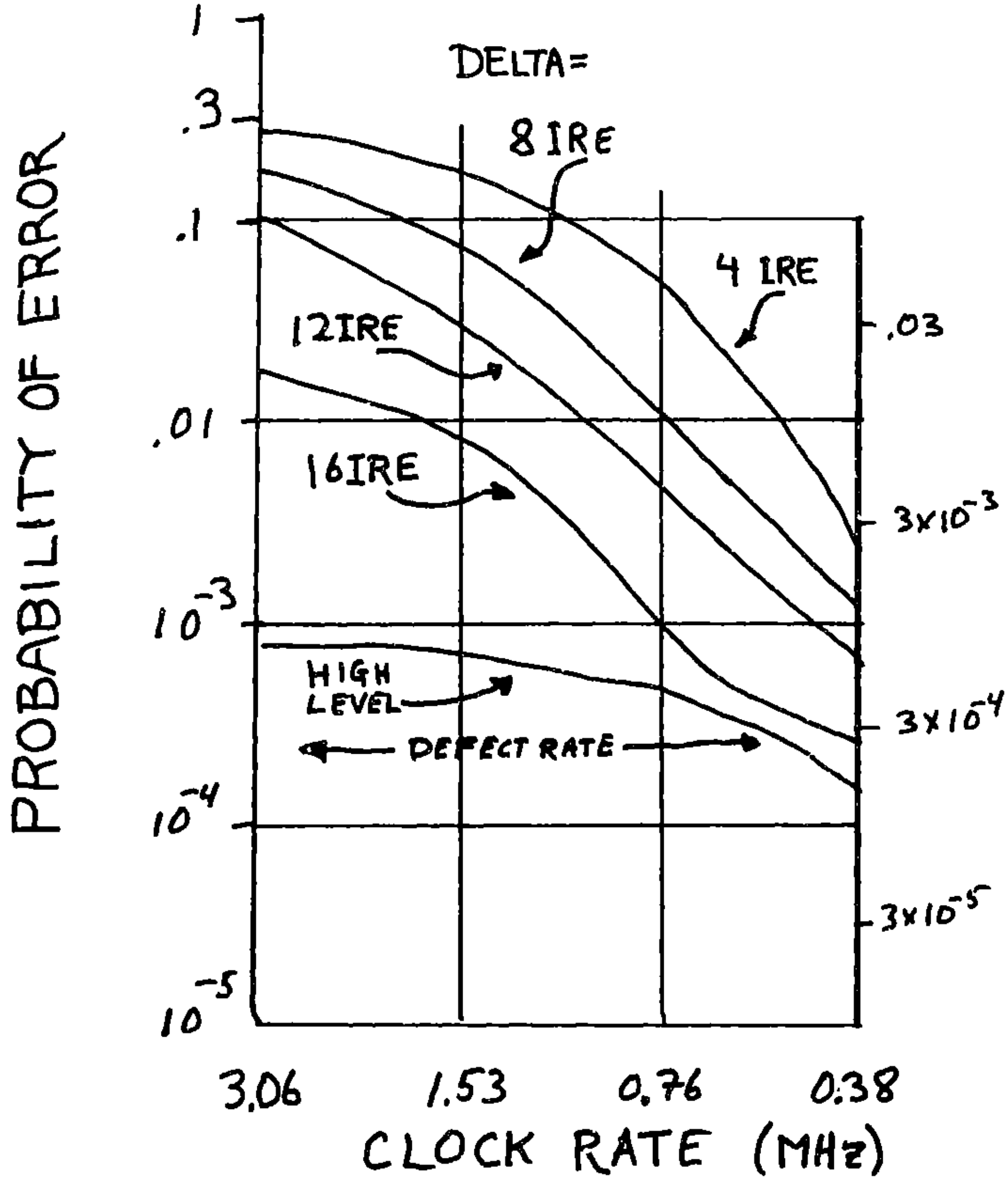


Figure 16: Error probabilities for two-level signals, averaged over all offsets and radii.

