THE DIGITAL MAGNETIC RECORDING CHANNEL

MUNRO K. (MIKE) HAYNES

IBM CORPORATION

SYMBOLS

- DIGITS
- CLAY TABLETS, PAPYRUS
- TORCHES
- PRINTING PRESS
- SEMAPHORE
- TELEGRAPH
- SUBMARINE CABLE
- TYPEWRITER
- PUNCHED CARD
- RADIO TELEGRAPH
- TELEPRINTER
- PUNCHED PAPER TAPE
- MAGNETIC DRUM
- MAGNETIC TAPE
- MAGNETIC DISK
- RADAR DATA TRANS.
- TELEMETRY
- SATELLITE DATA
- OPTICAL DISK

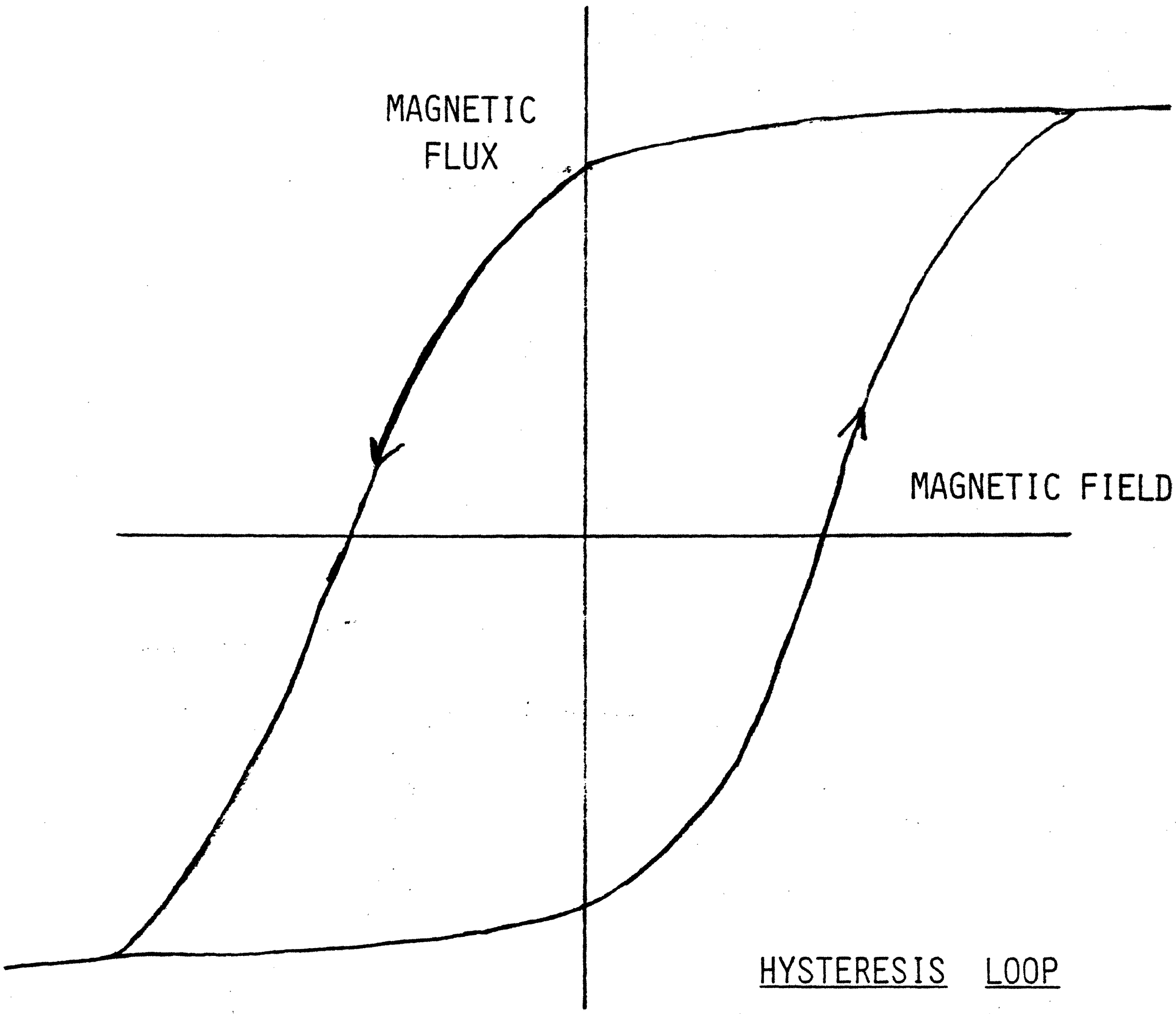
SOUND

- TELEPHONE
- PHONOGRAPH
- MAGNETIC WIRE
- RADIO TELEPHONE
- MAGNETIC TAPE
- PCM TELEPHONY
- MULTILEVEL TRANS.
- DIGITAL AUDIO
- OPTICAL DISK

IMAGES

- PHOTOGRAPH
- MOTION PICTURE
- MICROFILM
- FACSIMILE
- VIDEO PHONE
- TELEVISION
- VIDEO TAPE
- VIDEO DISK
- DIGITAL VIDEO
- MAVICA

DEVELOPMENT OF INFORMATION STORAGE AND TRANSMISSION



HYSTERESIS LOOP

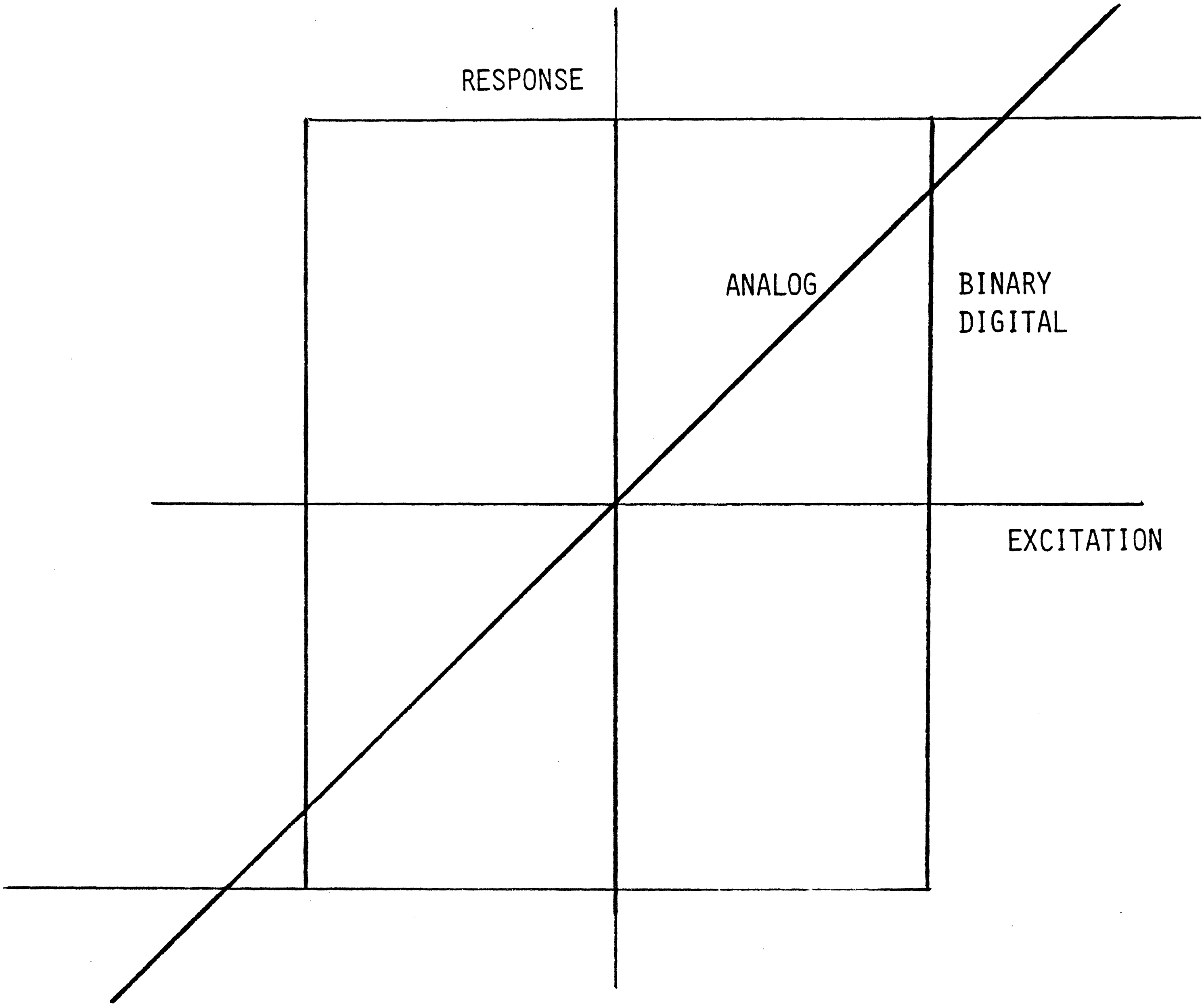
HYSTERESIS -- LAG

NON-LINEAR
SATURATION
ENERGY LOSS
TIME DEPENDENT

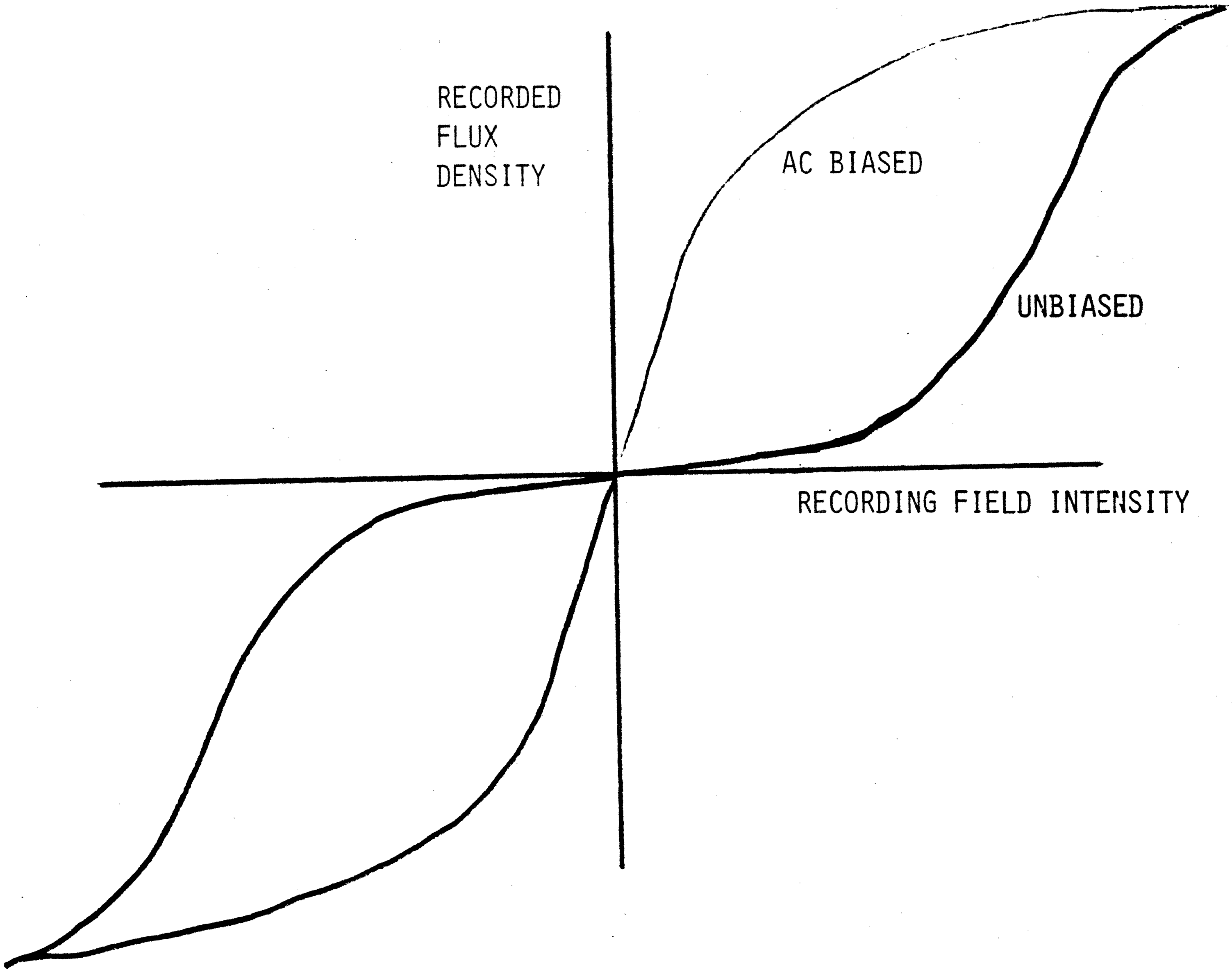
AN ESSENTIAL REQUIREMENT
FOR STORAGE-- MAGNETIC CORES

MAGNETIC RECORDING

HYSTERESIS
MECHANICAL MOTION



IDEAL TRANSFER-RESPONSE CHARACTERISTICS



MAGNETIC RECORDING CHANNEL

TRANSFER RESPONSE CHARACTERISTICS

AN 'ANALOG' CHANNEL
- NONLINEARITY
- SATURATION
- DISTORTION
- NOISE

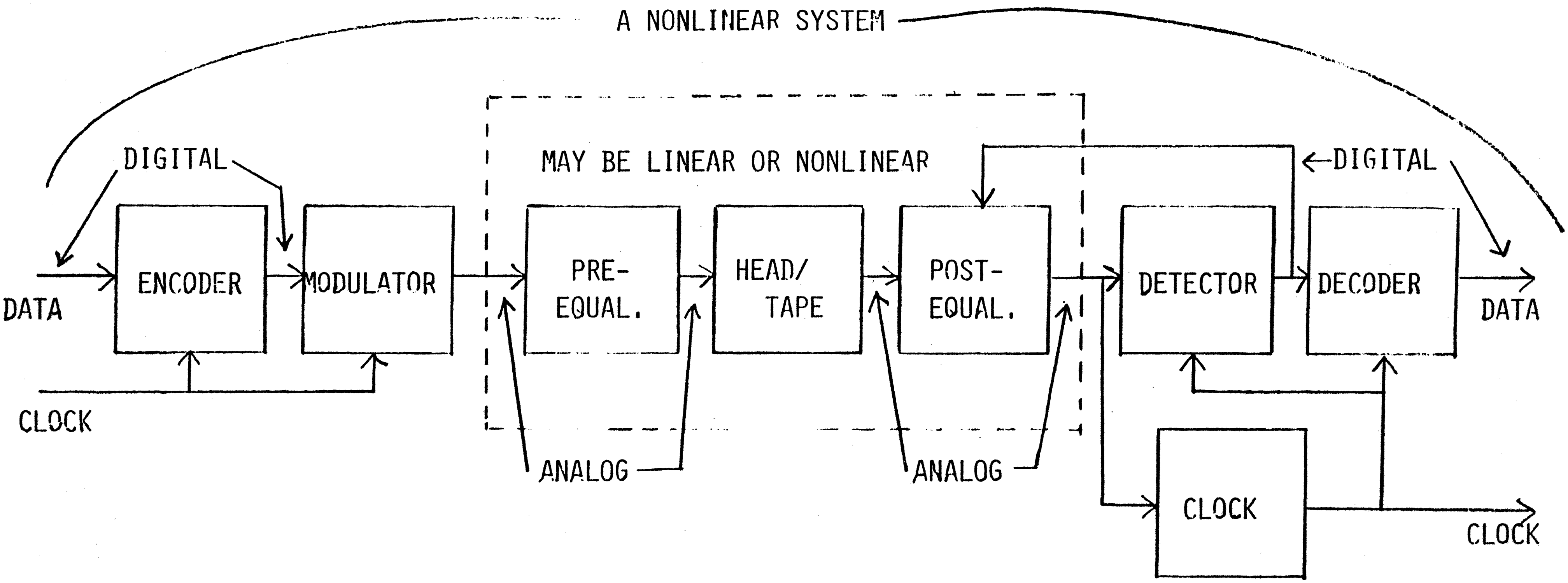
ANALOG RECORDING

- LINEARIZE
  - DC BIAS
  - AC BIAS

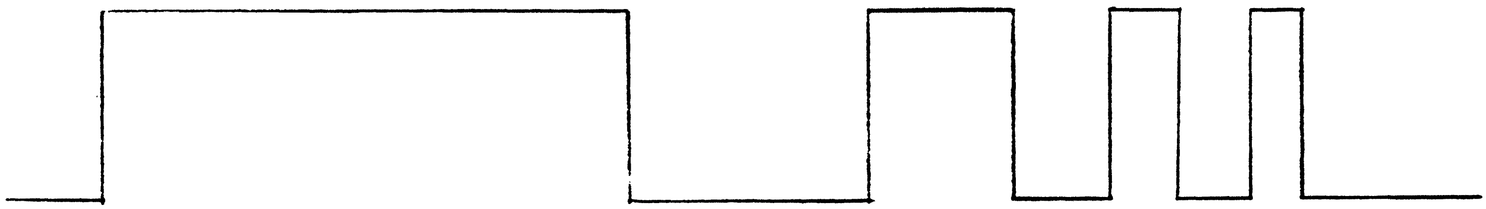
DIGITAL RECORDING

- SATURATE
  - TWO STATES
  - RECORD TRANSITIONS
- QUASI-LINEAR
  - SIGNAL PROCESSING
- LINEARIZE

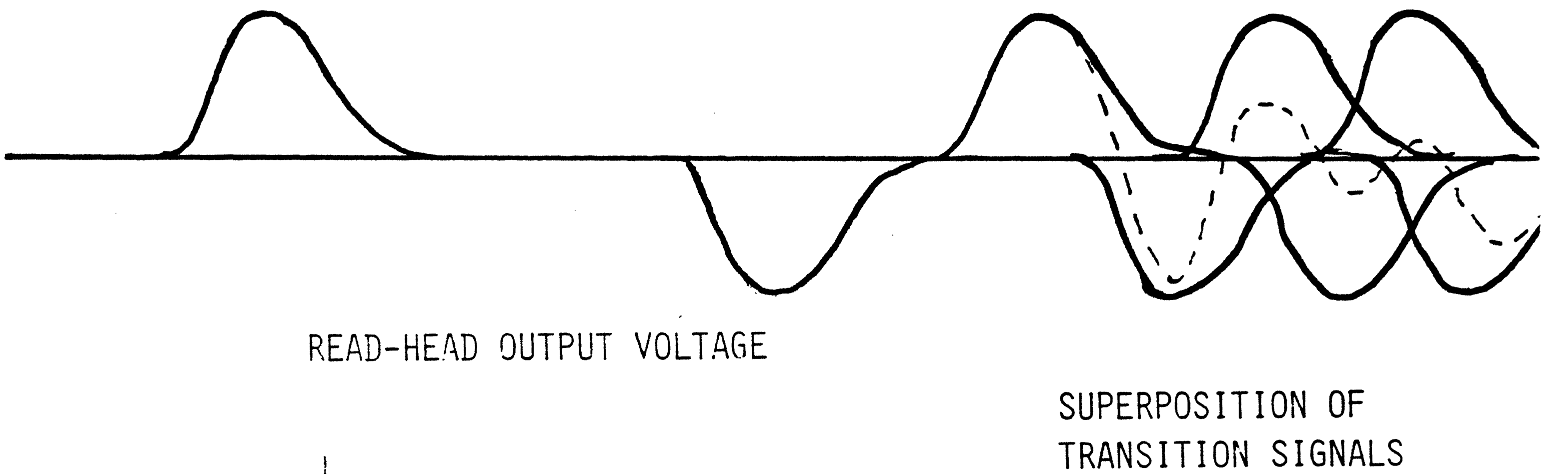
APPLICATION STRATEGIES FOR MAGNETIC RECORDING CHANNEL



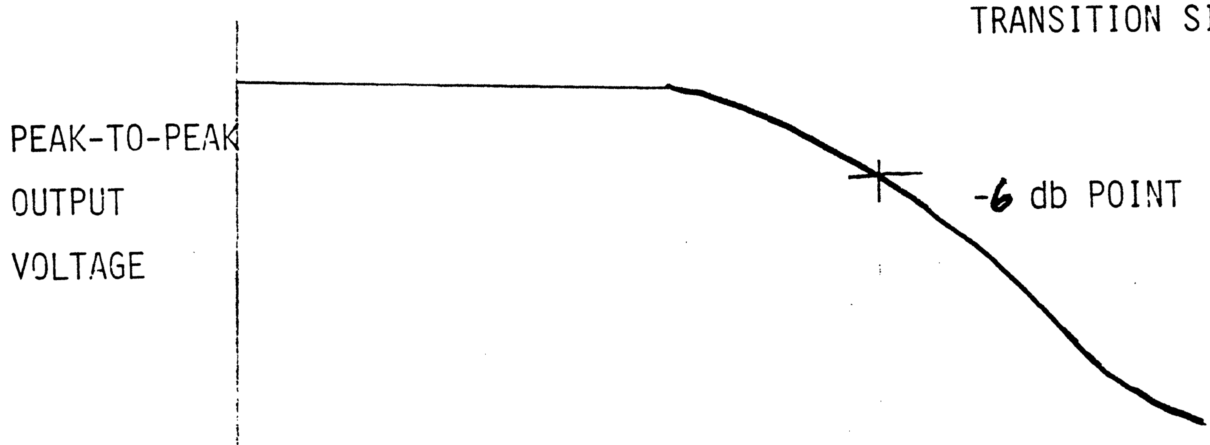
A DIGITAL-DATA RECORDING SYSTEM



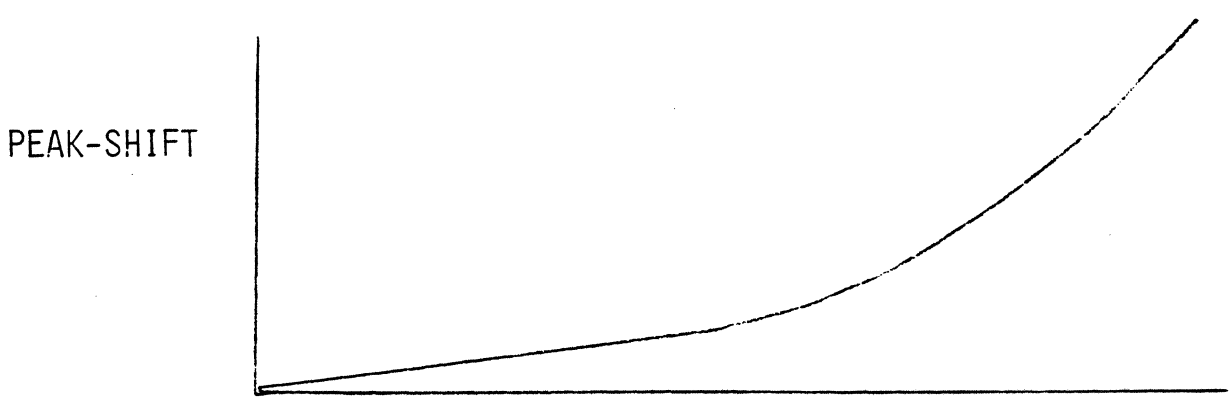
WRITE CURRENT



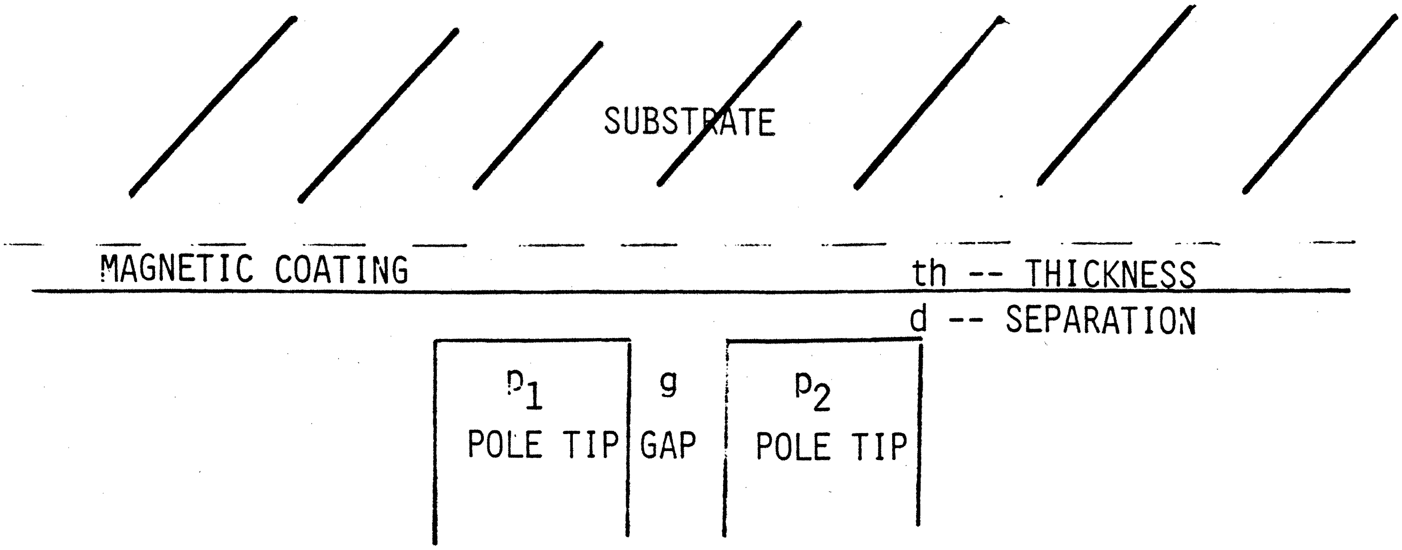
READ-HEAD OUTPUT VOLTAGE



RECORDING DENSITY (TRANSITIONS PER INCH)



RECORDING DENSITY



RECORDING DENSITY LIMITERS IN SATURATION RECORDING

- MEDIA THICKNESS
- SEPARATION
- GAP LENGTH
- POLE TIP LENGTH
- TRANSITION LENGTH
  - DEMAGNETIZATION
  - WRITE FIELD GRADIENT

SATURATION-RECORDING ANALYSIS

THIN MEDIA

SELF-CONSISTENT FIELD CALCULATIONS

ARCTANGENT TRANSITION SHAPE

$$M_x = \frac{2M_o}{\pi} \arctan x/a \,, \quad a = \text{transition length}$$

LORENZTIAN PULSE RESPONSE

$$e(t) = \frac{1}{1 + (2t/PW_{50})^2}$$

PULSE WIDTH, $PW_{50} = (g^2 + 4(d+a)(d+a+th))^{\frac{1}{2}}$

QUASI-LINEAR ANALYSIS

THICK MEDIA

SUBSTRATE CHARACTERISTICS

NON-SATURATE RECORDING

"PREFERRED DEPTH", UNBIASED OR AC BIAS

FREQUENCY-DOMAIN MEASUREMENT AND ANALYSIS

LINEAR ANALYSIS, FOURIER TRANSFORMS

DATA TRANSMISSION THEORY

EQUALIZATION, OPTIMIZATION

R.O.McCary, "Saturation Magnetic Recording Process," IEEE Trans. Mag. V. MAG-7, March 1971, pp4-16.

B.K.Middleton and P.L. Wisely, "Pulse Superposition and High-Density Recording," IEEE Trans. Mag., V. MAG-14, Sept. 1978, pp 1043-50.

CATEGORIES OF SIGNAL DISTORTION

LINEAR

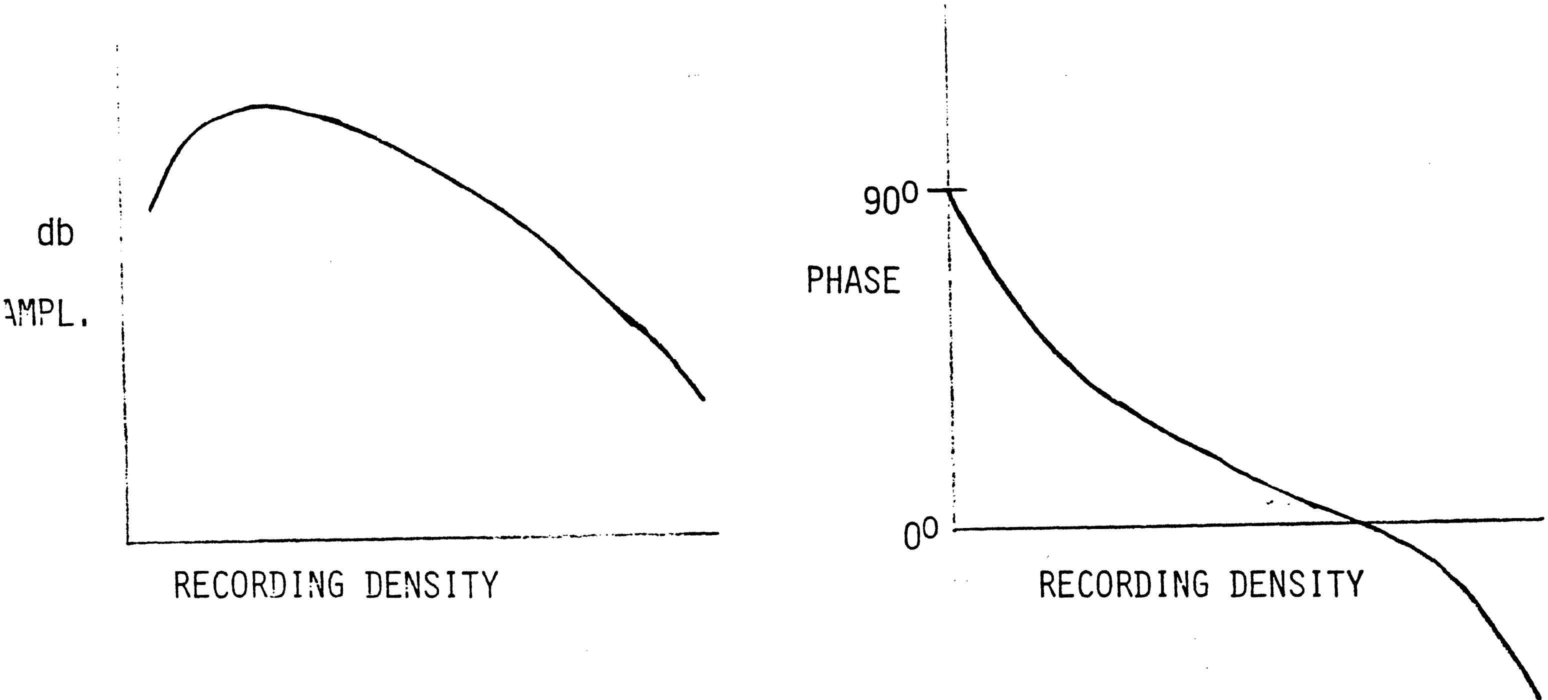
- FREQUENCY DISTORTION
- AMPLITUDE AND PHASE VARIATION VS FREQUENCY

NONLINEAR, NO MEMORY EFFECTS

- HARMONIC DISTORTION
- INTERMODULATION DISTORTION

NONLINEAR WITH MEMORY

- NONLINEAR INTERSYMBOL INTERFERENCE



<u>FREQUENCY DISTORTION</u>

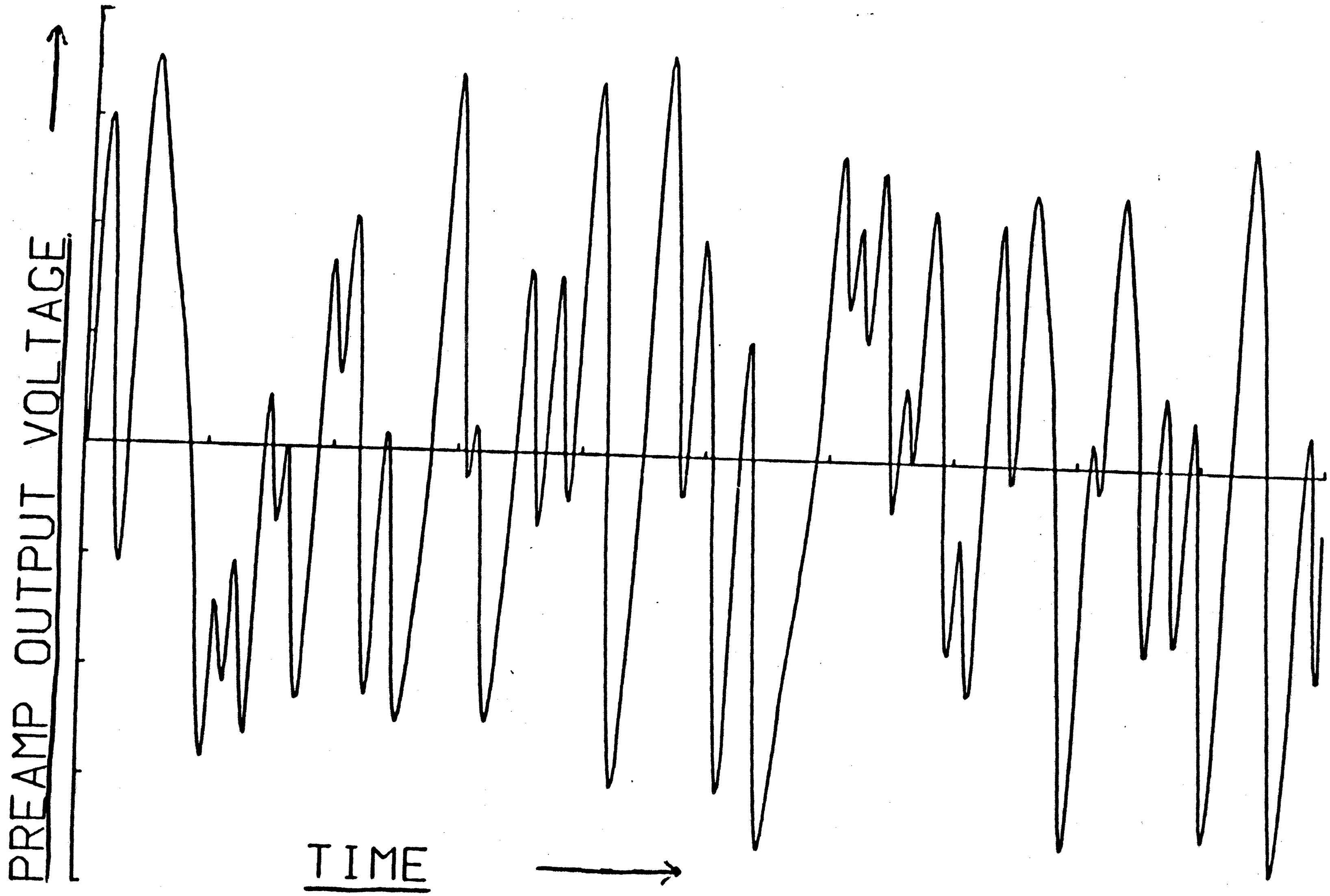
WALLACE'S EQUATIONS
- SEPARATION
- GAP
- THICKNESS

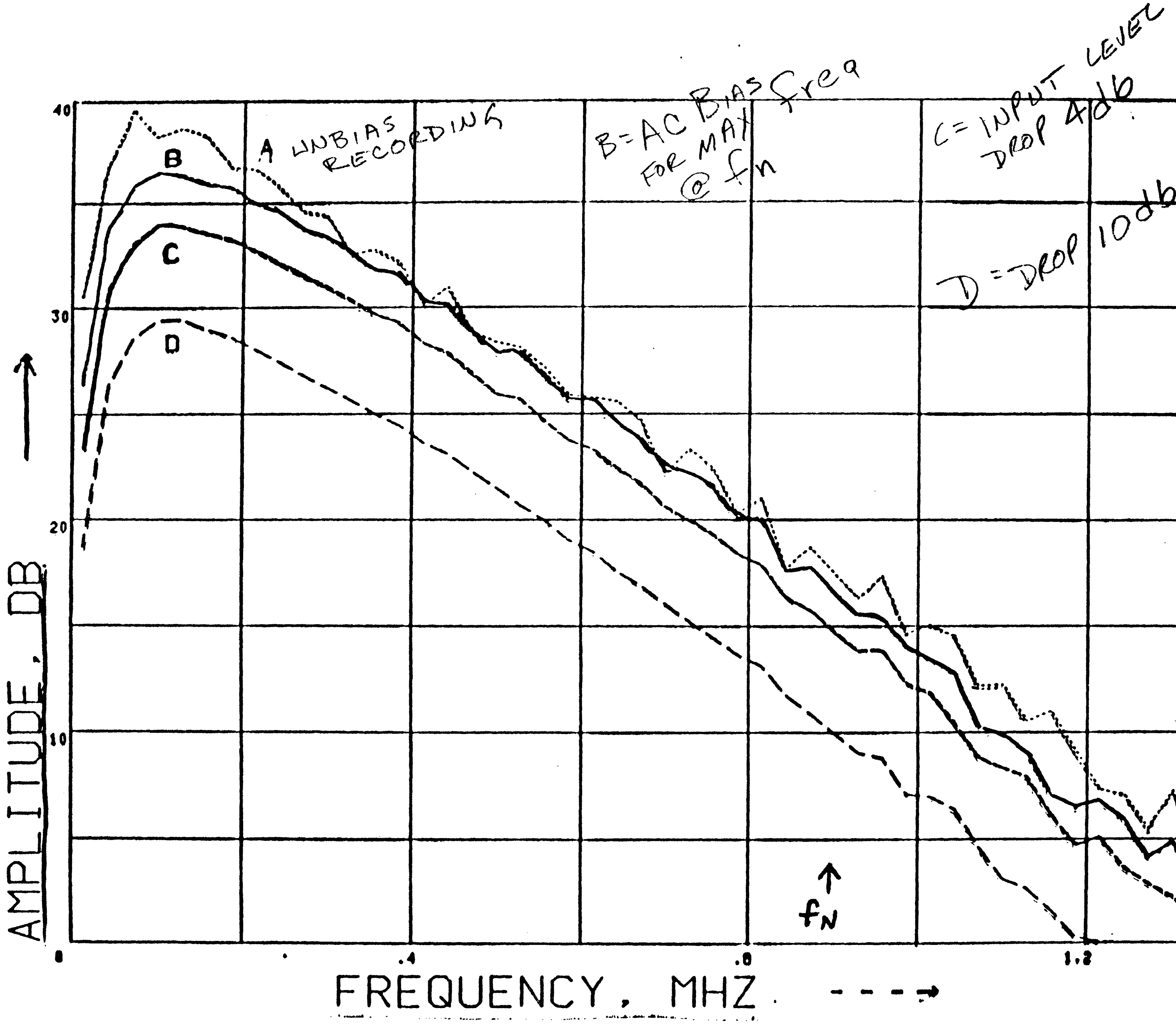
PHASE EFFECT DURING RECORDING

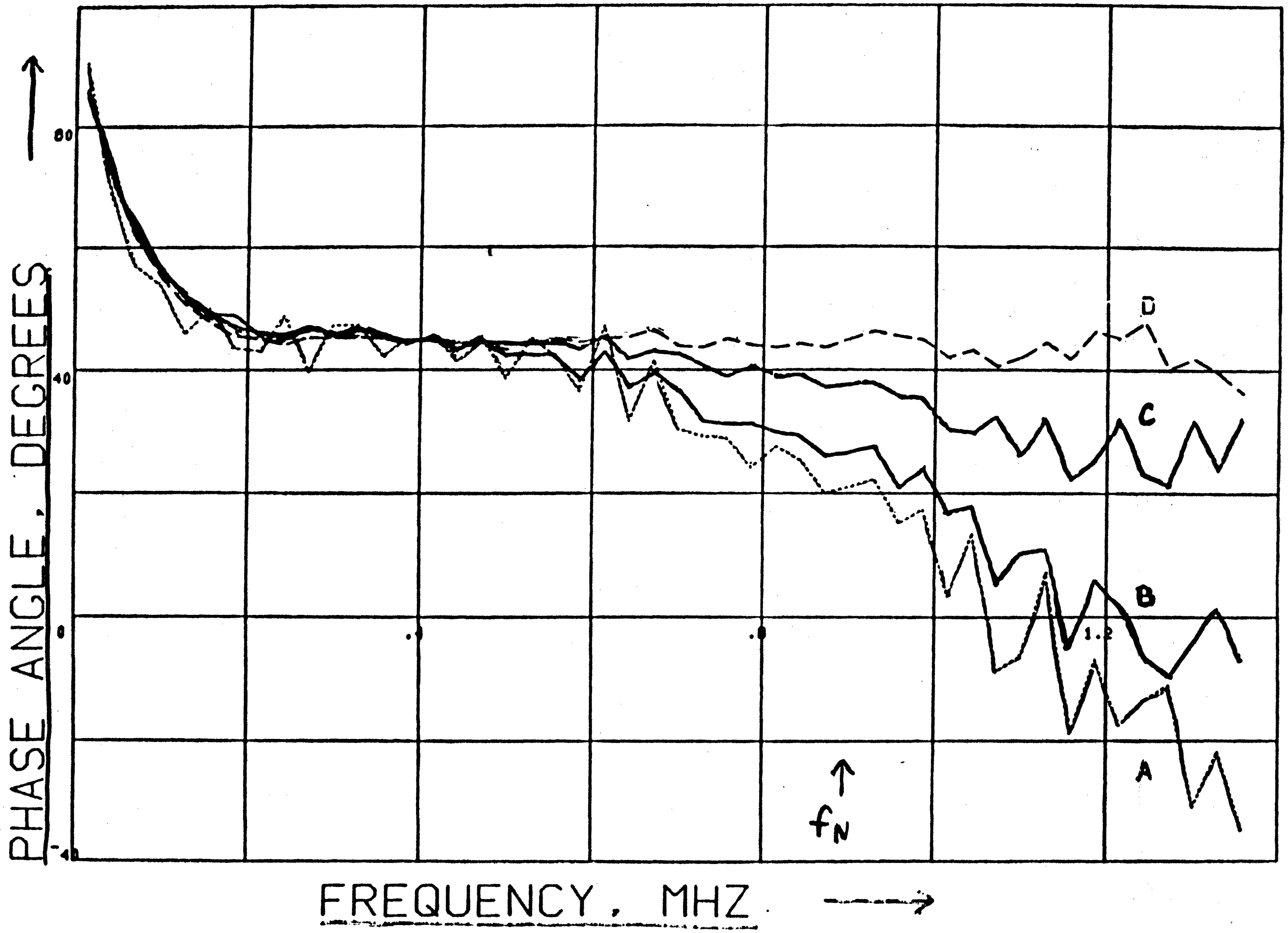
LINEAR EFFECTS

CORRECTABLE BY EQUALIZATION

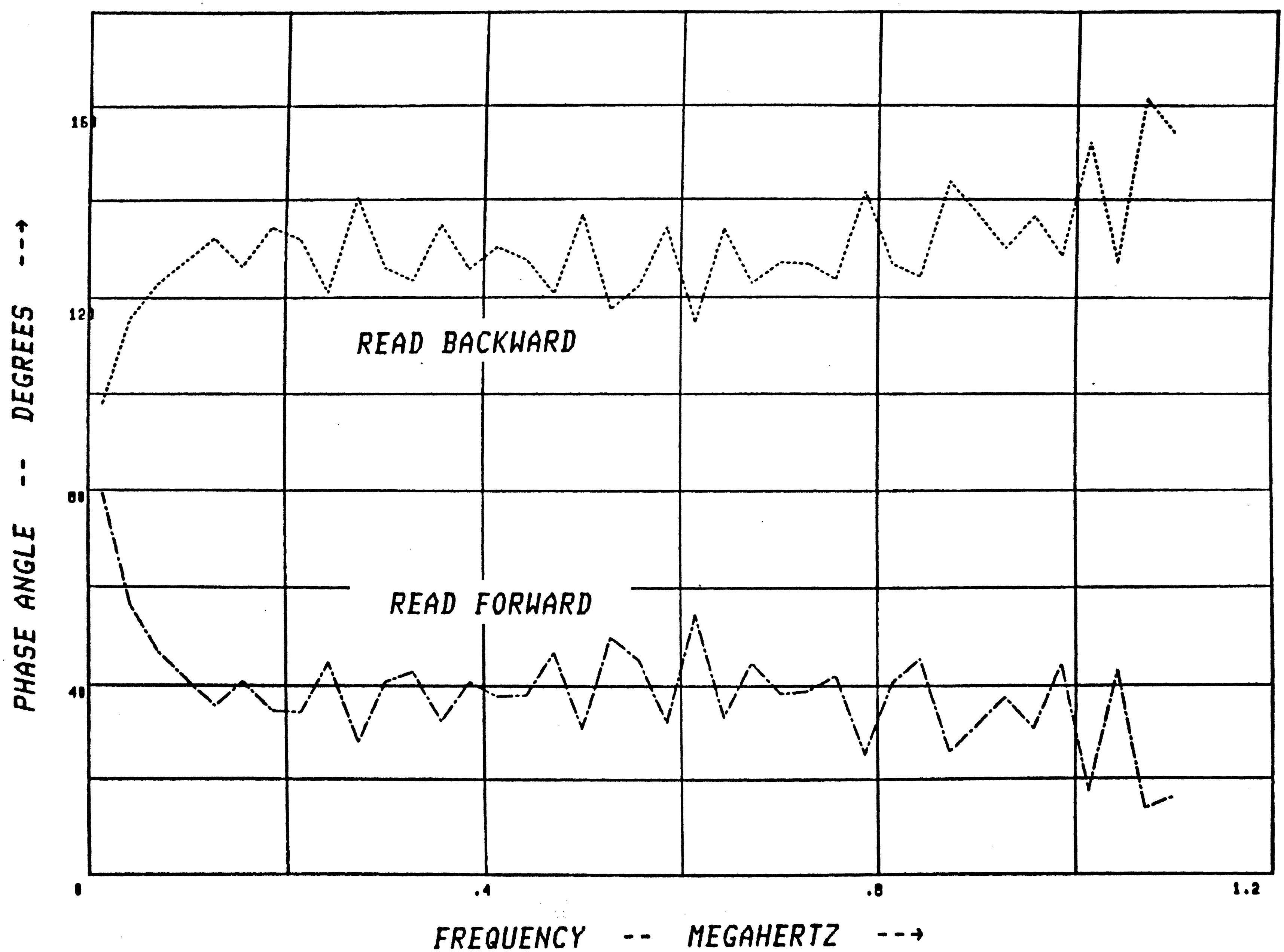
M.K. Haynes, "Experimental Determination of the Loss and Phase Transfer Functions of a Magnetic Recording Channel," IEEE Trans. Mag. V. MAG-13, Sept.1977, pp1284-86.