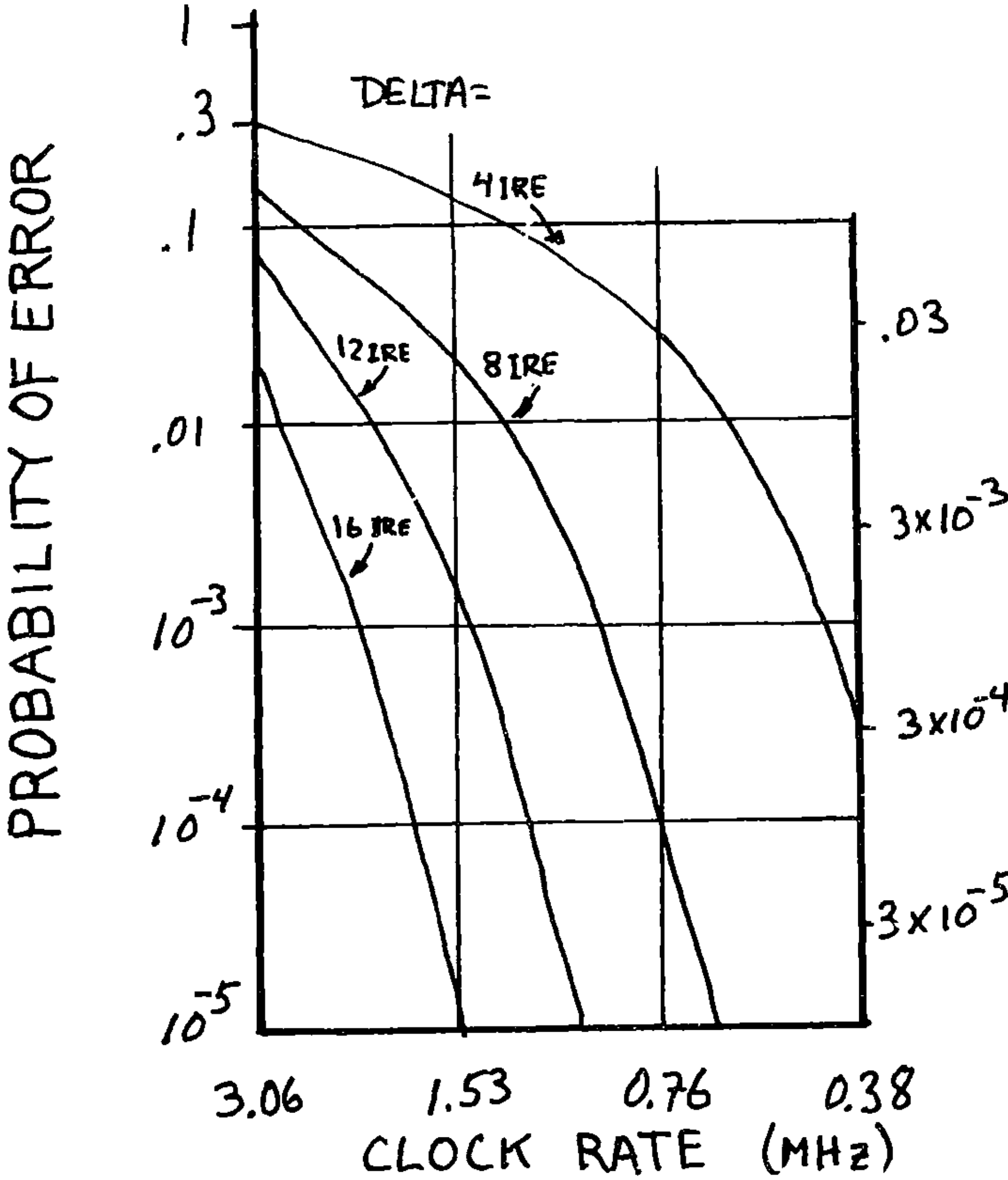


Figure 17: THEORETICAL ERROR RATES

as computed in Appendix 1

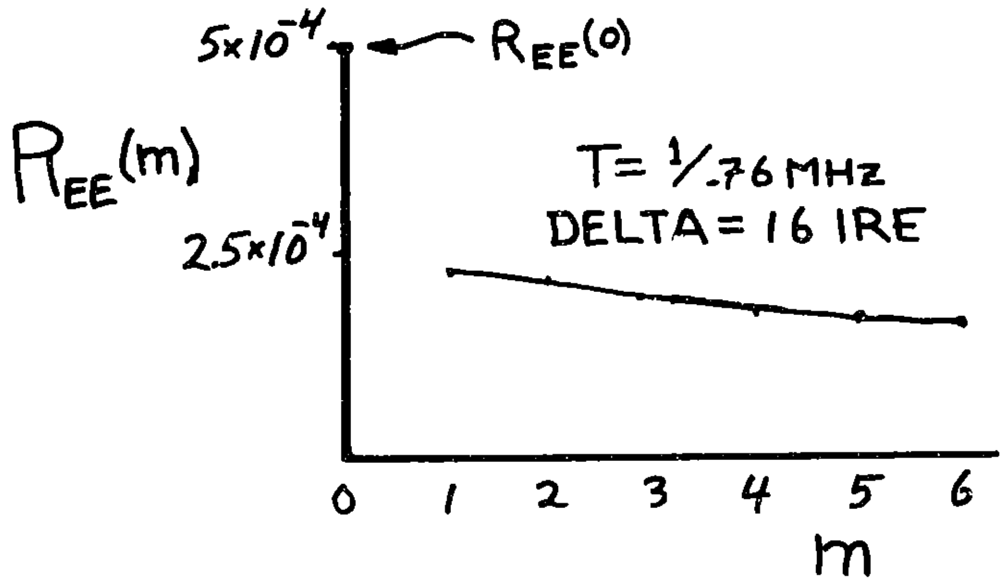


Figure 18: ERROR CORRELATION

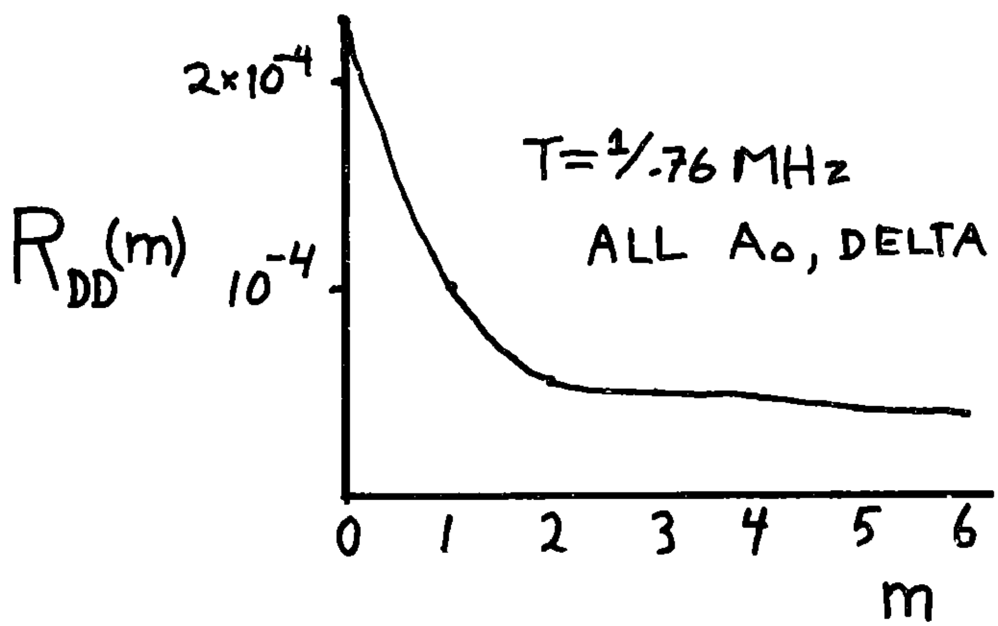


Figure 19: DEFECT CORRELATION

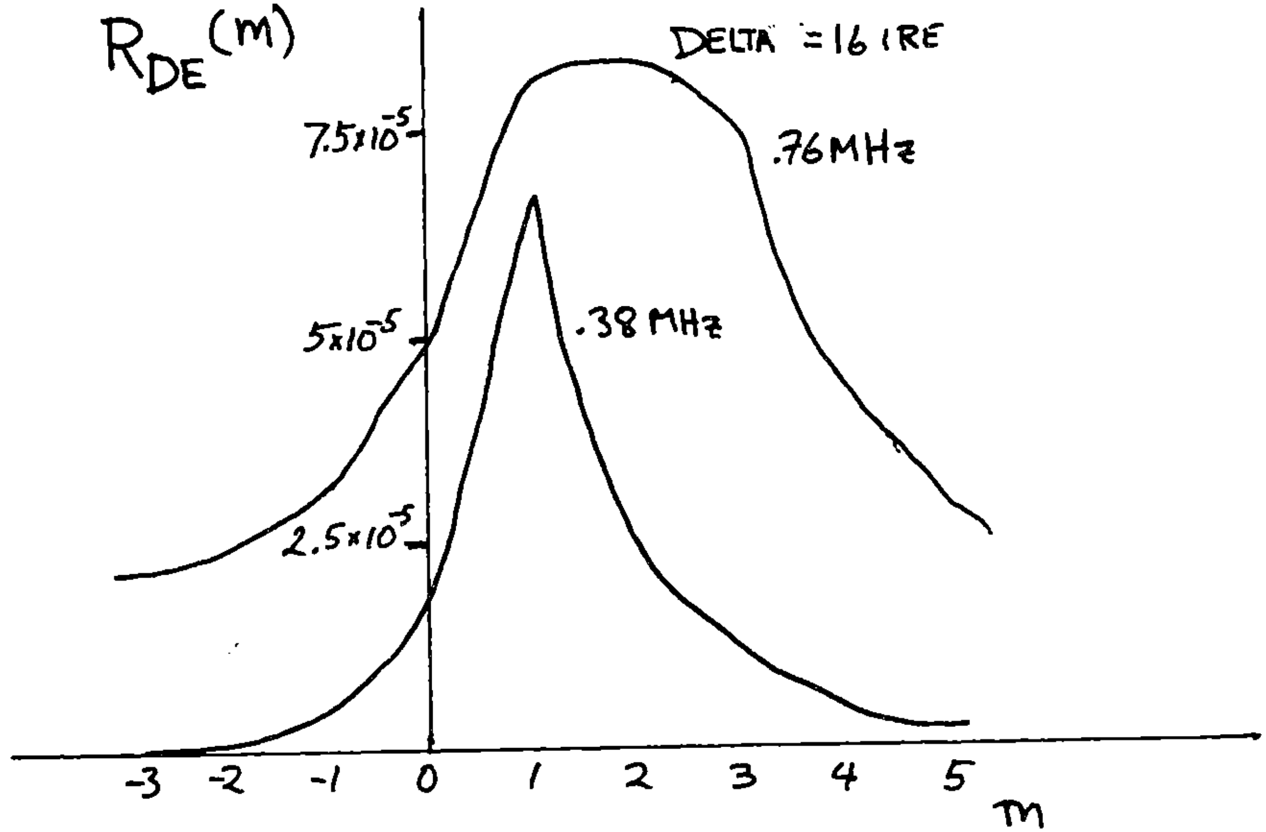


FIGURE 20: DEFECT-ERROR CROSS CORRELATION