PREAMP OUTPUT VOLTAGE
TIME

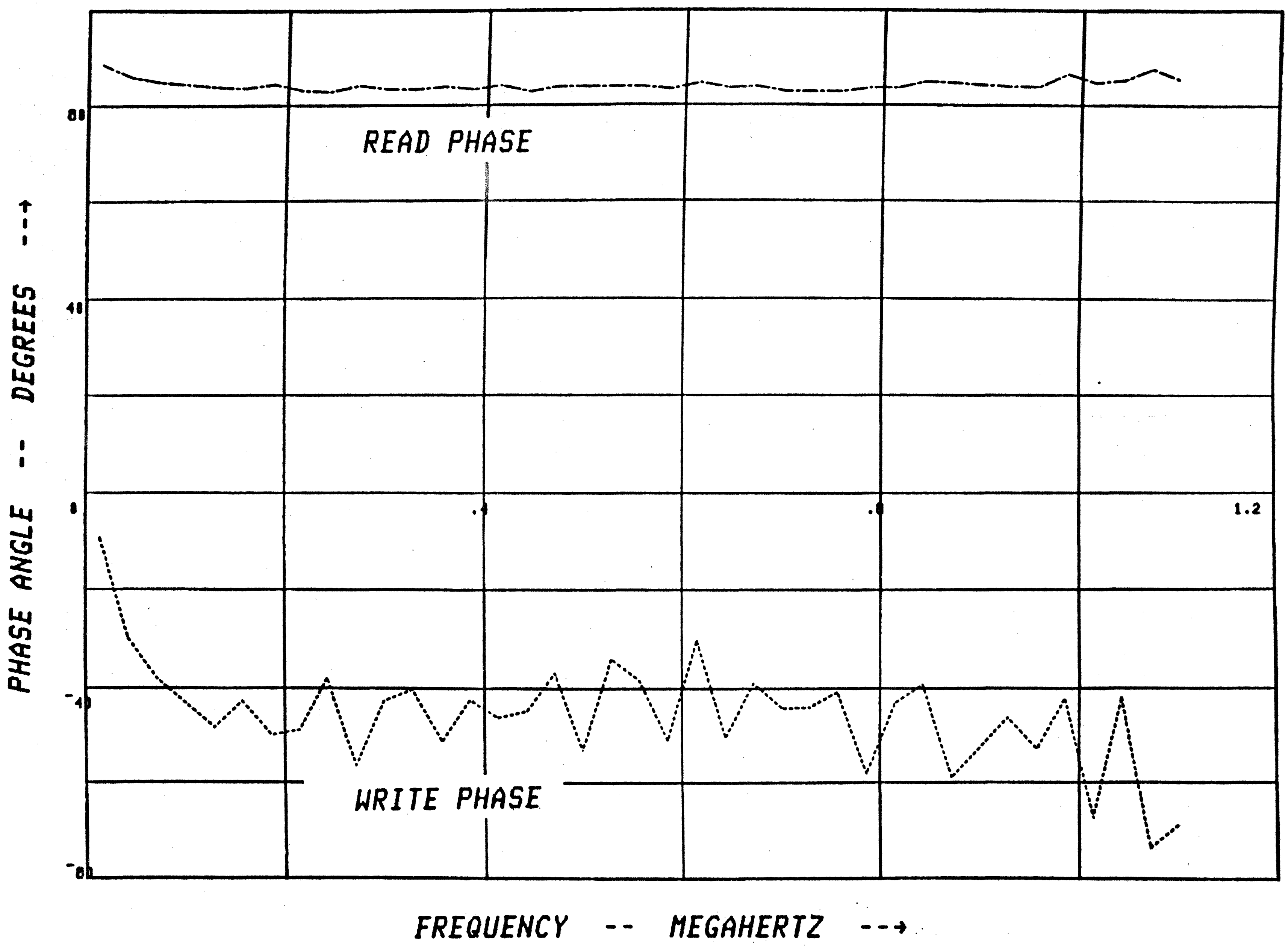

A UNBIAS RECORDING
B=AC BIAS freq FOR MAX @ fn
C= INPUT LEVEL DROP 4db
D = DROP 10db
B
C
D
40
30
20
10
0
.4
.8
1.2
fN
AMPLITUDE, DB
FREQUENCY, MHZ



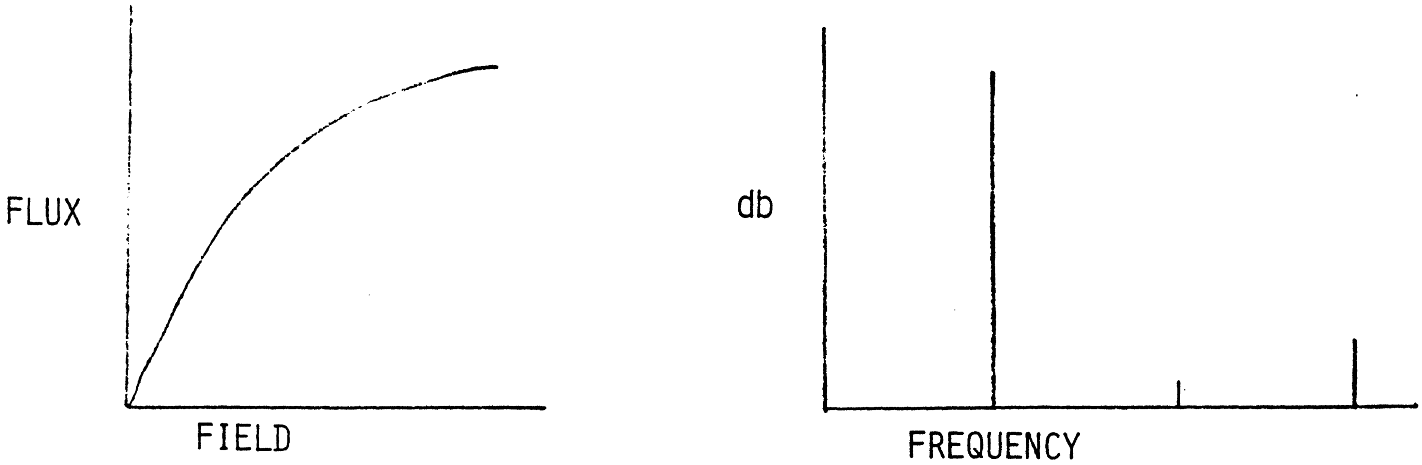
PHASE ANGLE, DEGREES
80
40
0
-40
.4
.8
1.2
D
C
B
A
f_N
FREQUENCY, MHZ



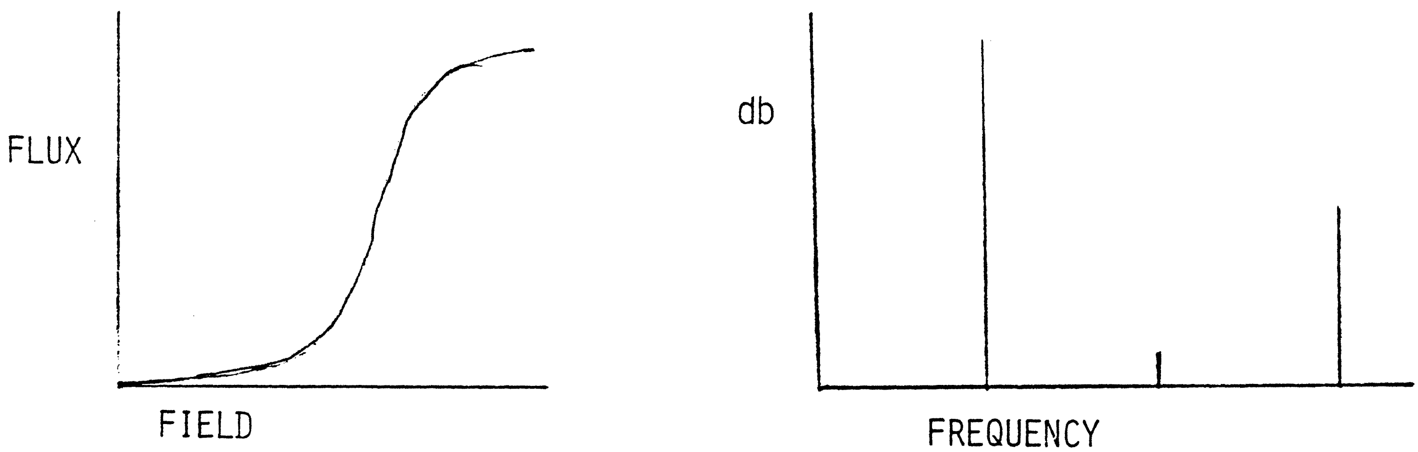
160
120
80
40
0
.4
.8
1.2
READ BACKWARD
READ FORWARD
PHASE ANGLE -- DEGREES --→
FREQUENCY -- MEGAHERTZ --→


READ PHASE
WRITE PHASE
PHASE ANGLE -- DEGREES --→
FREQUENCY -- MEGAHERTZ --→
80
40
0
-40
-80
.4
.8
1.2

HARMONIC DISTORTION



AC BIAS RECORDING



UNBIASED RECORDING

NONLINEARITY AS A POWER SERIES

NO EVEN HARMONICS (IF EVENLY BALANCED)

UNCORRECTABLE BY LINEAR EQUALIZATION

EXTENSION TO INTERMODULATION

NO MEMORY EFFECTS

SUPERPOSITION APPLICABLE

NONLINEAR INTERSYMBOL INTERFERENCE

A HIGH DENSITY PHENOMENON

RELATED TO THE EXTENT OF WRITE-HEAD FIELD, AND THE TRANSITION LENGTH, AS COMPARED TO THE BIT SPACING

DEMAGNETIZATION INTERACTION

DATA PATTERN DEPENDENT

SUPERPOSITION FAILURE

UNCORRECTABLE BY LINEAR EQUALIZATION

SHOWN IN:-

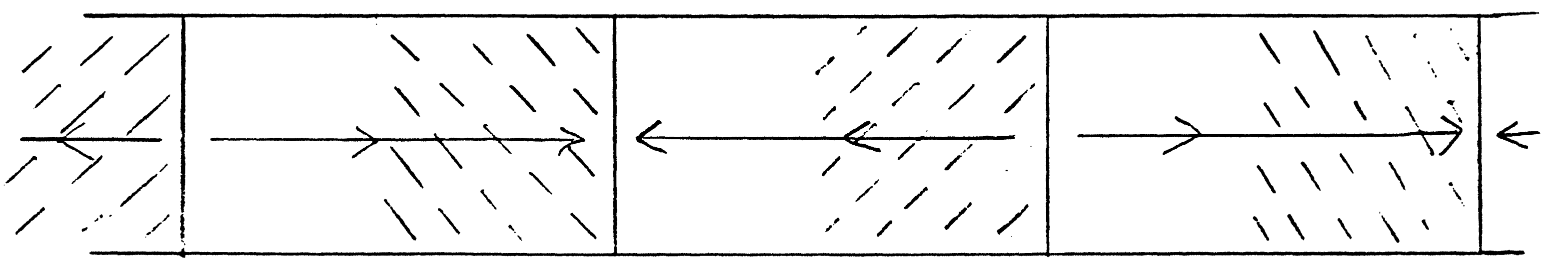
- SELF-CONSISTENT FIELD CALCULATIONS
- SCALE-MODELING EXPERIMENTS
- TIME-DOMAIN MEASUREMENTS
- TRANSFER-FUNCTION MEASUREMENTS

C.S. Chi, "Spacing Loss and Non-linear Distortion in Digital Magnetic Recording," IEEE Trans. Mag. V. MAG-16, Sept. 1980,pp976-78.

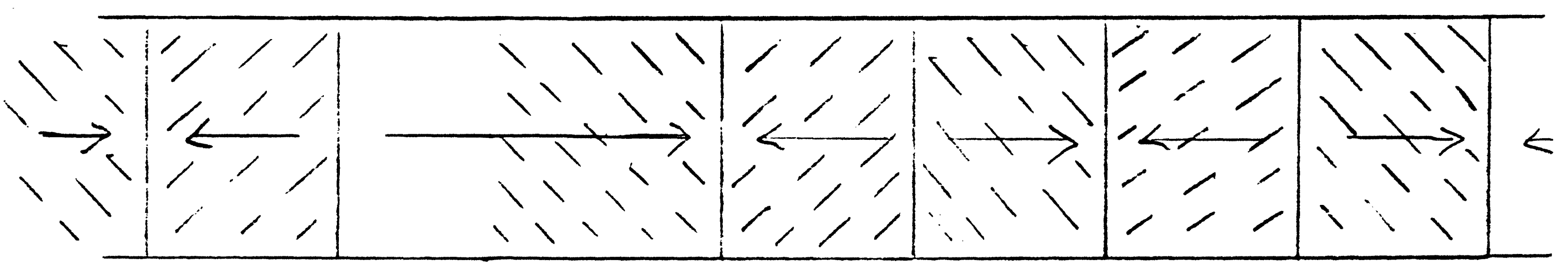
R. W. Wood & R.W. Donaldson, "The Helical-Scan Magnetic Tape Recorder as a Digital Communication Channel," IEEE Trans. Mag. V. MAG-15, March 1979, pp 935-43.

NONLINEAR INTERSYMBOL INTERFERENCE

"SNOWSHOE" EFFECT



LOW RECORDING DENSITY



HIGH RECORDING DENSITY

SHADED AREA = TRANSITION REGION

NOISE SOURCES IN DIGITAL RECORDING

HEAD NOISE

AMPLIFIER NOISE

MEDIA NOISE

- PARTICULATE, DOMAIN, DEFECTS
- MODULATION NOISE

INTERFERENCES

STRAY COUPLING

- FEEDTHROUGH
- MULTI-TRACK HEADS

HEAD FRINGE-FIELDS

- SIDE WRITING
- SIDE READING
- CORNER READING

OVERWRITE NOISE

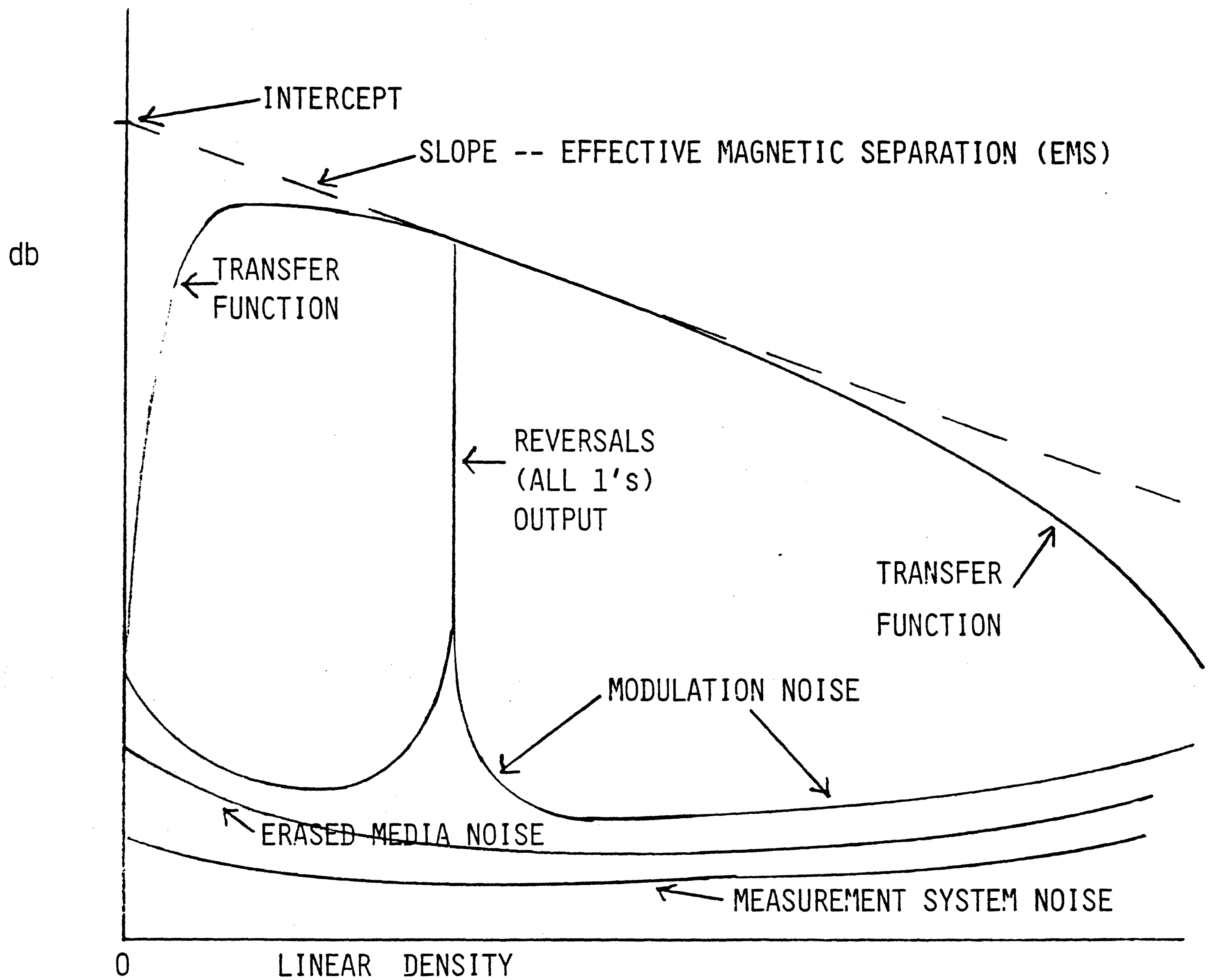
TRACK MISREGISTRATION

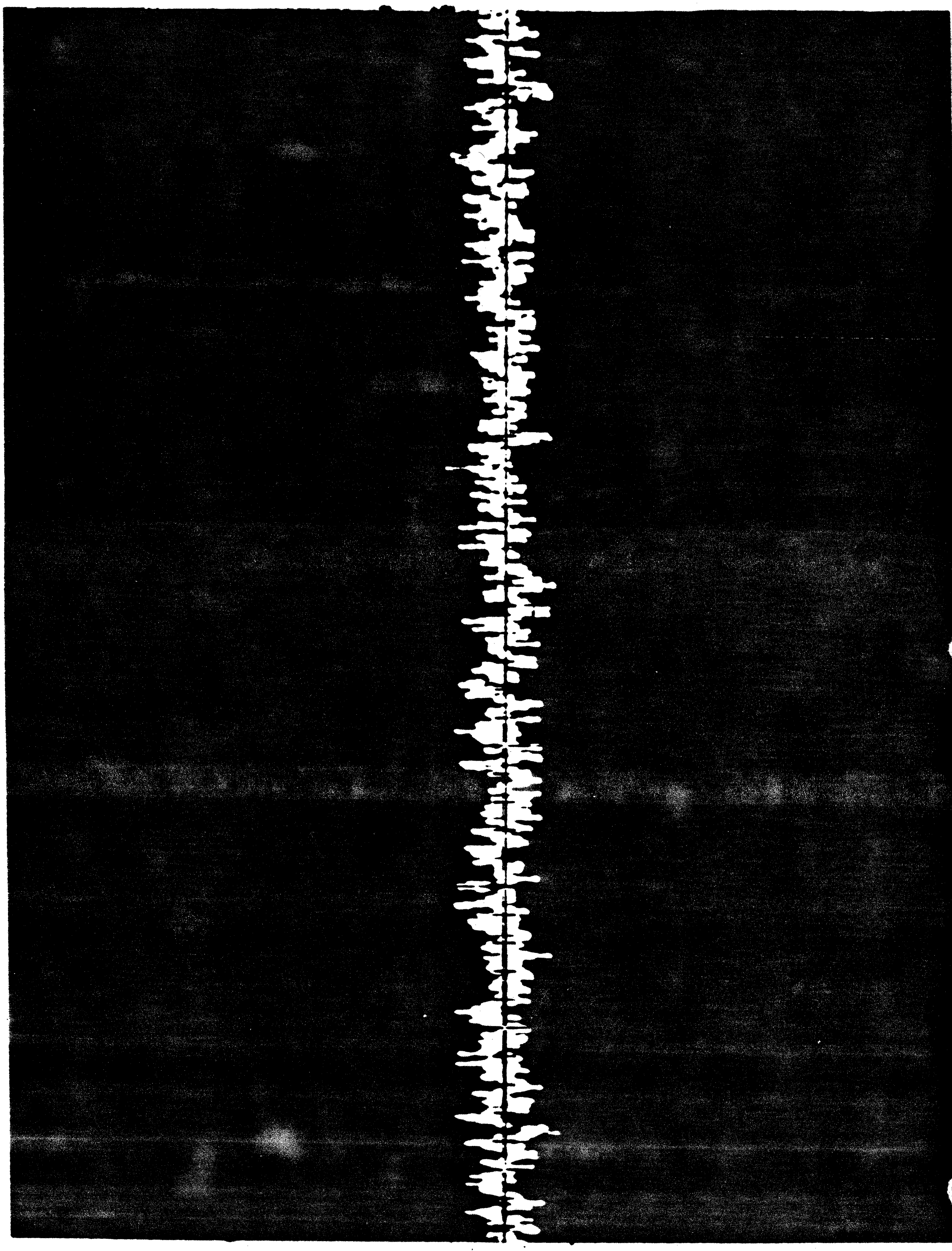
- OFF-TRACK
- ADJACENT TRACK
- OLD INFORMATION

MECHANICAL VIBRATIONS AND VARIATIONS

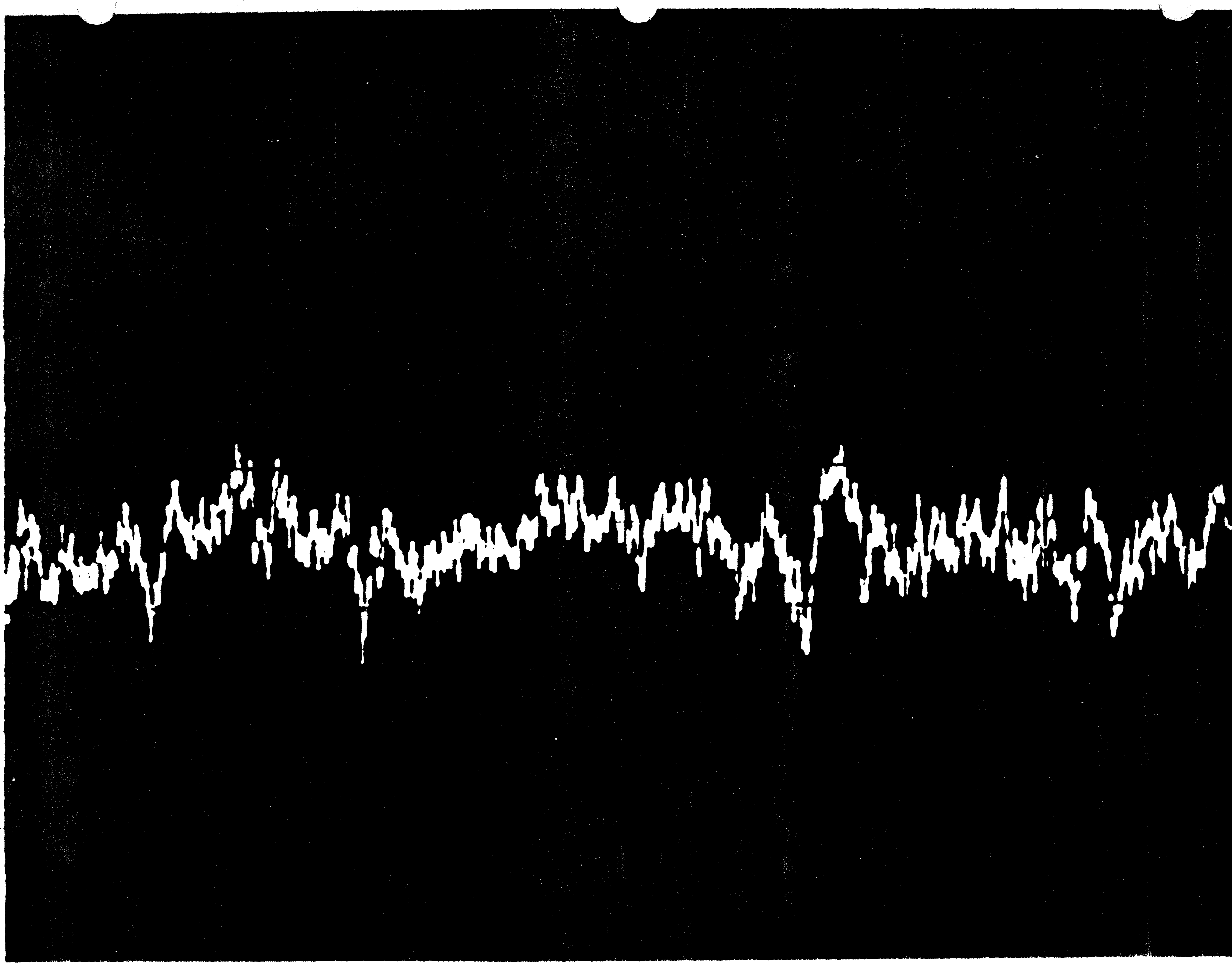
- VELOCITY
- TRACKING

DENSITY RESPONSE AND NOISE





MODULATION NOISE



Digital Computation of Noise Spectrum

Given a Time Series: x_t, $t = 0, 1, 2 \cdots N$

Mean: $\bar{x} = \frac{1}{N} \sum_{t=1}^{N} x_t$

Variance: $\sigma_x^2 = \frac{1}{N} \sum_{t=1}^{N} (x_t - \bar{x})^2$

Auto-Covariance: $c_{xx}(k) = \frac{1}{N} \sum_{t=1}^{N-k} (x_t - \bar{x})(x_{t+k} - \bar{x})$

$k = 0, 1, 2 \cdots (N-1)$

$k = \text{lag}$

$c_{xx}(0) = \sigma_x^2$

Autocorrelation Function: $r_{xx}(k) = \frac{c_{xx}(k)}{c_{xx}(0)}$

Spectral Density Function:

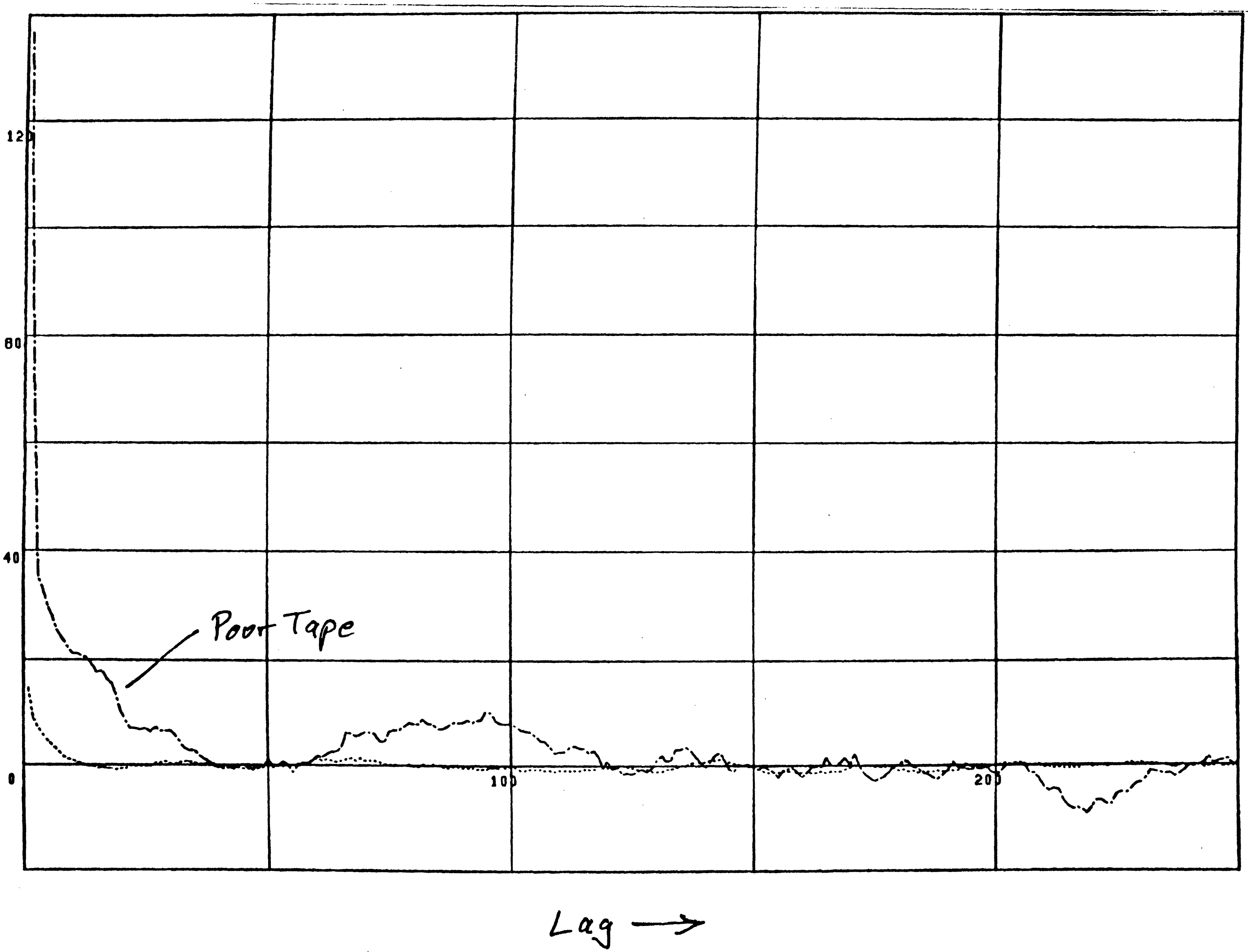
$\bar{R}_{xx}(f)$ = Fourier Transform of Autocorrelation Function

Power Spectrum:

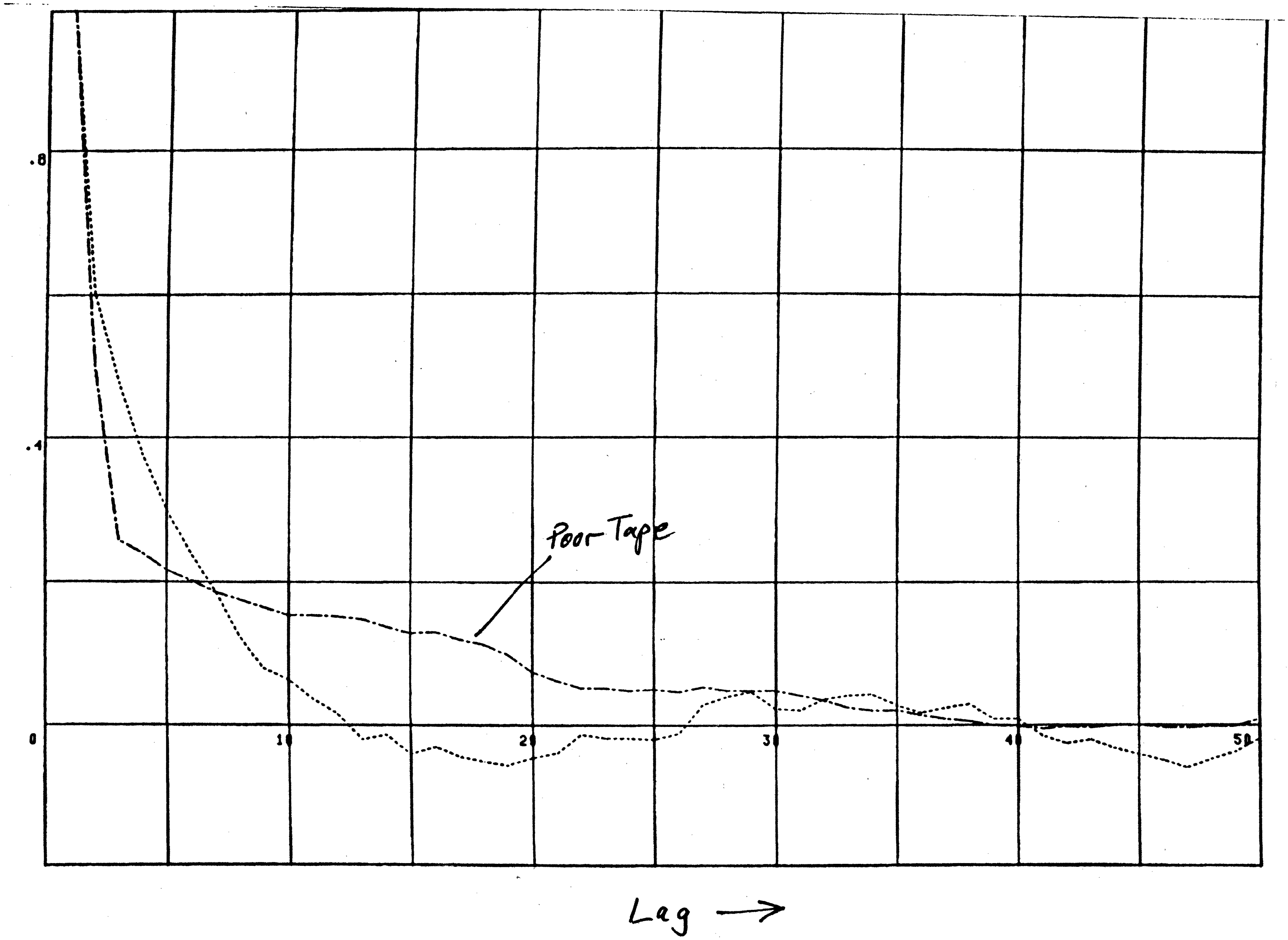
$\bar{C}_{xx}(f) = \sigma_x^2 \times$ Spectral Density Function

nkins & Watts, *Spectral Analysis and its Applications*, San Francisco: Holden Day, 1968