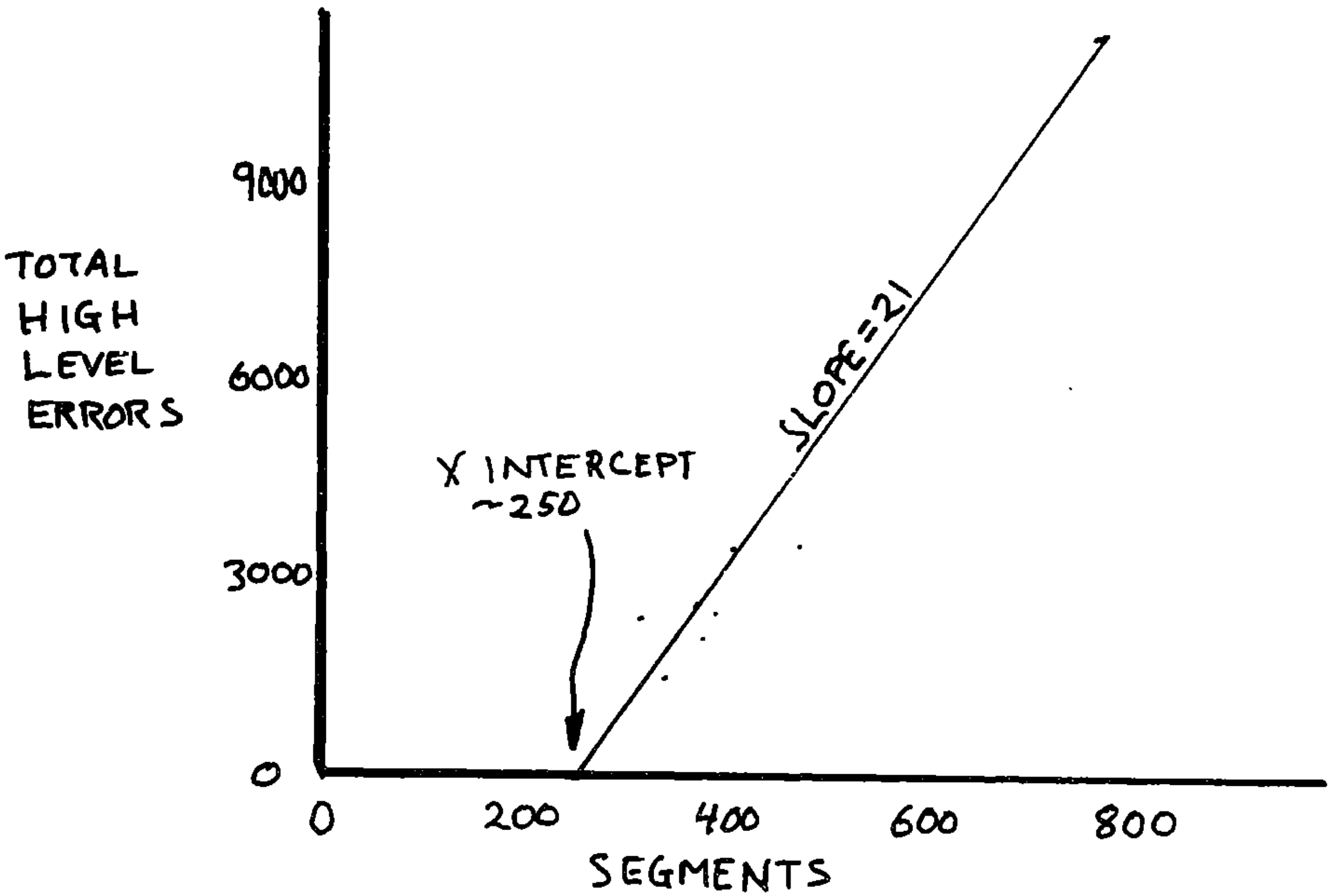


Figure 21: TOTAL HIGH LEVEL ERRORS VS. HIGH LEVEL 89Bit ERROR SEGMENTS

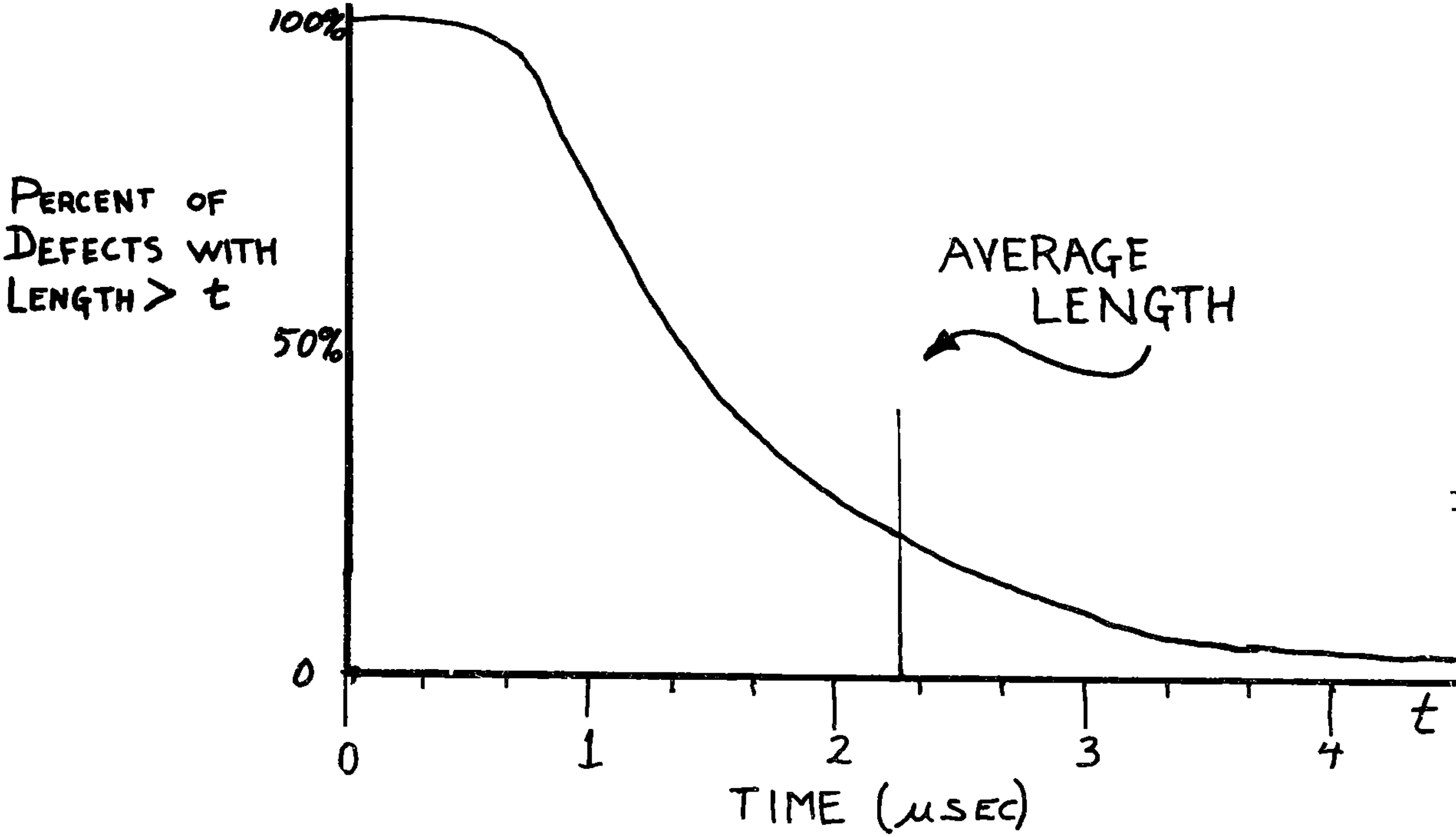


Figure 22: Defect Gate "On" Time

APPENDIX 1. Analysis of error probability in Gaussian noise.

Computation of noise output energy:

Assume that the received noise spectrum, $S_N(f)$, is a filtered form of a theoretical white Gaussian process, $S_W(f)$.

$$S_W(f) = \frac{N_f}{2}$$

$$S_N(f) = H_1(f)^2 x S_W(f)$$

$$H_1(f) = f/f_o$$

Where f_o and N_f are arbitrary constants, set such that:

$$S_N(f_o) = S_W(f_o) = \frac{N_f}{2}$$

The decoder system processes $S_n(f)$ in two ways. First it passes it through a low pass filter, $H_2(f)$, then it integrates the filter output, performing a filter function, $H_3(f)$. Neglecting phase terms,

$$H_2(f) = \mu_{-1}(f+f_m) - \mu_{-1}(f-f_m)$$

$$f_m = 3.0\text{ MHz}, \quad H_2(0) = 1 \rightarrow \text{UNITY GAIN}$$

$$H_3(f) = \int_{-T/2}^{T/2} \frac{\cos 2\pi f t}{T}\, dt$$

$$= \frac{\sin \pi f T}{\pi f T} \qquad H_3(0) = 1 \rightarrow \text{UNITY GAIN}$$

$$S_{DET}(f) = H_1^2(f) \times H_2^2(f) \times H_3^2(f) \times S_W(f)$$

$$S_{DET}(f) = \frac{N_f}{2}\left(\mu_{-1}(f+f_m) - \mu_{-1}(f-f_m)\right)\left(\frac{\sin \pi f T}{\pi f_o T}\right)^2$$