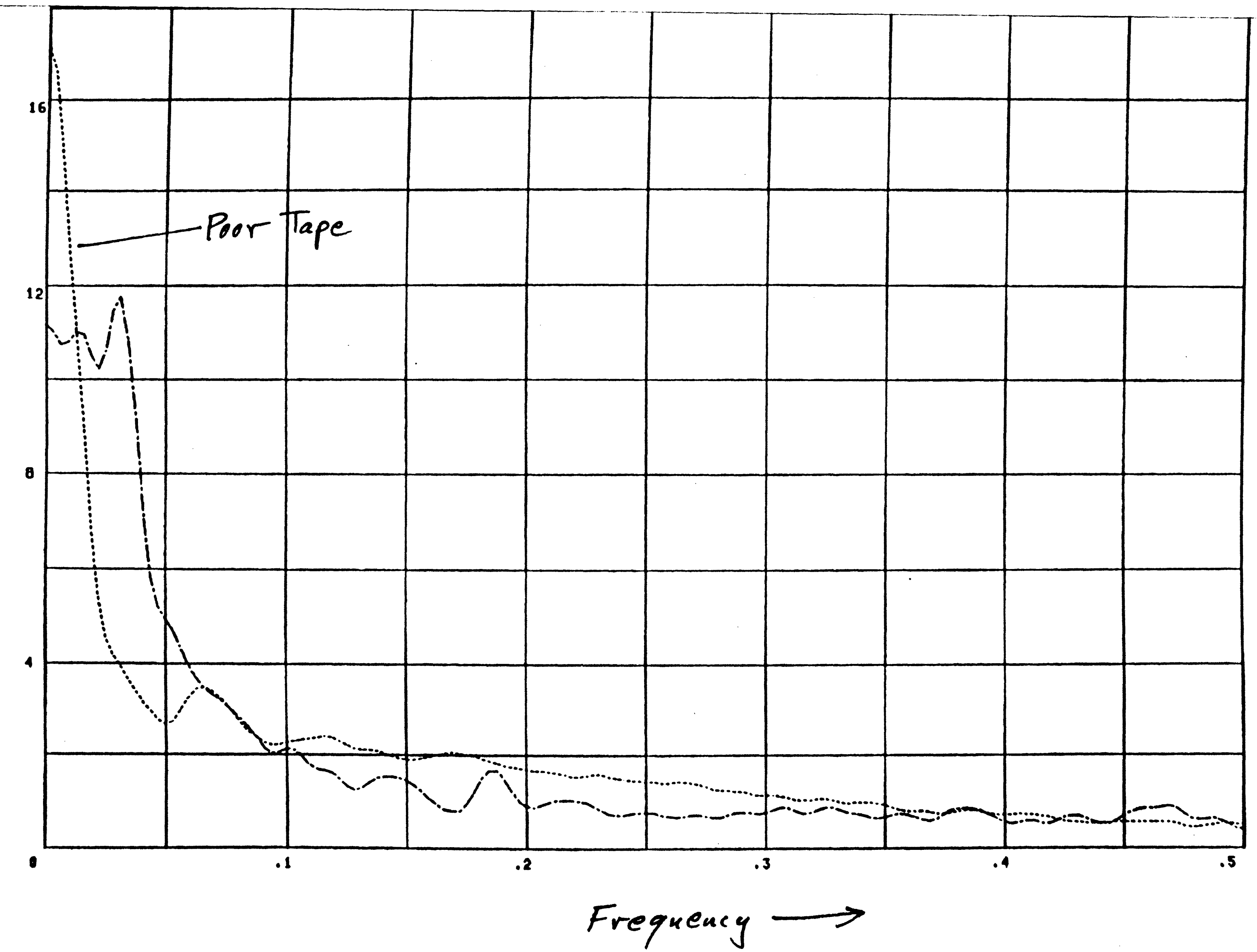
AUTO-COVARIANCE



AUTO-CORRELATION FUNCTION

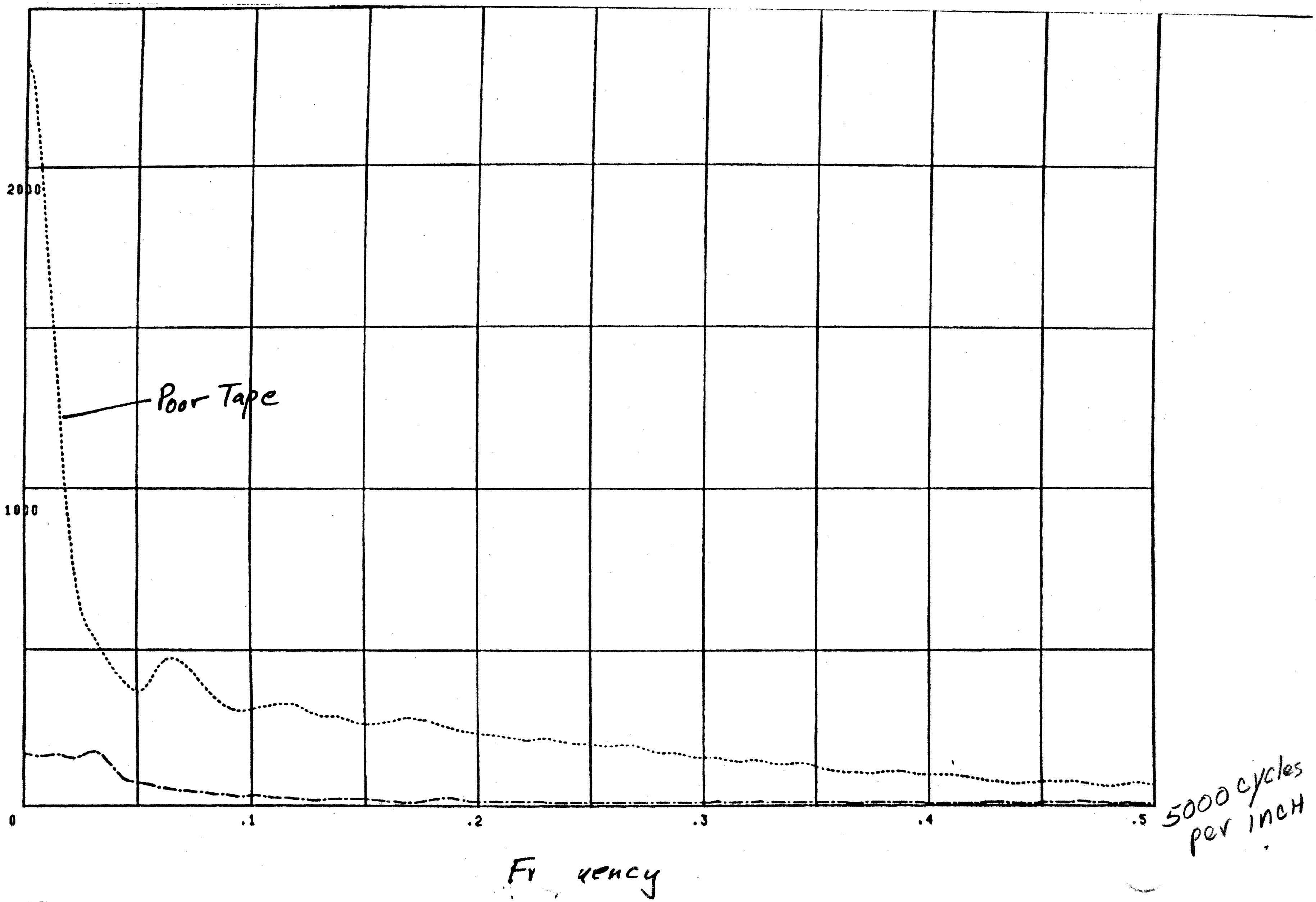


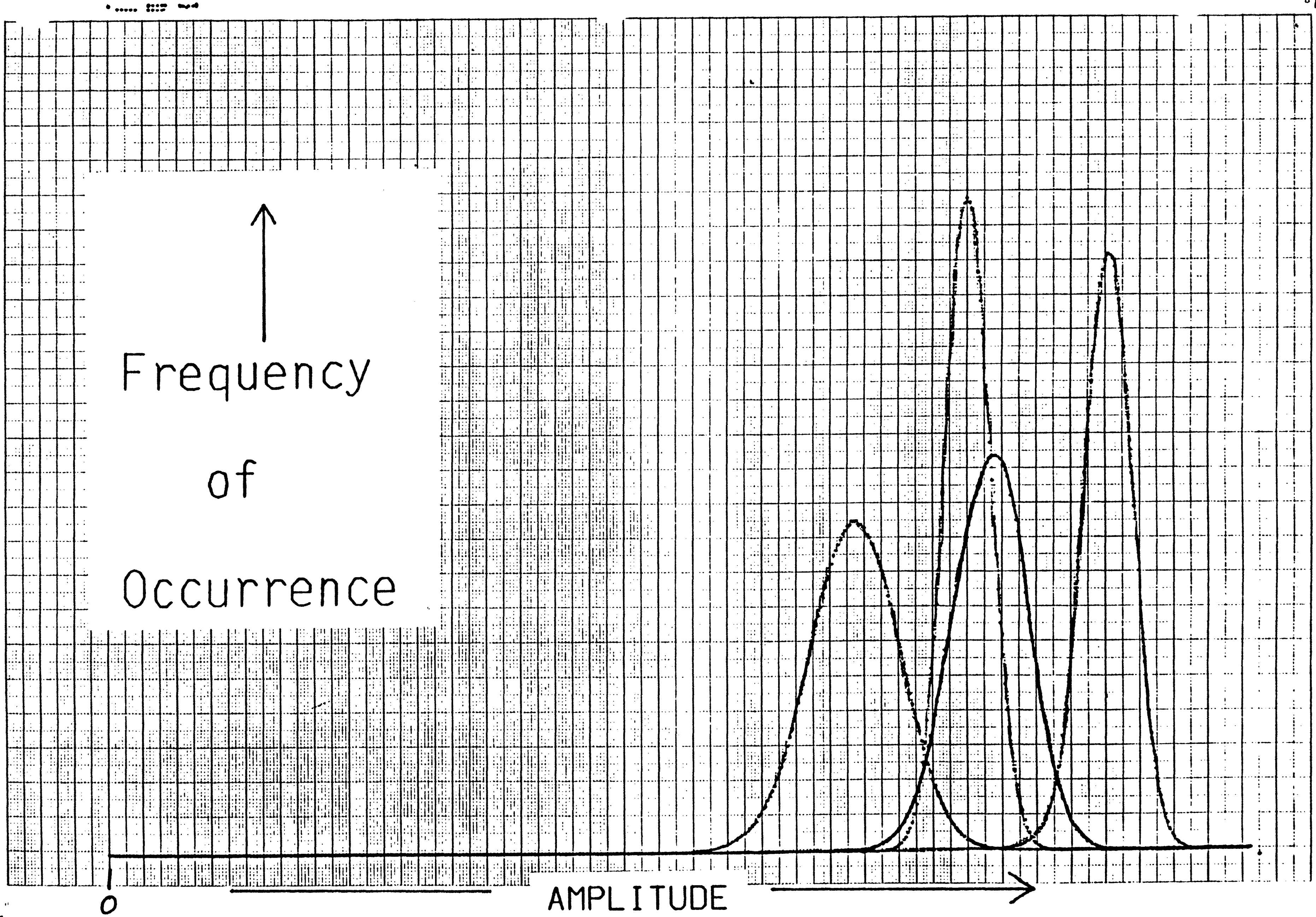
SPECTRAL DISTRIBUTION



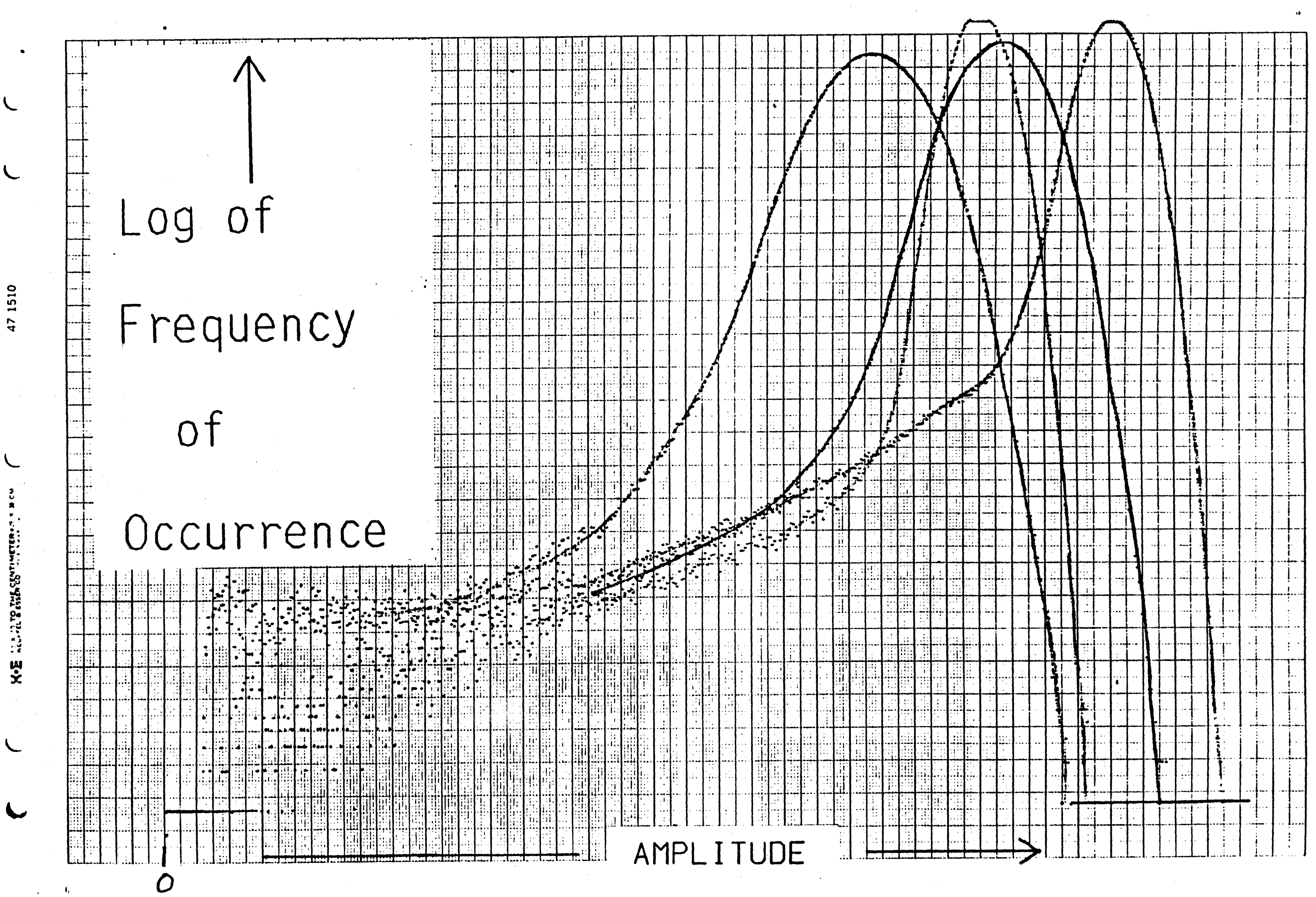
20000 fcpi
30 IPS

NOISE SPECTRUM

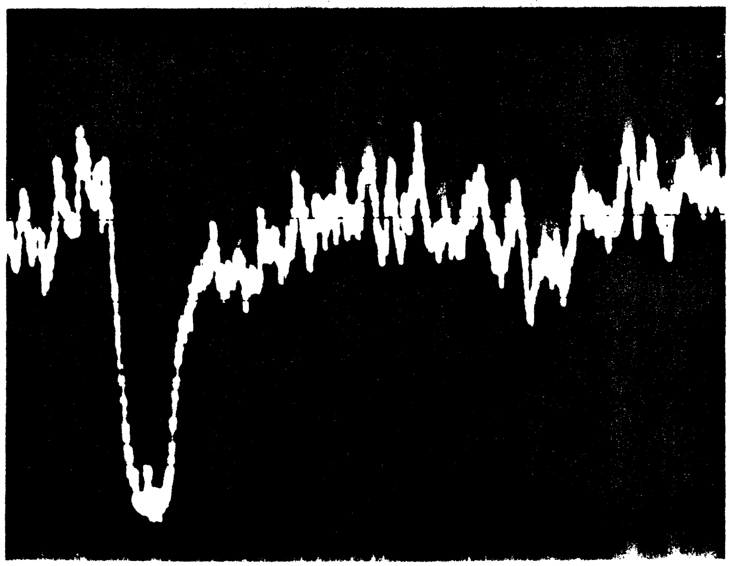




HISTOGRAM OF AMPLITUDE VARIATIONS AT 20 KFCI



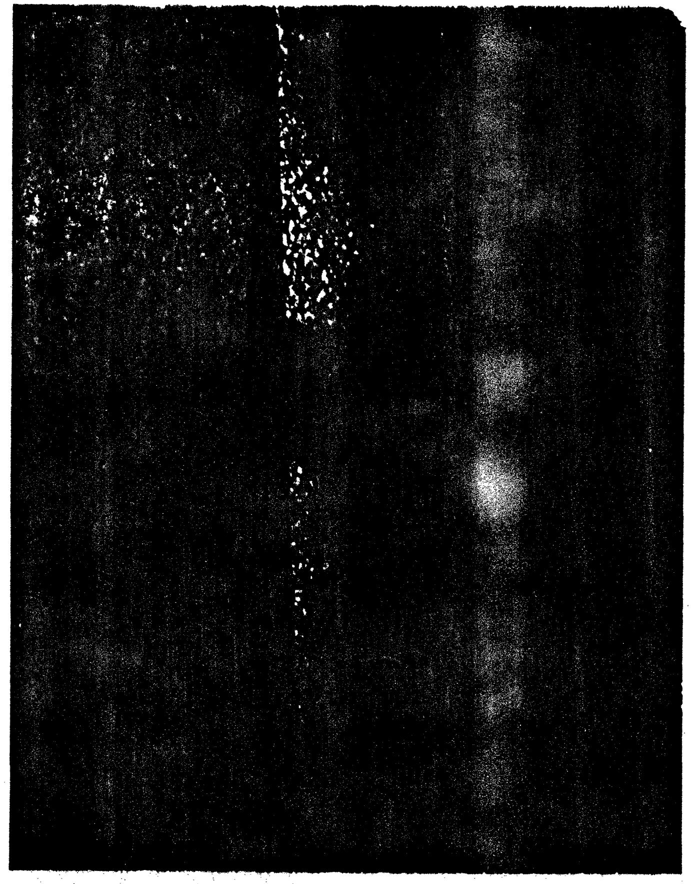
LOGARITHMIC HISTOGRAM OF AMPLITUDE VARIATIONS



— 0

"Drop - Out"

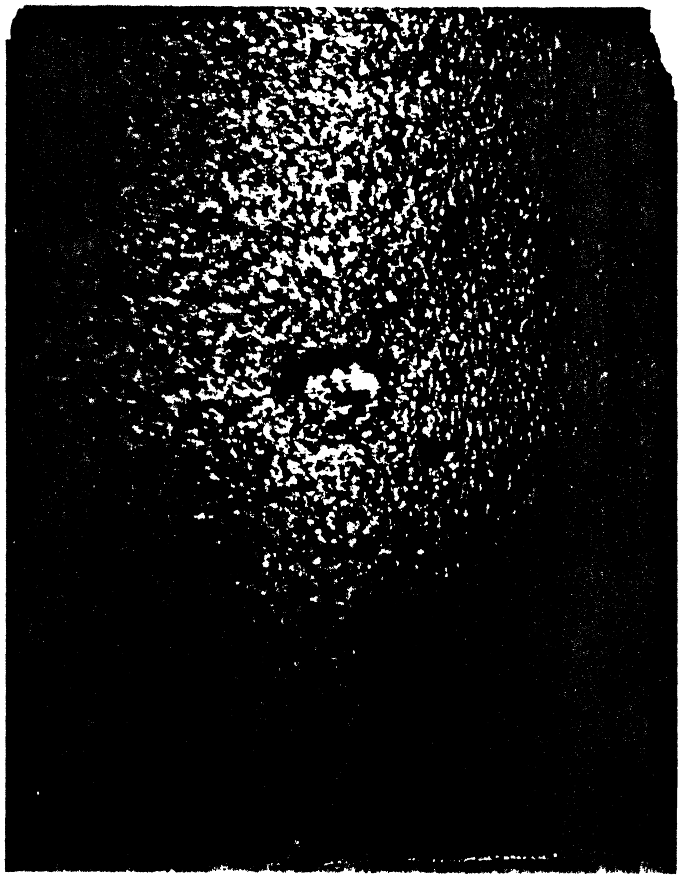
0.020" / div.



Recorded Track
with Drop-out

"Developed" with
Ferrofluid

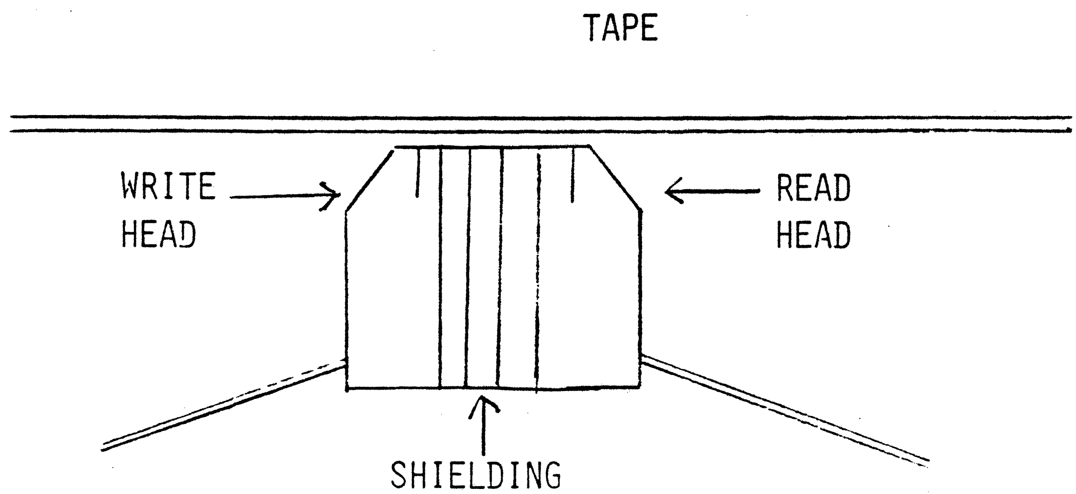
Track Width ≈ 0.018"



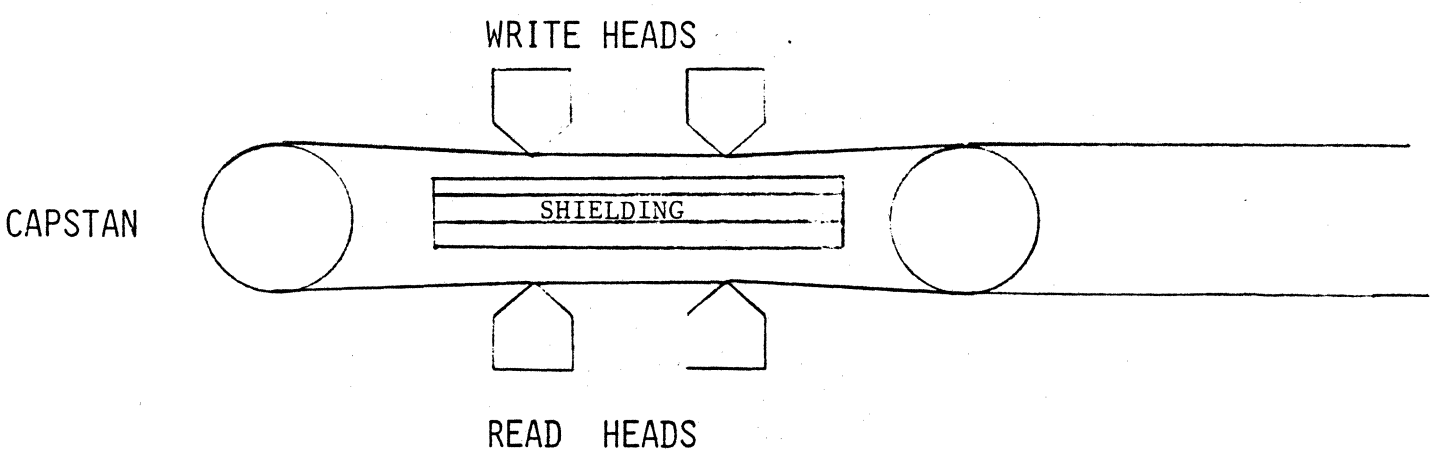
Oxide Clump at Dropout Center

Diameter ≈ 0.001"

FEEDTHROUGH NOISE



COMBINED READ-WRITE HEAD



SEPARATE READ AND WRITE HEADS

COUPLING FROM WRITE HEAD AND CABLES TO READ HEAD

READ-WHILE-WRITE OPERATION ONLY

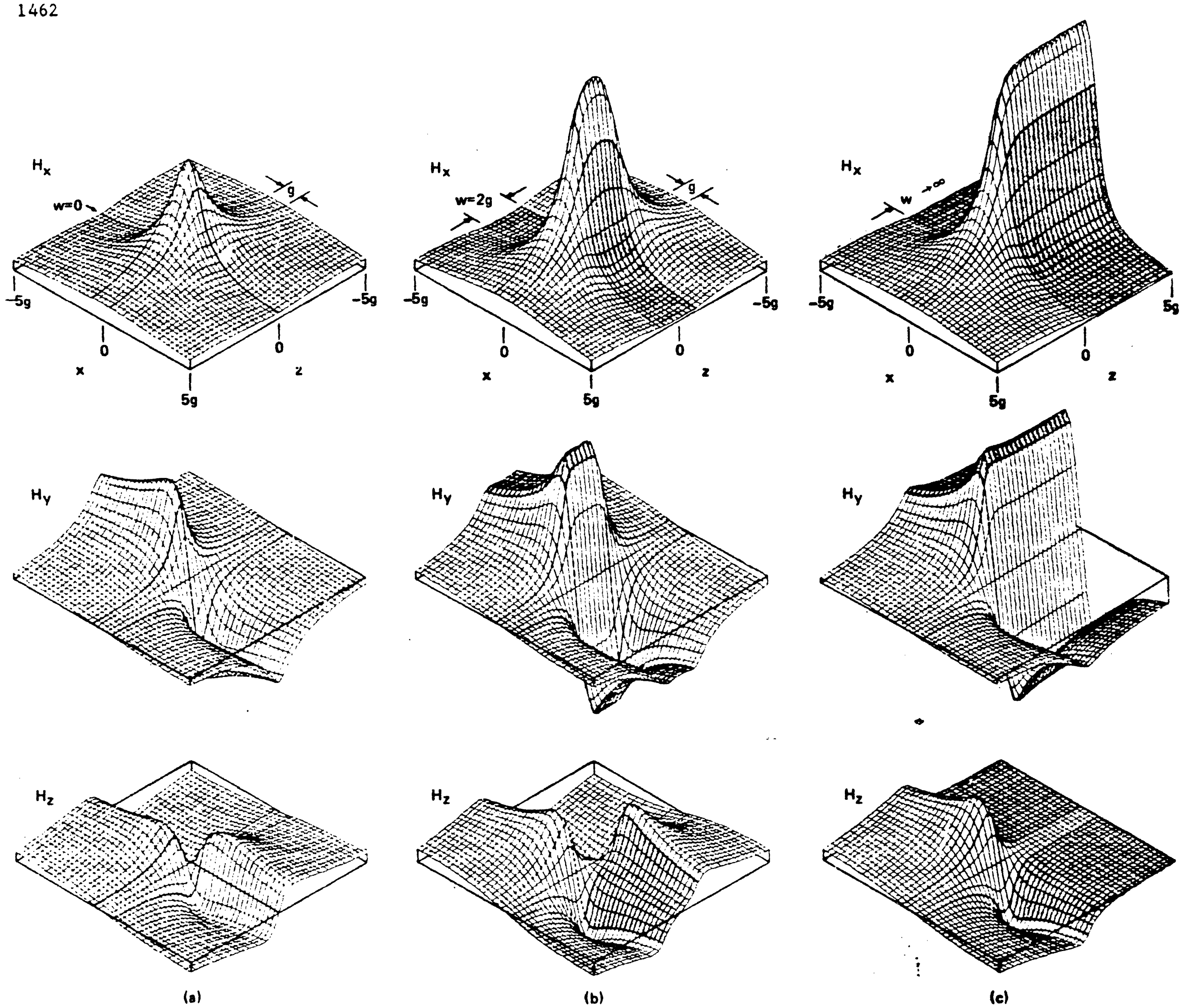


Figure 4. Magnetic fields at y=g/2 for (a) zero width head, (b) finite width head, w=2g, and (c) semi-infinite width head. Components are: longitudinal (H_x), vertical (H_y), and transverse (H_z). Projected onto each field surface are the outlines of the top of the head with edge extensions.

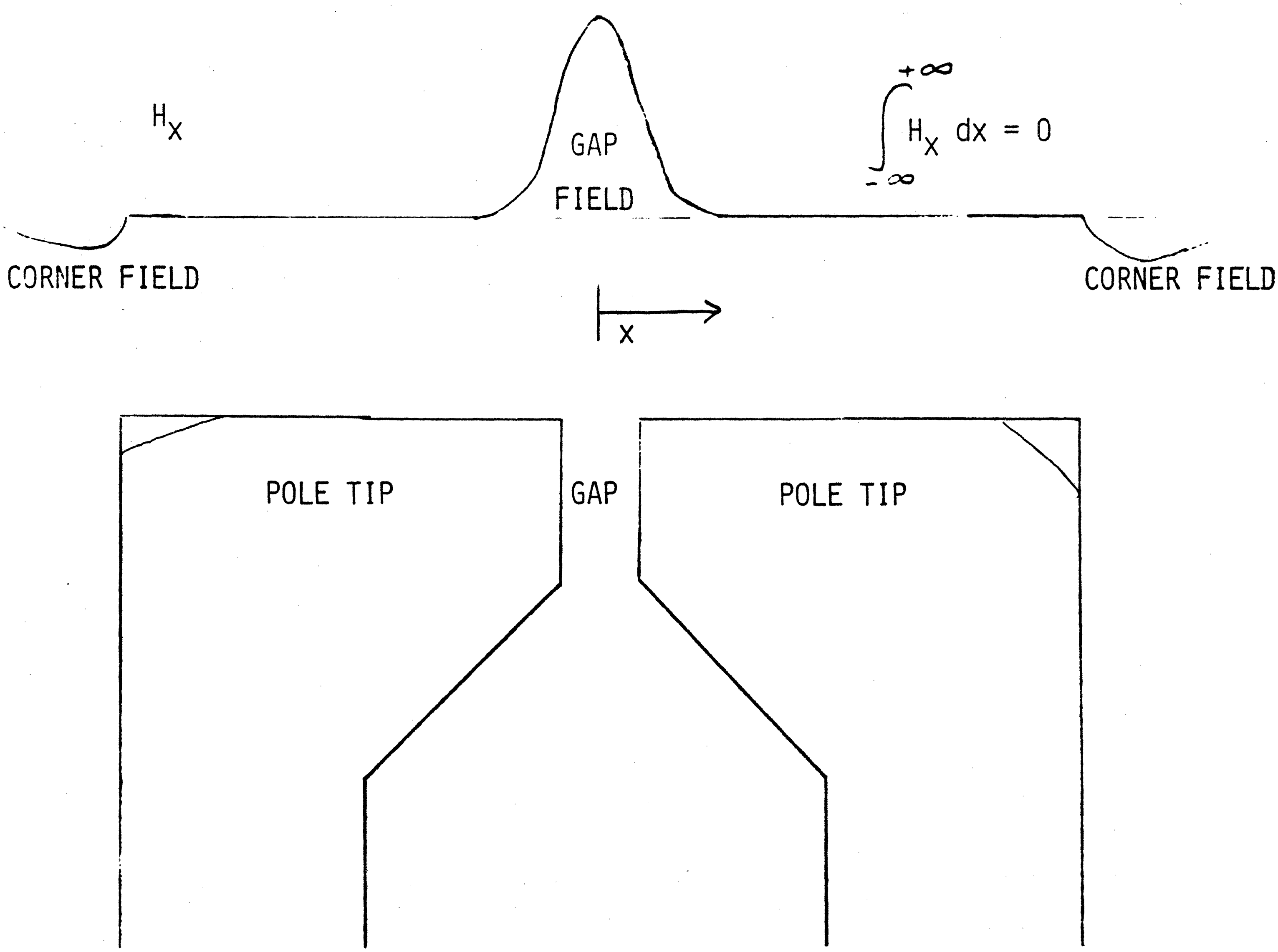
HEAD FIELD DISTRIBUTIONS

D. A. Lindholm, "Magnetic Fields of Finite Track Width Heads," IEEE Trans. Mag. Vol. MAG-13, Sept. 1977

READ-SEPARATION DEPENDENT

DENSITY DEPENDENT

HEAD-CORNER READING EFFECT



OVERWRITE-ERASURE NOISE

ERASE PROBLEM

DC ERASE, AC ERASE

DENSITY DEPENDENCE

TRANSITION REGION

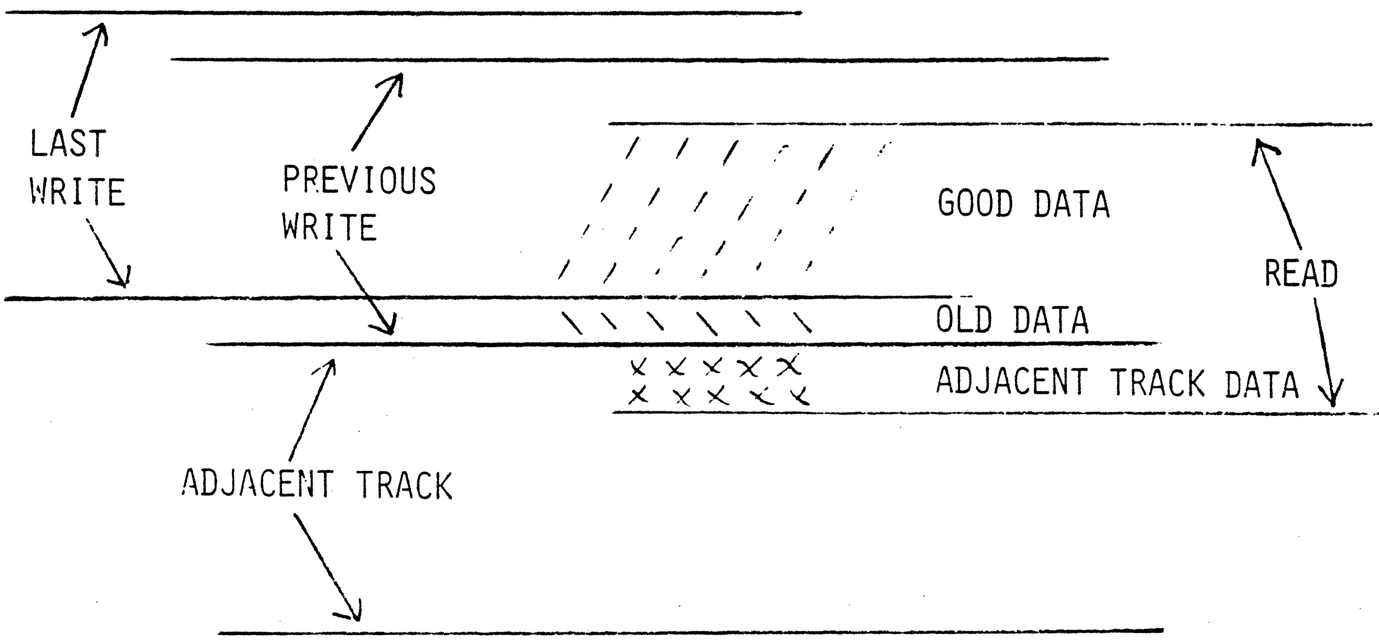
FINITE DEPTH RECORDING

FLYING-HEIGHT VARIATION

UNBIASED, AC BIAS, RECORDING

CODED WRITE-DATA SPECTRUM

TRACK MISREGISTRATION (TMR)



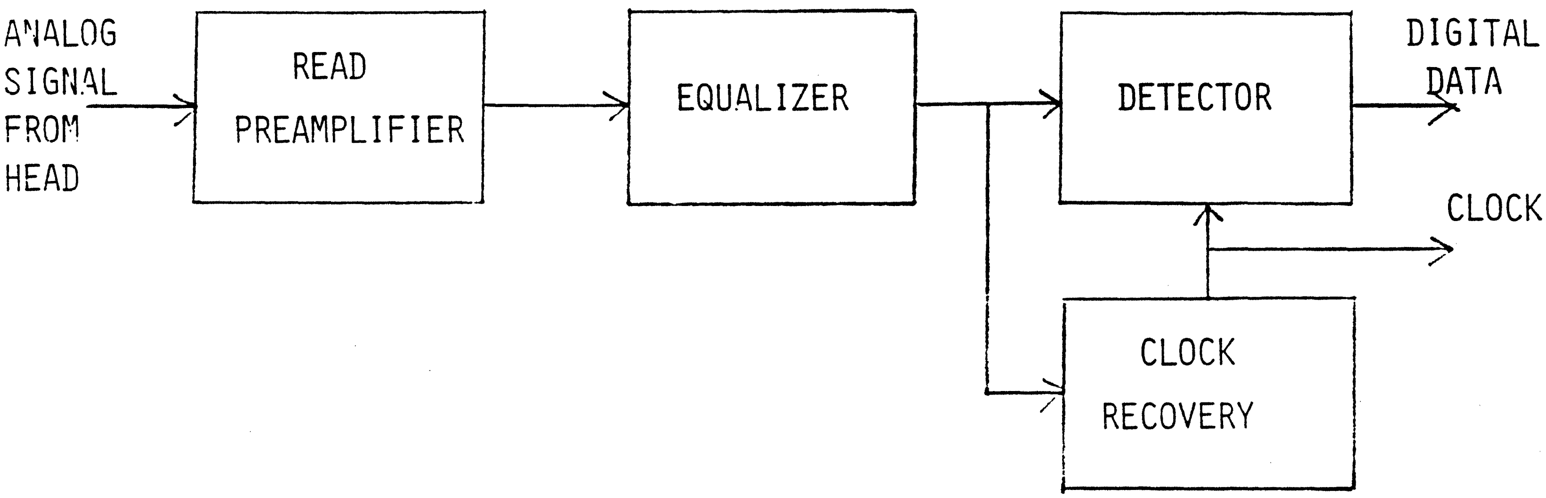
GUARD BAND

TUNNEL ERASE

WRITE WIDE, READ NARROW

SERVO TRACK FOLLOWING

READ-ELECTRONICS CHAIN

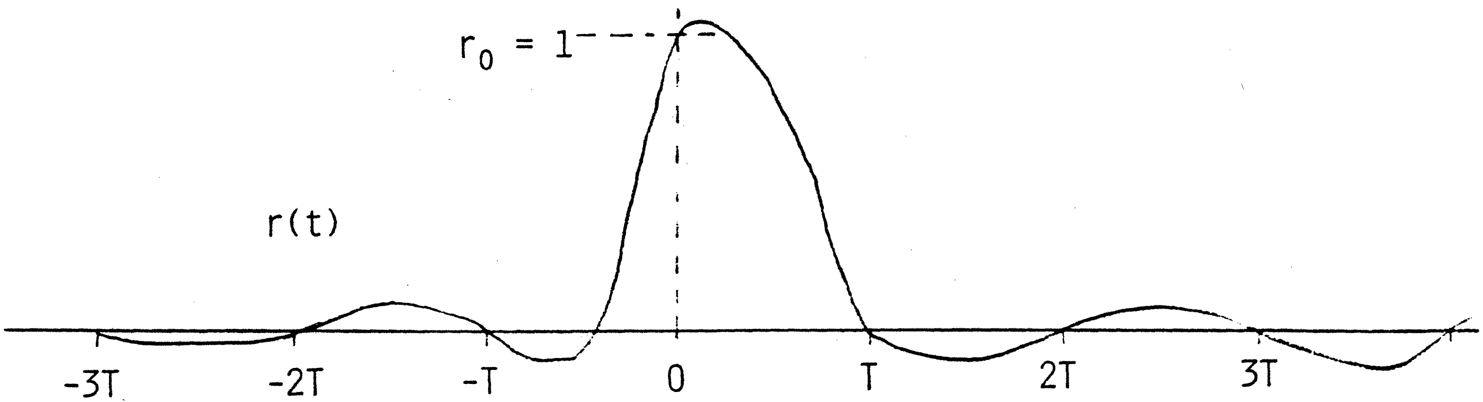


BENNETT & DAVY, DATA TRANSMISSION, NEW YORK: McGRAW-HILL, 1965.

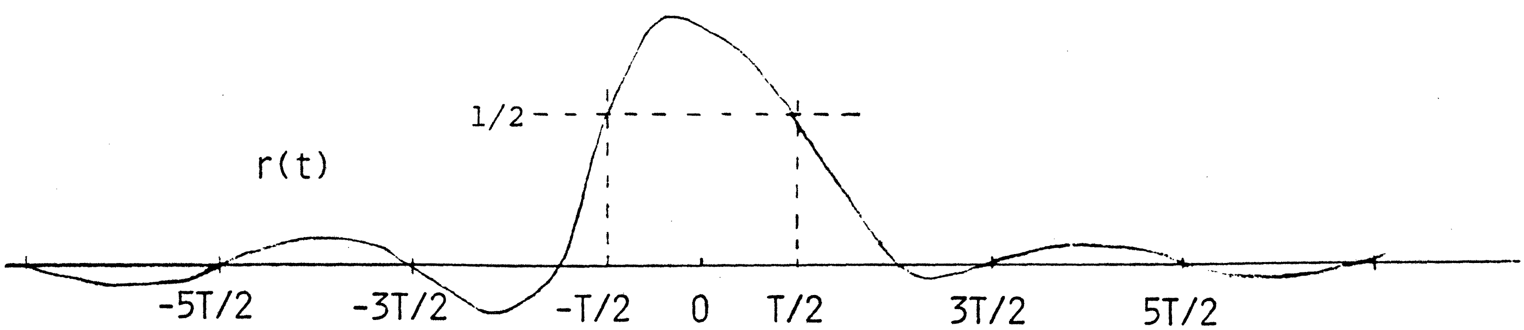
EQUALIZATION:-

GIBBY & SMITH, B.S.T.J., V44, Sept. 1965, pp 1487-1510

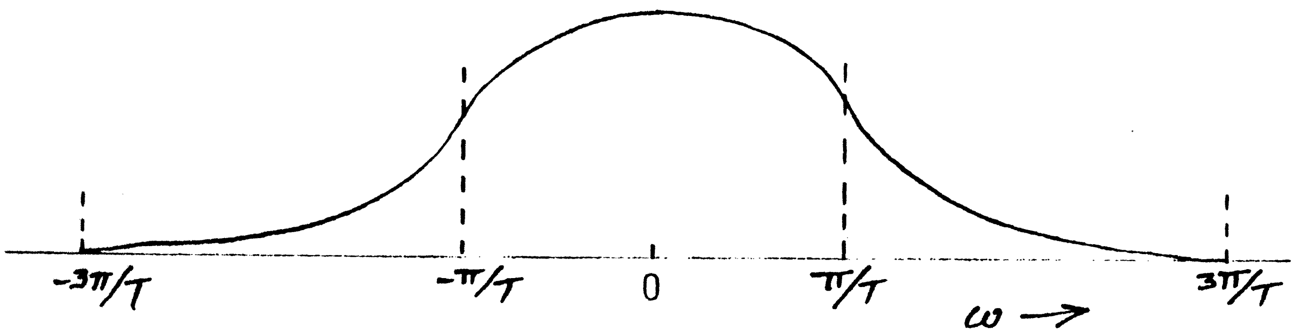
EQUALIZING SAMPLED DATA



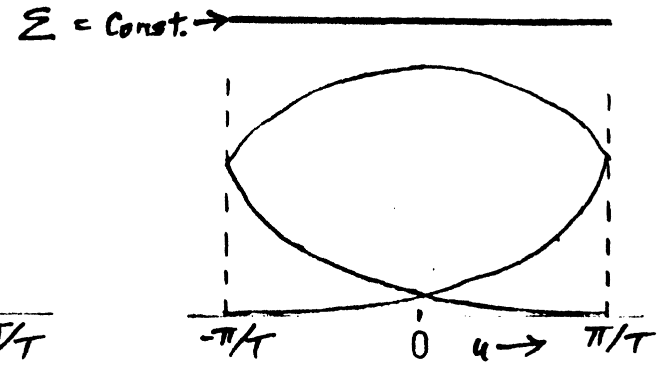
CONTROLLING AMPLITUDE AT SAMPLE POINTS



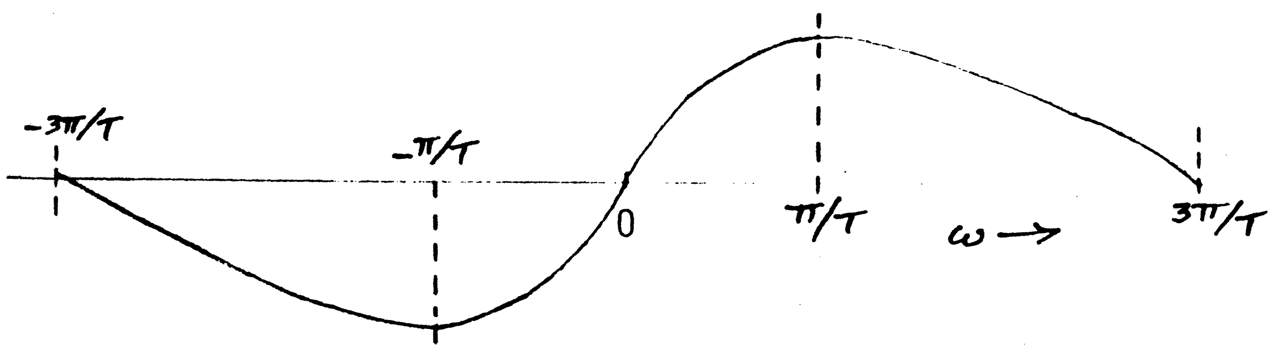
CONTROLLING PULSE WIDTH BETWEEN SAMPLE POINTS