Where $S_{DET}(f)$ is the detected signal's noise power per Hz.

$$\overline{n^2_{DET}} = \frac{N_f}{2\pi^2 f_o^2 T^2}\int_{-f_m}^{f_m} \sin^2 \pi f T \, df$$

$$= \frac{3\times 10^6 N_f}{2\pi^2 f_o^2 T^2}$$

For the specific test signals recorded, T= $1/3.06\times10^6$, $2/3.06\times10^6$, $4/3.06\times10^6$, and $8/3.06\times10^6$ sec. $\overline{n^2_{DET}}$ is the variance of the detected signal. To determine when an error occurs on the channel, we must calculate the mean of the detected signal as well. If we know the voltage produced in the detector at t=0 (all phase delays were dropped) due to the transmitted signal (V_{SIG}), we can determine the probability that the instantaneous noise voltage will exceed the detected signal at t=0.

If * represents convolution and V_{in} is the recorded pulse signal with height $V_o \triangleq \frac{\text{delta}}{2}$

$$V_{SIG} = V_{IN}(t) * h_2(t) * h_3(t)\Big|_{t=0}$$

$$= \Bigg[V_o \times \left(\mu_{-1}\left(t+\tfrac{T}{2}\right) - \mu_{-1}\left(t-\tfrac{T}{2}\right)\right) * \int_{-f_m}^{f_m} \cos 2\pi f t \, dt * \frac{1}{T}\left(\mu_{-1}\left(t+\tfrac{T}{2}\right) - \mu_{-1}\left(t-\tfrac{T}{2}\right)\right)\Bigg]\Bigg|_{t=0}$$

$$V_{SIG} = 2V_0 \int_0^T \frac{\sin 2\pi f_m t}{\pi t}\, dt - \frac{2V_0}{T} \int_0^T \frac{\sin 2\pi f_m t}{\pi}\, dt$$

Setting $\theta = 2\pi f_m t$:

$$V_{SIG} = \frac{2V_0}{\pi} \int_0^{2\pi f_m T} \frac{\sin \theta}{\theta}\, d\theta \quad - 0$$

$$= \frac{2V_0}{\pi} Si(2\pi f_m T)$$

Computing this function for data rates:

		3.06Mb/s	1.53Mb/s	.76Mb/s	.38Mb/s
$2\pi f_m T$	=	$\sim 2\pi$	$\sim 4\pi$	$\sim 8\pi$	$\sim 16\pi$

From tables:[12]

$\frac{2}{\pi} Si(\ \ )$	=	.903	.948	.974	.987

$\triangleq \alpha$

So we have a Gaussian distribution with mean $\alpha \cdot V_0$ and variance $\frac{3.06 \times 10^6 N_f}{2\pi^2 f_0^2 T^2}$. The probability that an error occurs is the integral of the Gaussian distribution: $Q\left(\frac{\alpha V_0}{\sqrt{\frac{3.06 \times 10^6 N_f}{2\pi^2 f_0^2 T^2}}}\right)$.

As measured on my disc, the signal to noise ratio for a 140 IRE p-p signal, measured with an ideal 10kHz. bandwidth filter is 50.5 dB at 500kHz.

$$N_f = \frac{\text{signal power}}{\text{S-N-R} \cdot \text{BW}} = 2.2 \times 10^{-6} \ \frac{\text{IRE}^2}{\text{Hz}}$$

$$f_0 = 5 \times 10^5 \text{ Hz}$$

Here is a partial table of $\frac{\alpha V_0}{\sqrt{\text{NOISE PWR}}}$ (where $V_0 = \frac{\text{DELTA}}{2}$).

		3.06 Mb/s	1.53 Mb/s	0.76 Mb/s	0.38 Mb/s
$V_0 =$	2 IRE	.5	1.05	2.15	4.4
	4	1.0	2.1	4.3	8.8
	6	1.5			
	8	2.0			

There is also some additional noise in the system which is white. This noise was measured at 55.5dB below the 140 IRE p-p signal. (the real value may be higher).

$$\overline{n_w^2} = \int_{-\infty}^{\infty} S_w H_2^2(f)\, H_3^2(f) = \int_{-3.06\text{MHz}}^{3.06\text{MHz}} \frac{N_w}{2} \frac{\sin^2 \pi f T}{\pi f T}\, df$$

This is approximately $\cong \dfrac{N_w}{2}\displaystyle\int_{-\infty}^{\infty} \frac{\sin^2 \theta}{\pi T \theta^2}\, d\theta$

$$\simeq \frac{N_w}{2T}$$

$$N_w = \frac{140^2\ IRE^2}{8 \times 10\text{KHz} \times 10^{5.55}} = 5.1 \times 10^{-7}$$

$$\overline{n_{Tot}^2} = \overline{n_{DET}^2} + \overline{n_W^2}$$

$\overline{n_W^2}$	1.07	.54	.27	.13
+ $\overline{n_{DET}^2}$	12.8	3.19	.80	.20
$\overline{n_{TOT}^2}$	13.9	3.7	1.07	.33

So $\dfrac{\alpha V_0}{\sqrt{NOISE_{tot}}} =$

$V_0 =$ 2 IRE	.48	.99	1.89	3.46
4 IRE	.96	1.98	3.78	6.93
6 IRE	1.44	2.97	5.67	10.39
8 IRE	1.92	3.96	7.56	13.85

These values give the following error rates.[13]

DELTA \ CLOCK RATE	3.06	1.53	0.76	0.38
4	.316	.161	.0294	2.7×10^{-4}
8	.169	.0239	7.8×10^{-5}	2×10^{-12}
12	.075	1.5×10^{-3}	7×10^{-9}	10^{-25}
16	.027	3.7×10^{-5}	10^{-14}	10^{-44}

The noise level measurements were made at the outside of the recording. One could expect some increase in noise for smaller radii.

APPENDIX 2: Burst length limits from correlation statistics

1) Error burst length lower bound.

The object of this calculation is to find the largest value of N such that the statement: "Half or more of the errors are in error bursts of length greater than N" is still true.

To find N, assume equality in the statement above and maximize the correlation, $R_{EE}(k)$.

Put 50% of the errors in bursts of length N, put all the rest in one burst (length$\rightarrow\infty$). The correlation for bursts of length N alone is:

$$R_{EE}^{N}(K) = R_{EE}(0) \times \frac{N-K}{2N} \quad \text{for } K < N$$

This can be verified by listing all possible bursts of length N and counting how many times the correlation function is one. For the long burst:

$$R_{EE}^{\infty}(K) = \tfrac{1}{2} \times R_{EE}(0)$$

If $R_{EE}(0)$ 1, then the correlation for linear combinations of events is the linear combination of the correlations.

$$R_{EE}(k) = .5\, R_{EE}^{N}(k) + .5\, R_{EE}^{\infty}(k)$$

$$= R_{EE}(0)\left(\frac{1}{4}\left(\frac{N-K}{N}\right) + \frac{1}{4}\right)$$

$$\frac{R_{EE}(k)}{R_{EE}(0)} = \frac{1}{4}\left(\frac{2N-K}{N}\right)$$

$$N = K \Big/ \left(2 - \frac{4\,R_{EE}(K)}{R_{EE}(0)}\right)$$

Therefore, $R_{EE}(6)/ R_{EE}(0) = .35$ implies that $N > 9$. Half of all errors are in bursts longer than 9 bits.

2) Defect length upper bound.

Here we are trying to find the smallest N where: " Half or less of the defects are in bursts of length N".

To minimize $R_{DD}(k)$, put all defects by themselves or in defects of length N.

For defects of length N:

$$R^N_{DD}(K) = R_{DD}(0) \times \frac{N-K}{N}$$

$$R^0_{DD}(K) = 0 \qquad K \neq 0$$

If $R_{DD}(0) \ll 1$ then:

$$R_{DD}(K) = .5\, R_{DD}(0) \times \frac{N-K}{N}$$

$$N = \frac{K}{1 - 2\frac{R_{DD}(K)}{R_{DD}(0)}}$$

For k=2, $R_{DD}(k)/ R_{DD}(0) = .227$. So N 4. Half of the defects last less than four clock pulses at .76MHz. (A much more accurate distribution is found in the investigative tests section.)