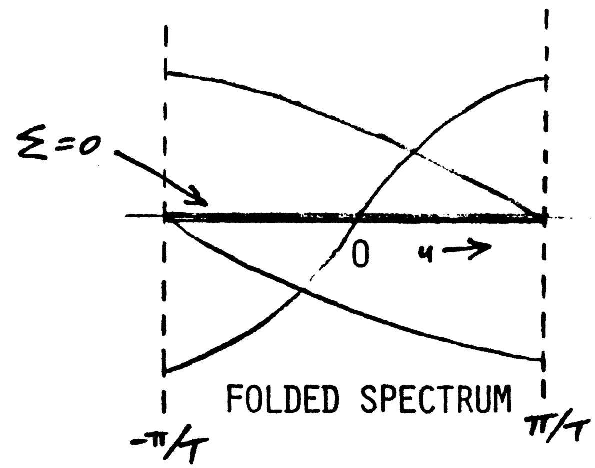
REAL COMPONENT OF SIGNAL SPECTRUM



FOLDED SPECTRUM

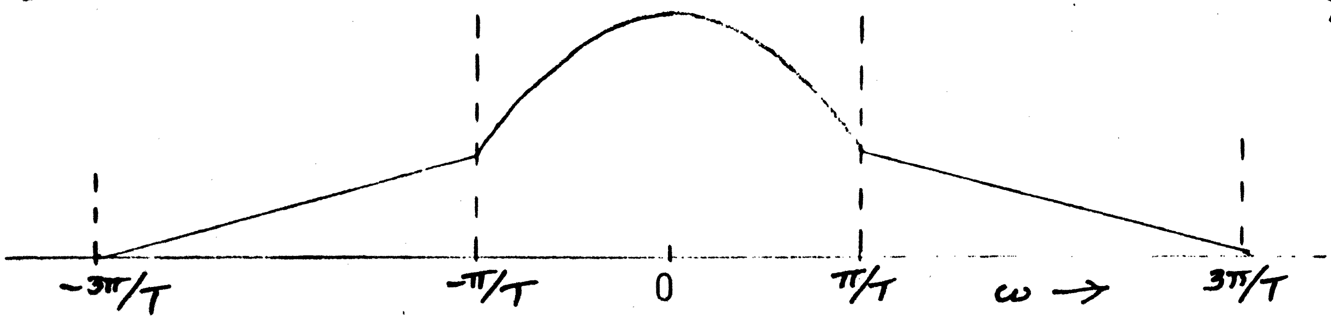


IMAGINARY COMPONENT OF SIGNAL SPECTRUM

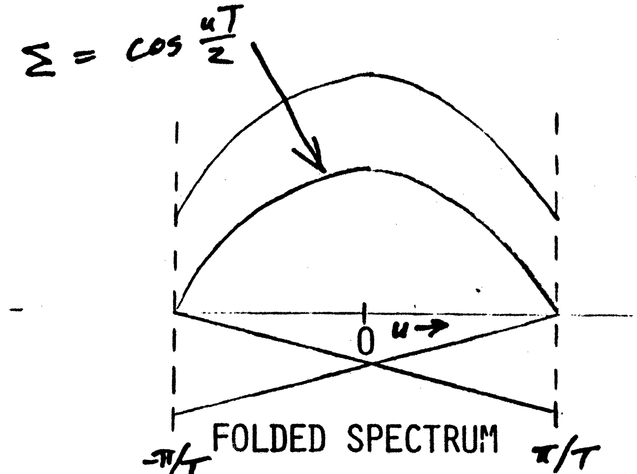


FOLDED SPECTRUM

EXAMPLE:-- SPECTRUM THAT CONTROLS AMPLITUDE AT SAMPLE POINTS

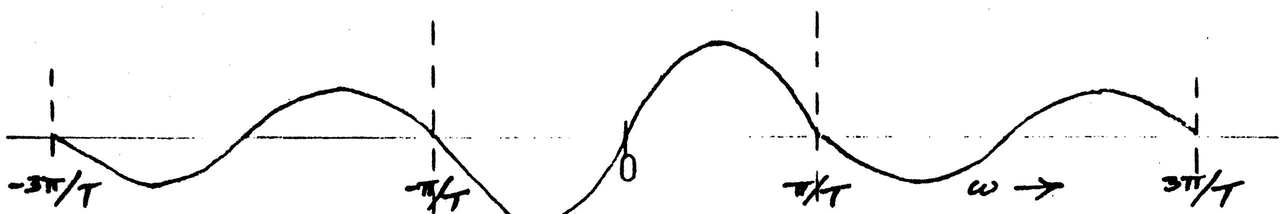


REAL COMPONENT OF SIGNAL SPECTRUM

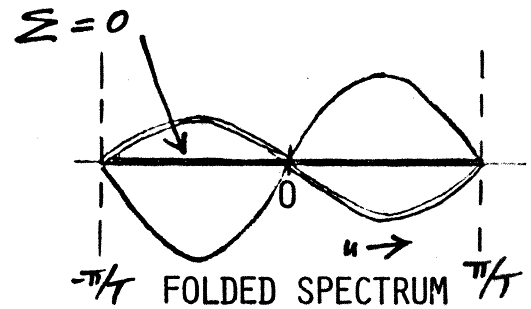


FOLDED SPECTRUM

Signs Alternate



IMAGINARY COMPONENT OF SIGNAL SPECTRUM

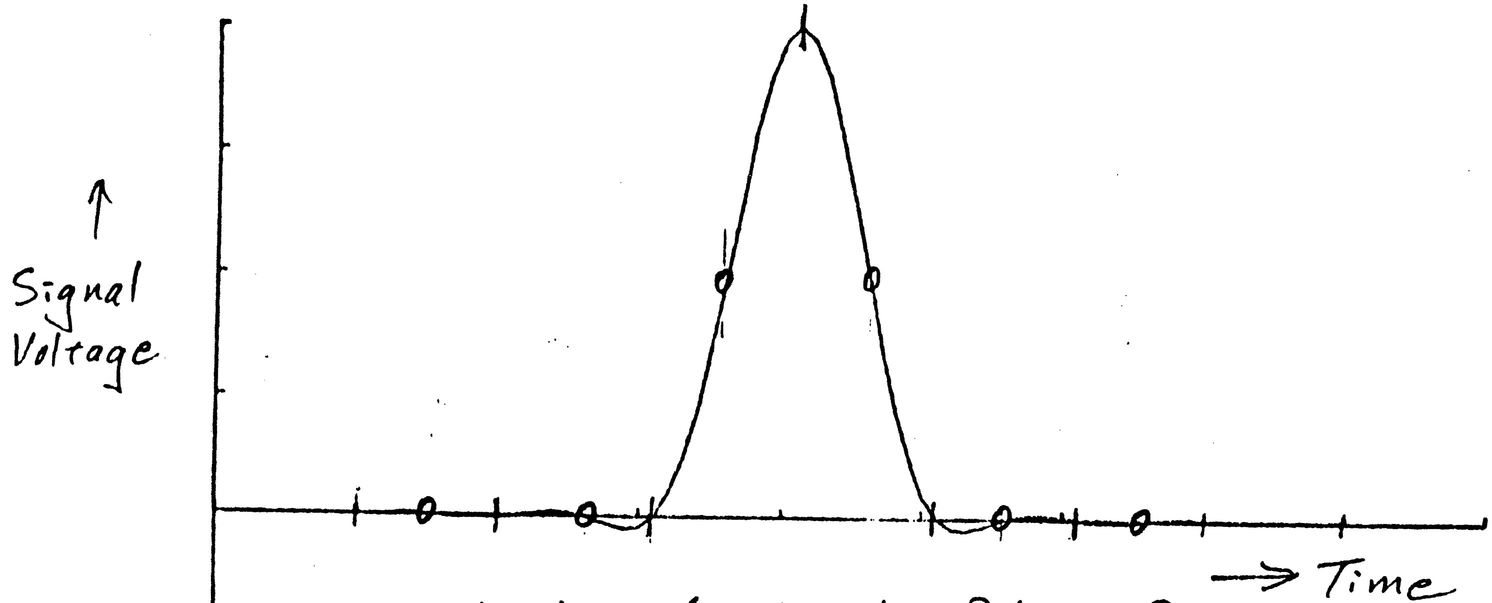


FOLDED SPECTRUM

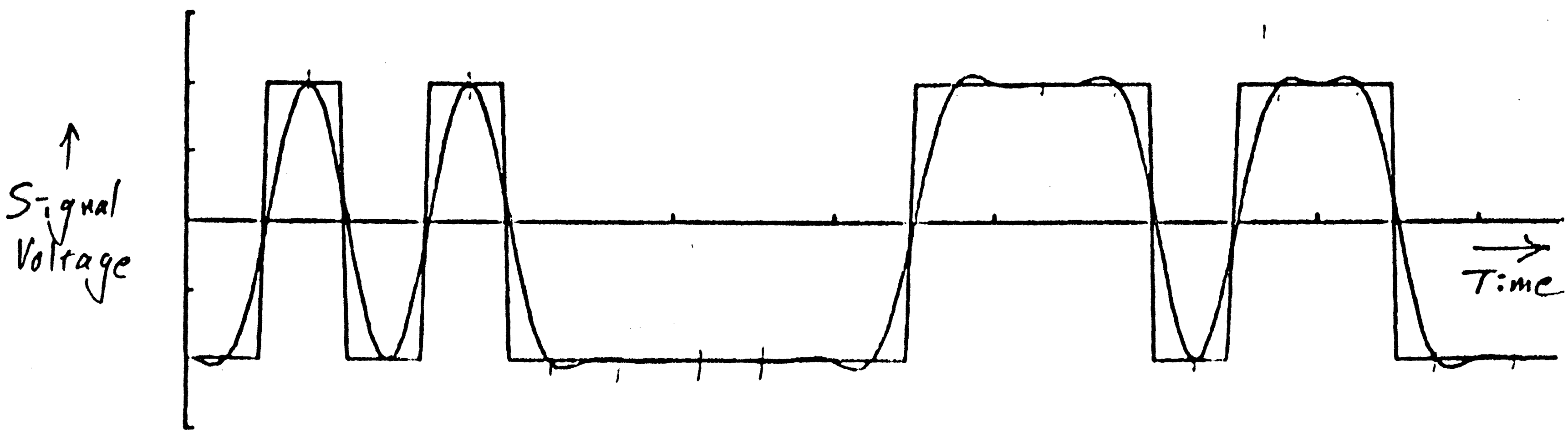
Signs Alternate

EXAMPLE:-- SPECTRUM THAT CONTROLS PULSE-WIDTH AT SAMPLE POINTS

"RAISED - COSINE" CHANNEL

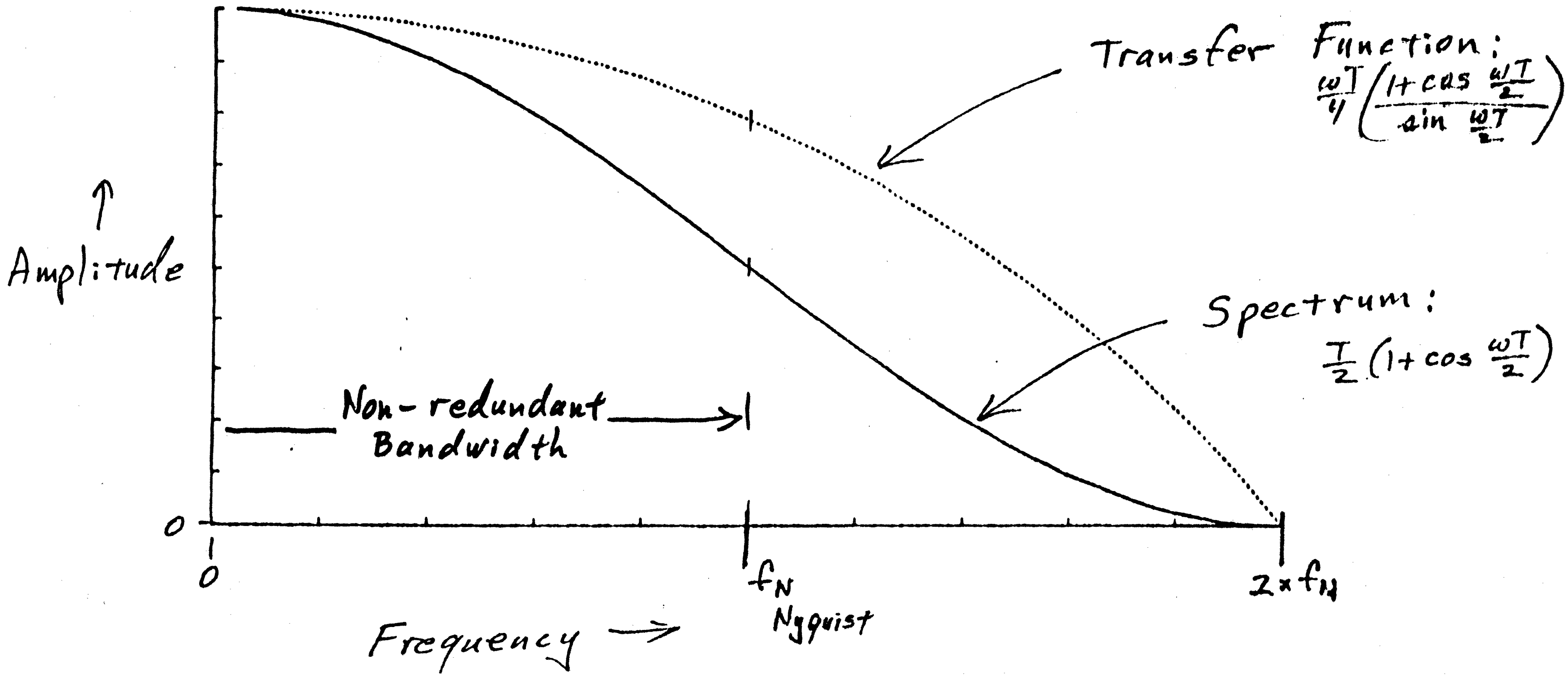


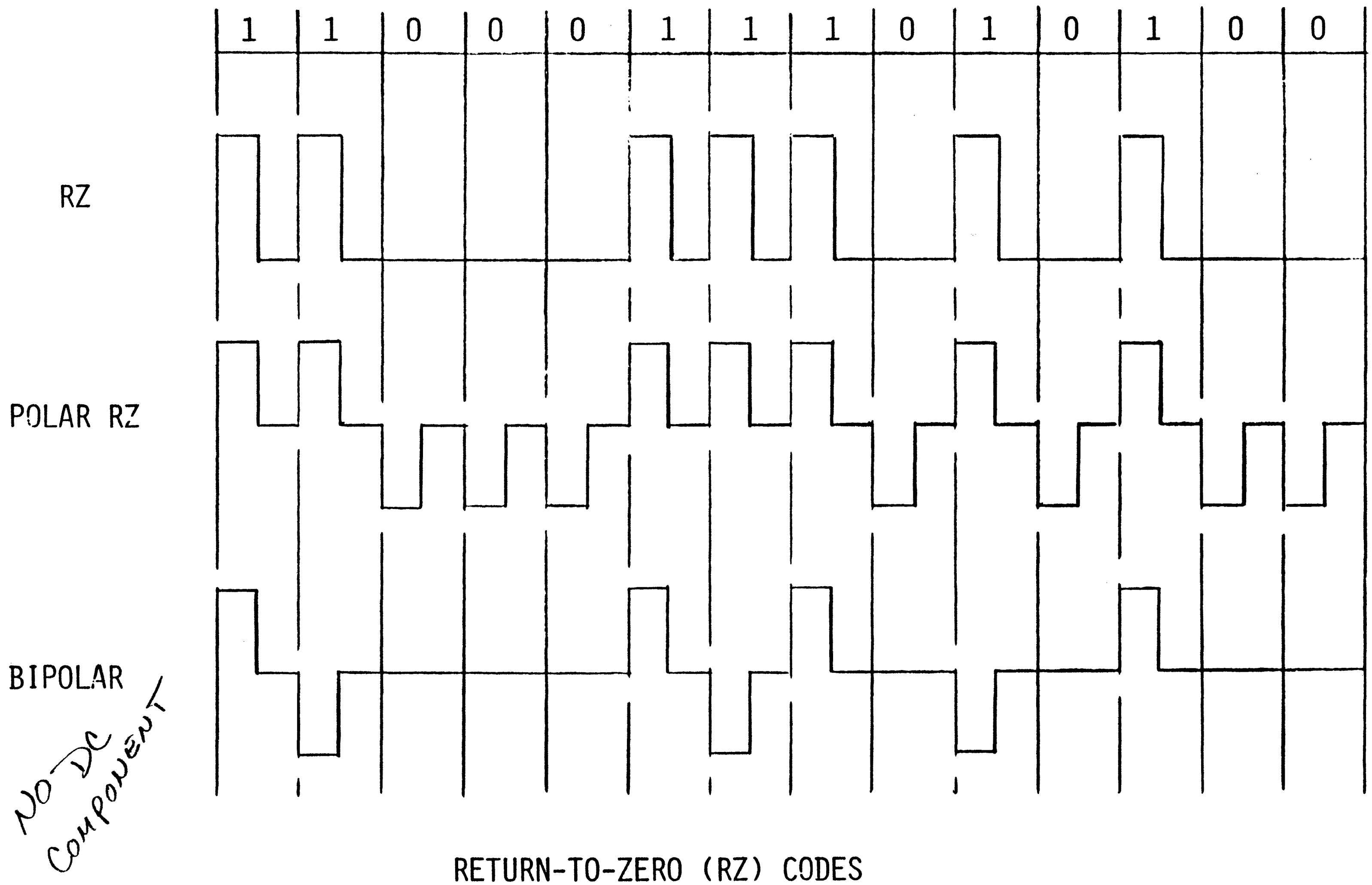
Isolated Single-Pulse Response



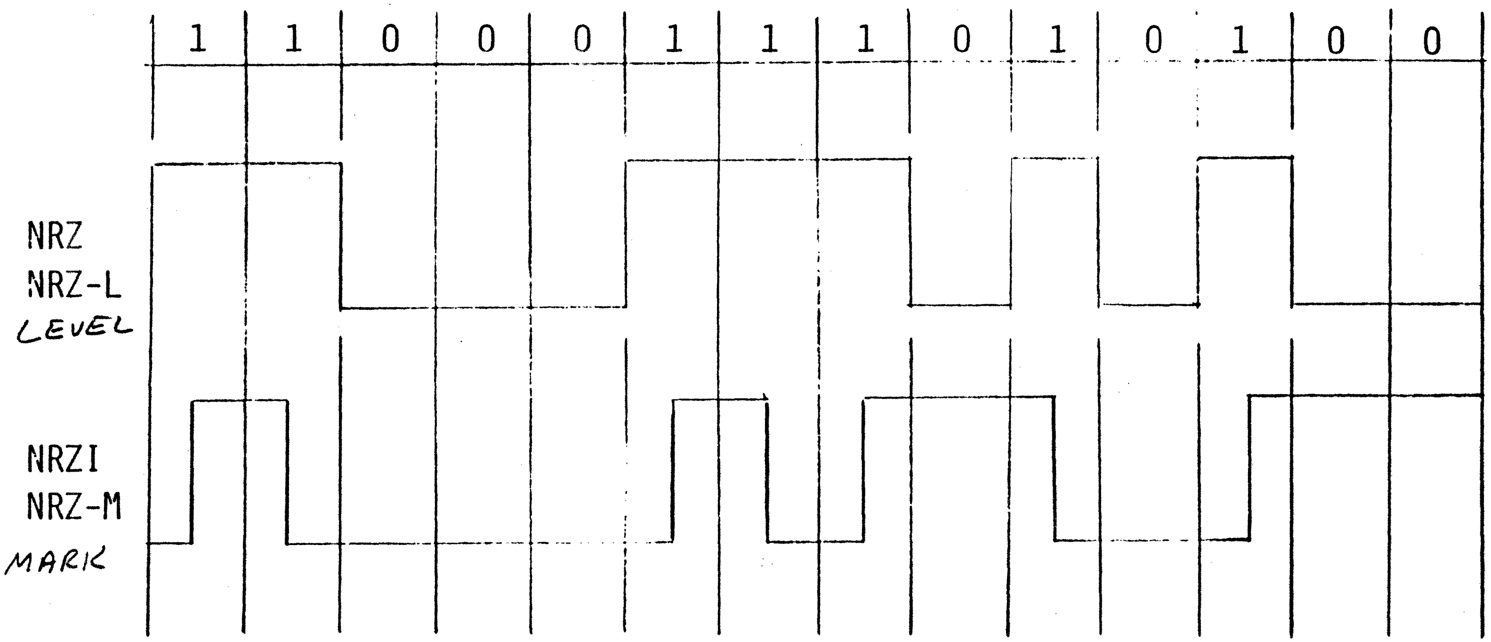
Pulse-Train Response

"RAISED - COSINE" CHANNEL

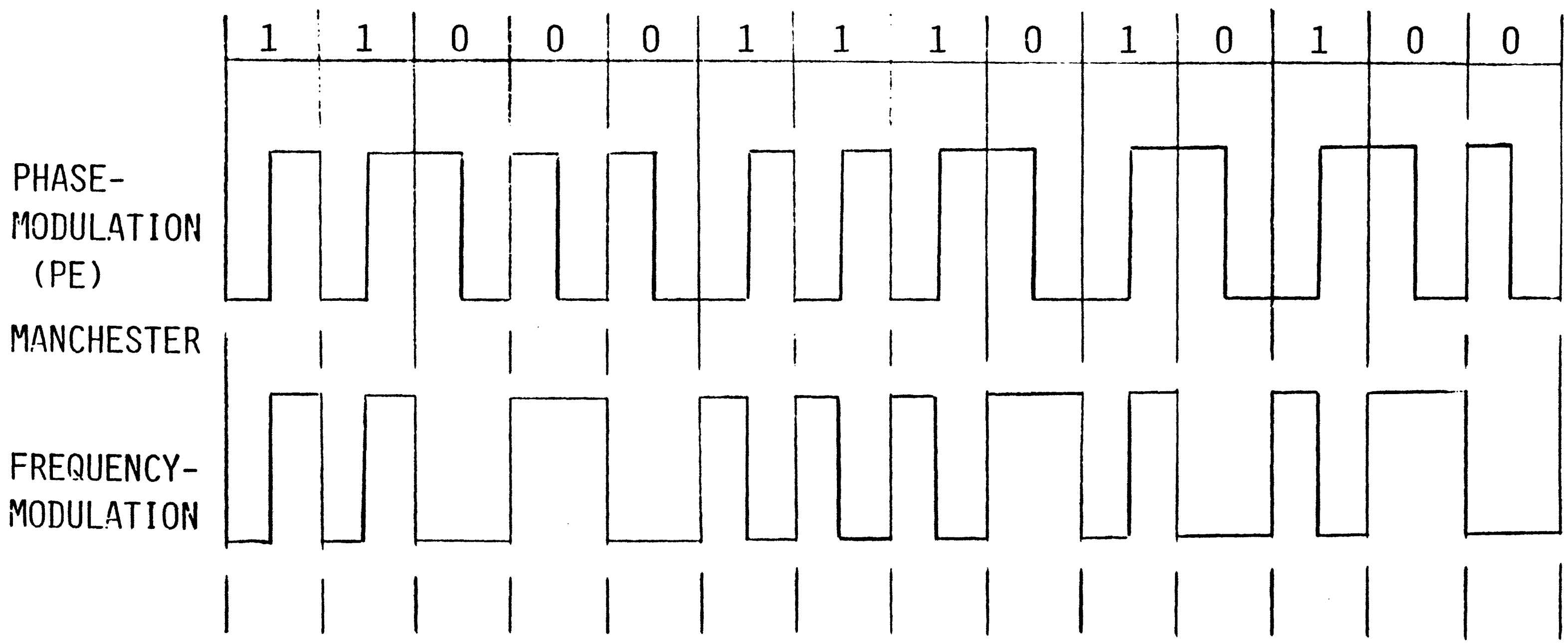




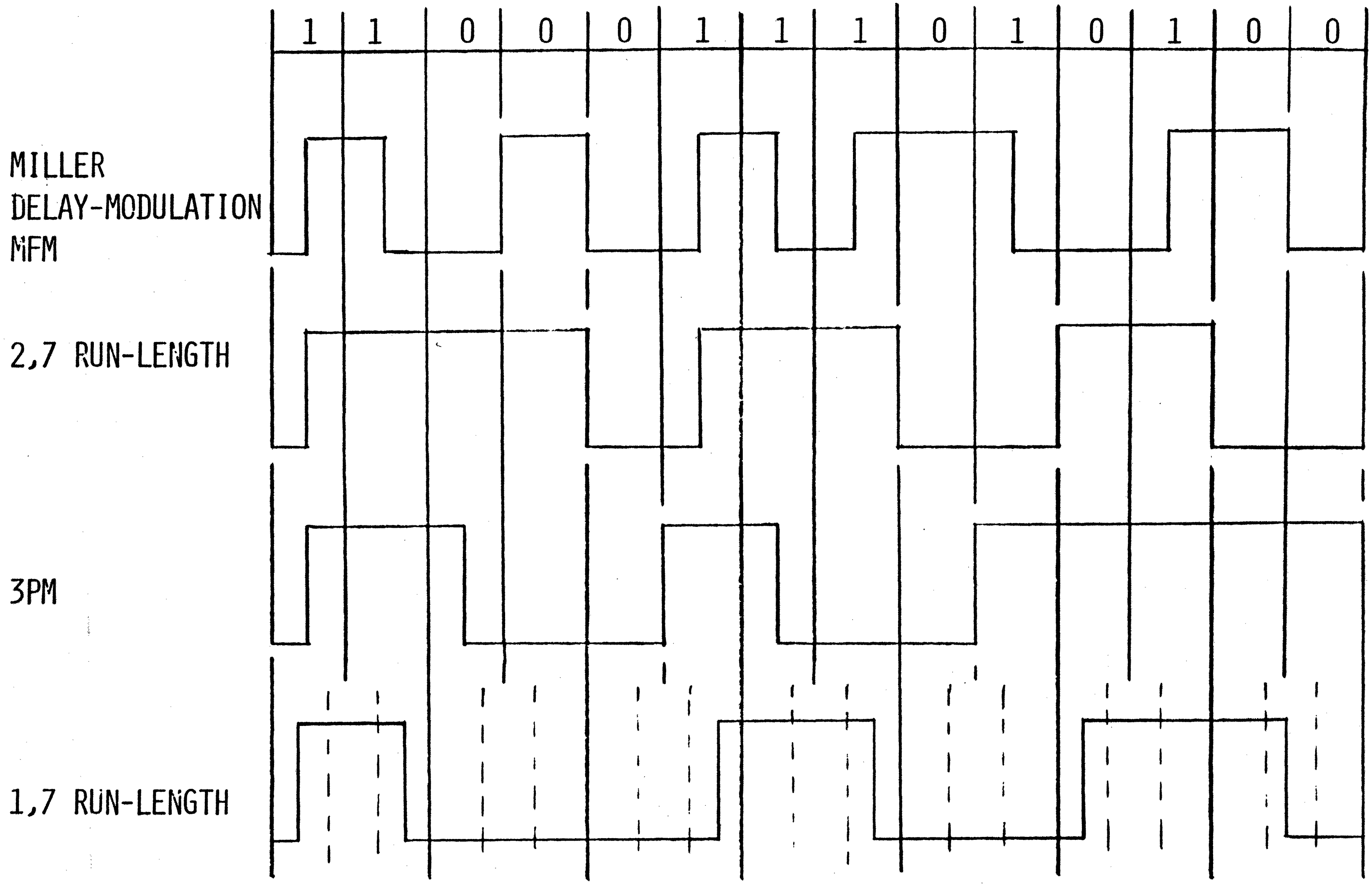
RETURN-TO-ZERO (RZ) CODES



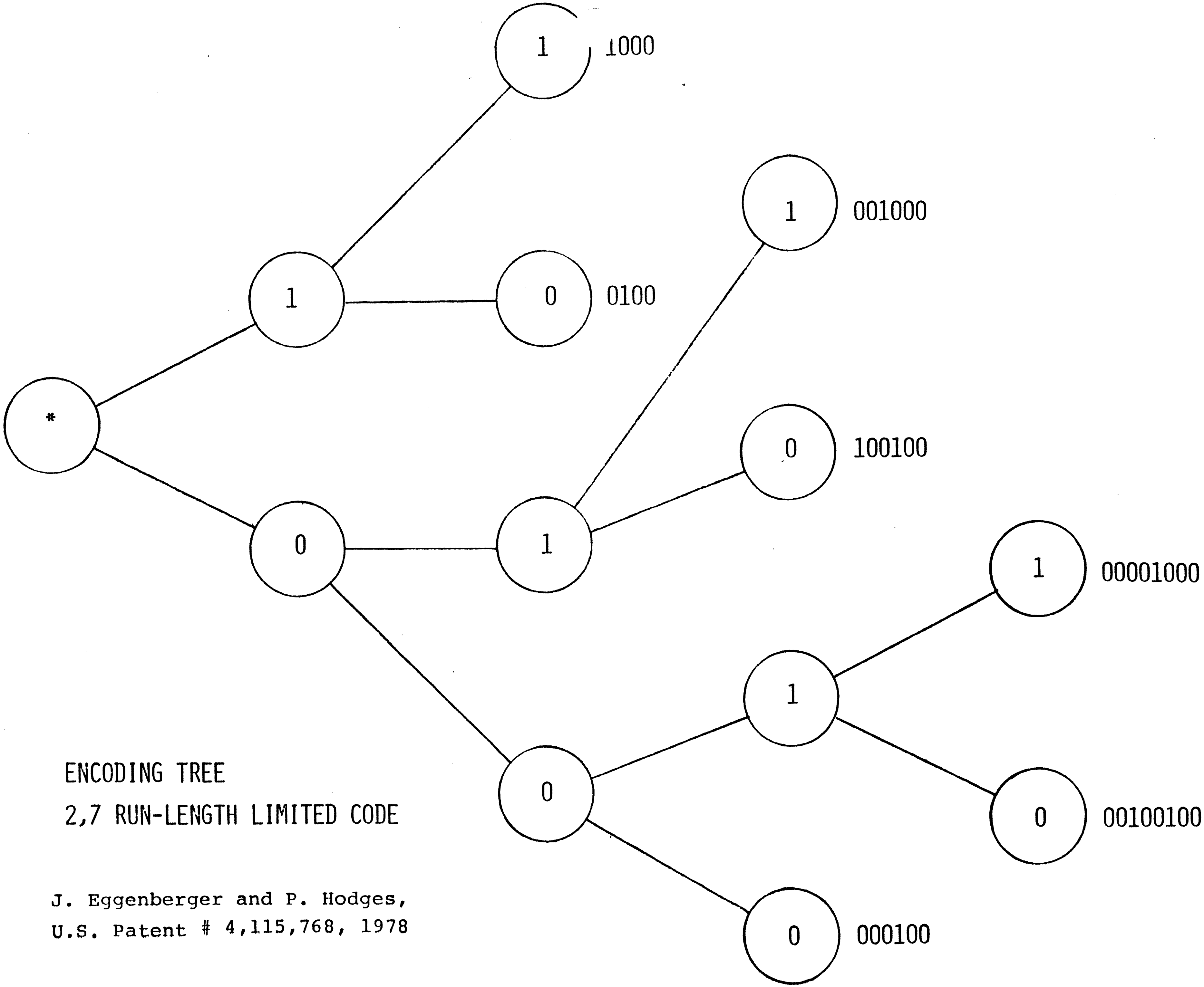
NON-RETURN-TO-ZERO (NRZ) CODES



DOUBLE-FREQUENCY CODES



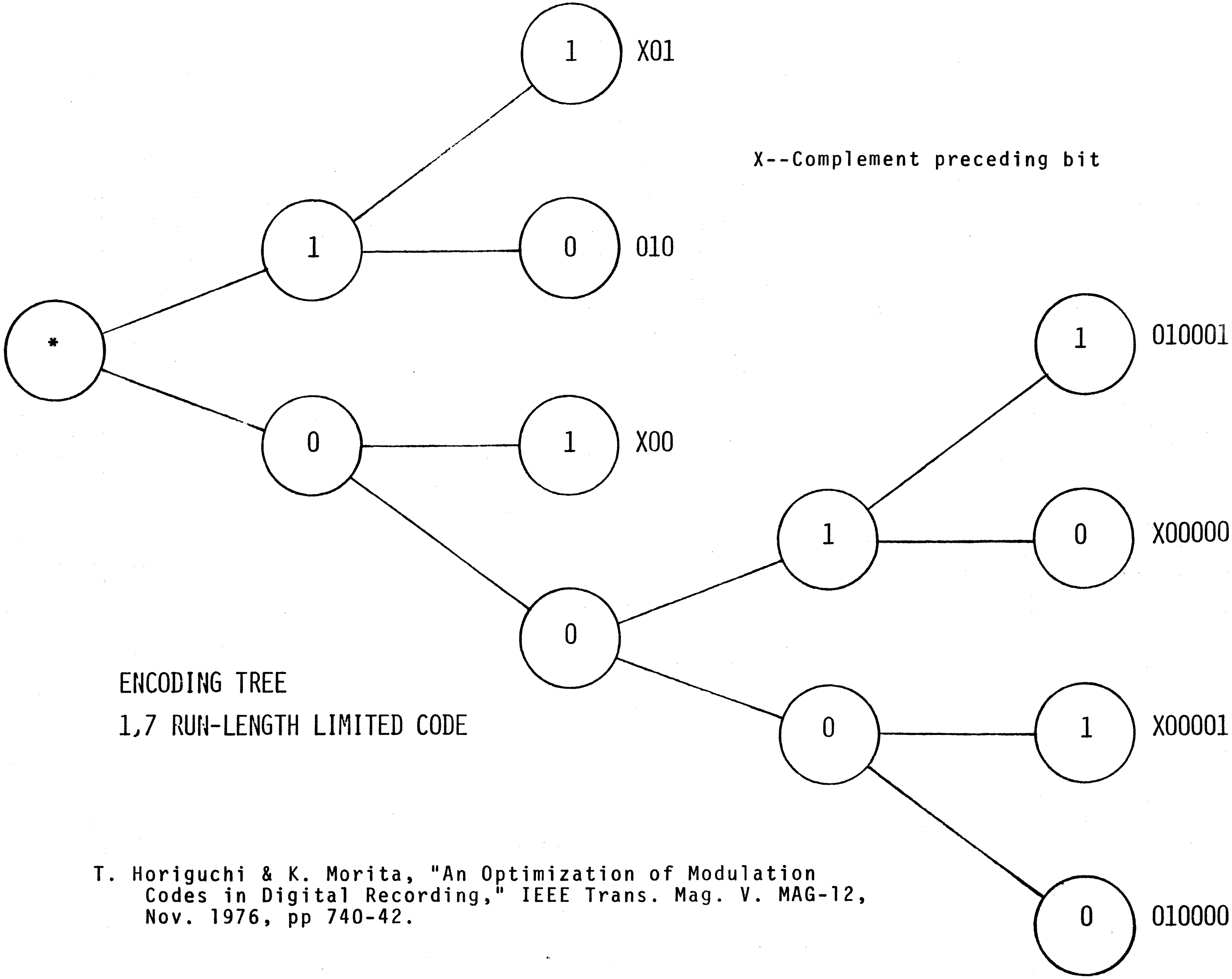
FRACTIONAL-WINDOW CODES



ENCODING TREE

2,7 RUN-LENGTH LIMITED CODE

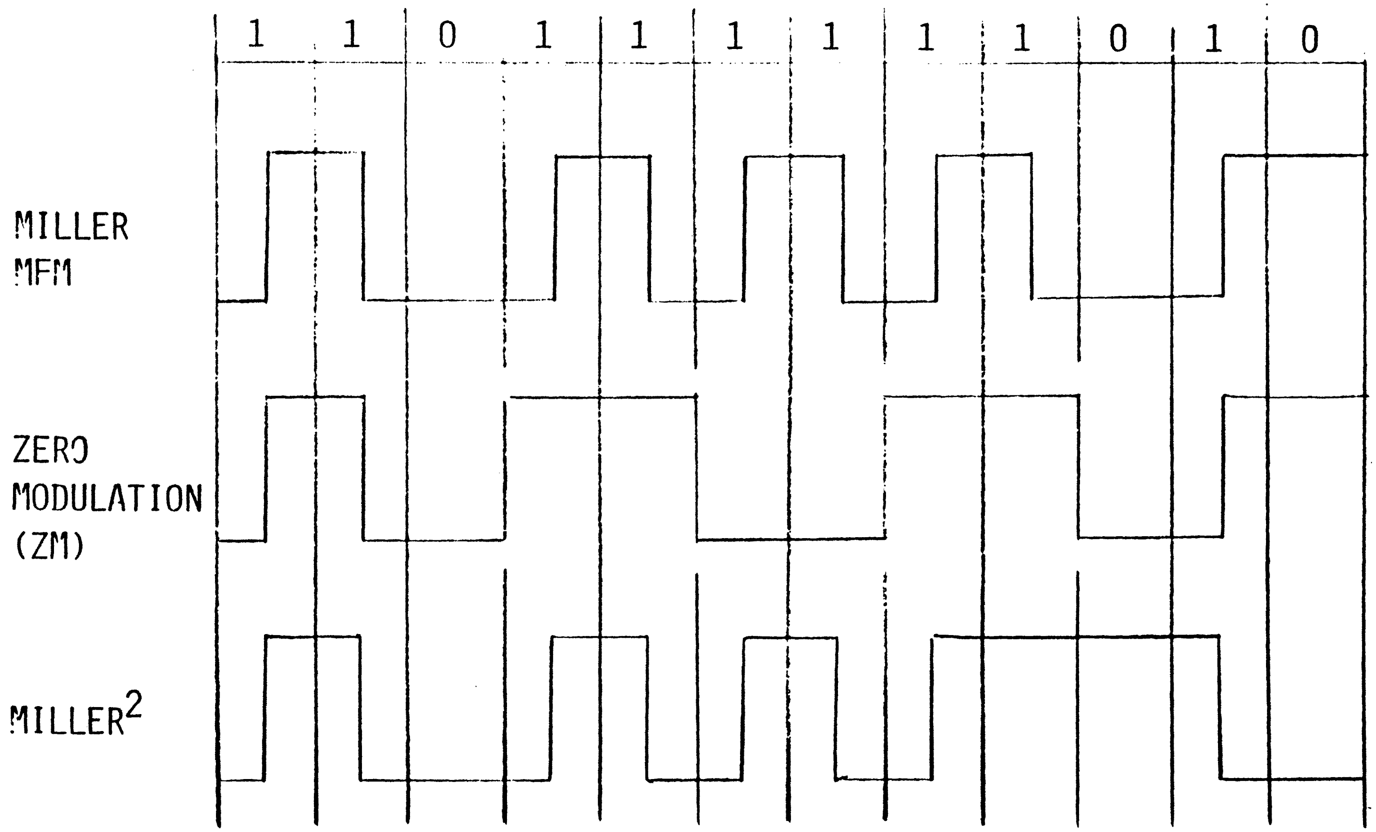
J. Eggenberger and P. Hodges,
U.S. Patent # 4,115,768, 1978



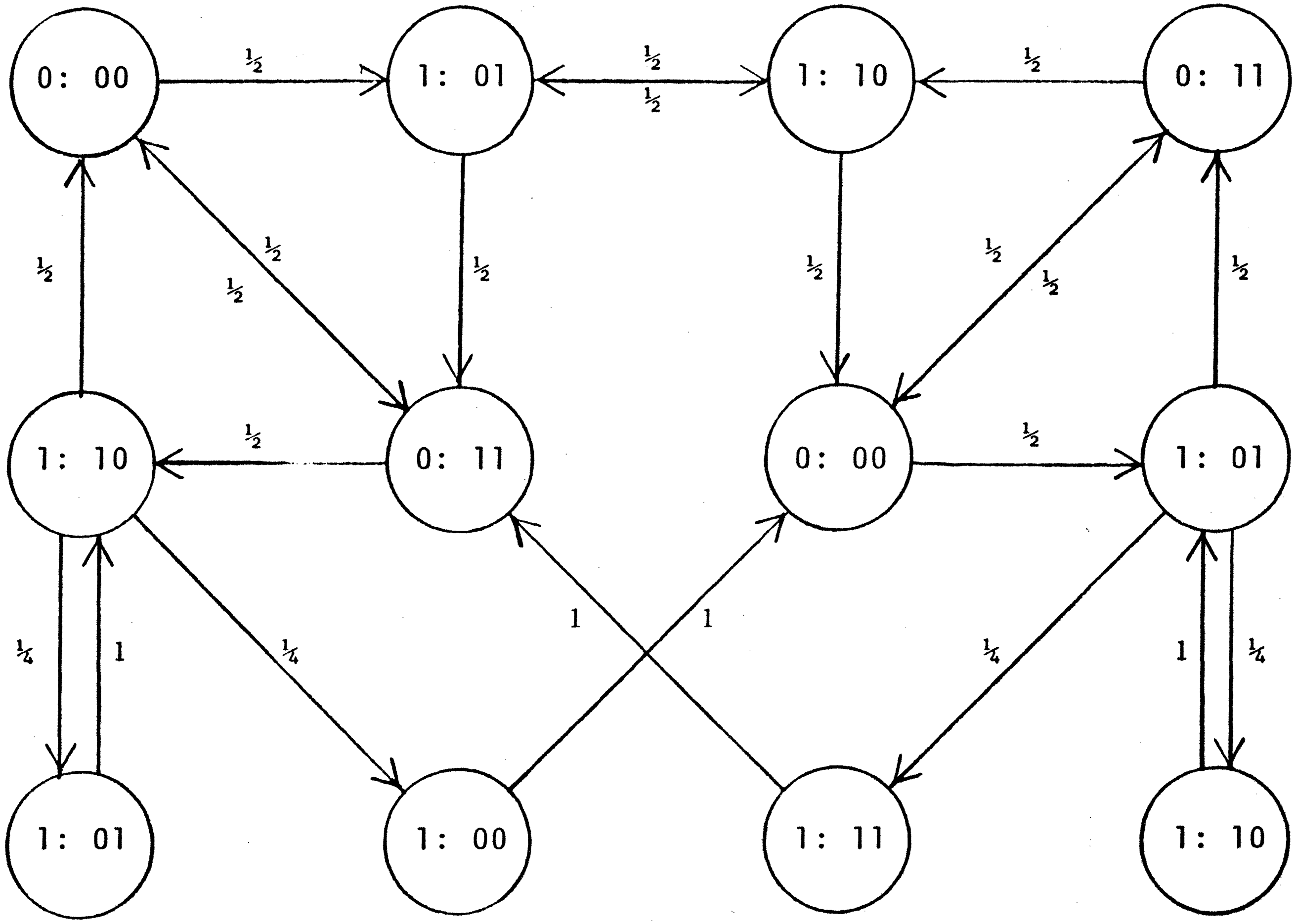
ENCODING TREE

1,7 RUN-LENGTH LIMITED CODE

T. Horiguchi & K. Morita, "An Optimization of Modulation Codes in Digital Recording," IEEE Trans. Mag. V. MAG-12, Nov. 1976, pp 740-42.



DC-FREE MODIFICATIONS OF MILLER-MFM CODE



ENCODING STATE DIAGRAM

MILLER^2 CODE

D.A. Lindholm, "Power Spectra of Channel Codes for Digital Magnetic Recording," IEEE Trans. Mag. V. MAG-14, Sept. 1978, PP321-23.

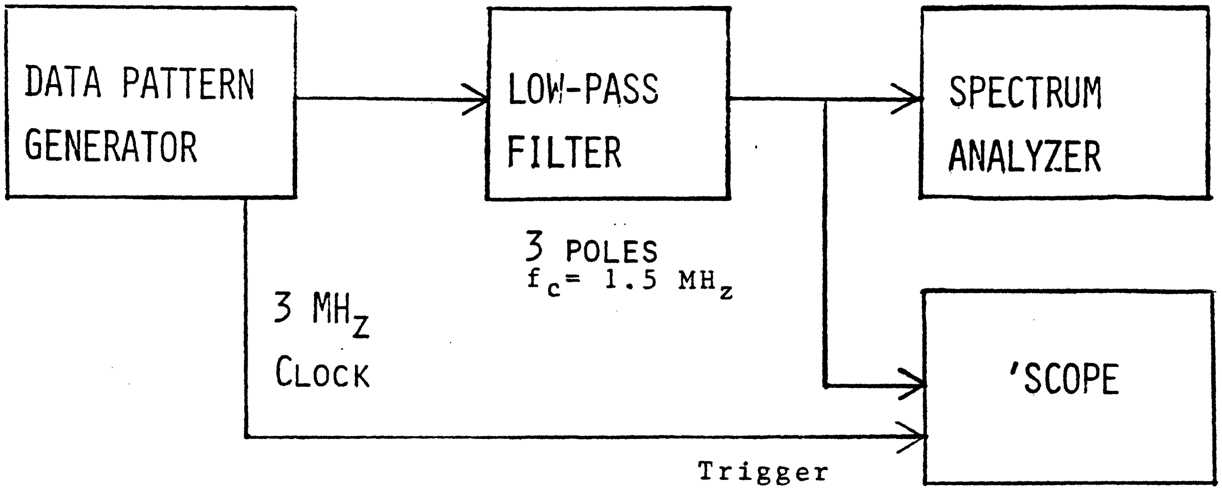
CHANNEL CODE PARAMETERS

T	DATA BIT TIME INTERVAL
m	# OF DATA BITS GROUPED
n	# OF CODE BITS IN GROUP
m/n	RATE
d	MINIMUM # OF ZEROS BETWEEN ONES
k	MAXIMUM # OF ZEROS BETWEEEN ONES
T_{min}	MINIMUM TIME BETWEEN TRANSITIONS
T_{max}	MAXIMUM TIME BETWEEN TRANSITIONS
DR	DENSITY RATIO = $T_{min}/T = \frac{\text{DATA DENSITY}}{\text{MAX. TRANS. DENSITY}}$
W	WINDOW = (m/n)T
DSV	MAXIMUM DIGITAL SUM VARIATION

W.D. Huber, "Selection of Modulation Code Parameters for Maximum Linear Density," IEEE Trans. Mag. V. MAG-16, Sept. 1980, pp 637-39.

CODE	m	n	RATE	d	k	T_{MIN}	T_{MAX}	DR	W	CLOCK	DSV
NRZI	1	1	1	0	∞	T	∞	1	T	1/T	∞
DOUBLE FREQUENCY	1	2	1/2	0	1	T/2	T	1/2	T/2	2/T	T
MILLER MFM	1	2	1/2	1	3	T	2T	1	T/2	2/T	∞
MILLER^2	1	2	1/2	1	5	T	3T	1	T/2	2/T	3T/2
GCR	4	5	0.8	0	2	0.8T	2.4T	0.8	0.8T	5/4T	∞
0,3 9/10	9	10	0.9	0	3	0.9T	3.6T	0.9	0.9T	10/9T	∞
1,7 RLL	2 4	3 6	0.667	1	7	1.333T	5.333T	4/3	0.667T	3/2T	∞
2,7 RLL	2 3 4	4 6 8	0.5	2	7	1.5T	4T	3/2	0.5T	2/T	∞
3,11 RLL	2 4 6	5 10 15	0.4	3	11	1.6T	4.8T	8/5	0.4T	5/2T	∞
	DATA BITS	CODE BITS	M/N	MIN Ø	MAX Ø	TIME BETWEEN TRANSISTIONS		T_{MIN}/T	(M/N)T		

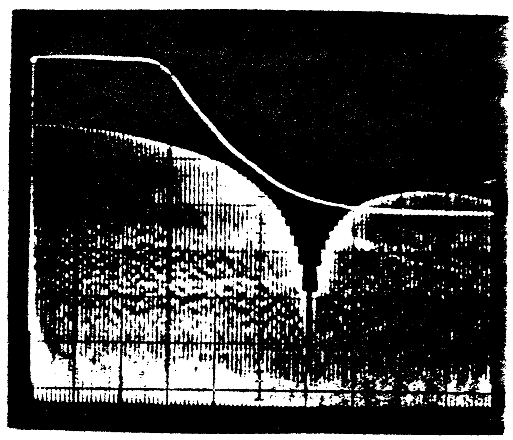
CHANNEL-CODE COMPARISON



EXPERIMENTAL SETUP

db

10db/div



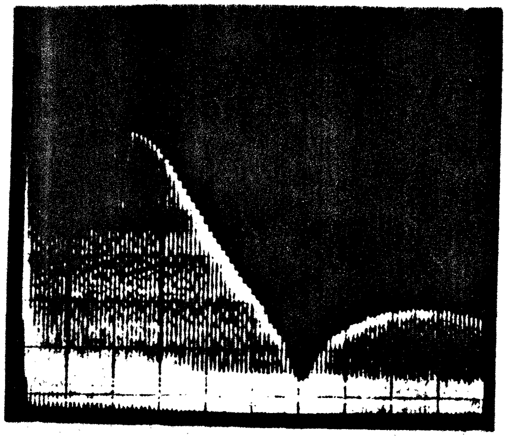
FILTER TRANSFER FUNCTION

UNFILTERED
3 MBIT/SEC
63 BIT PRBS

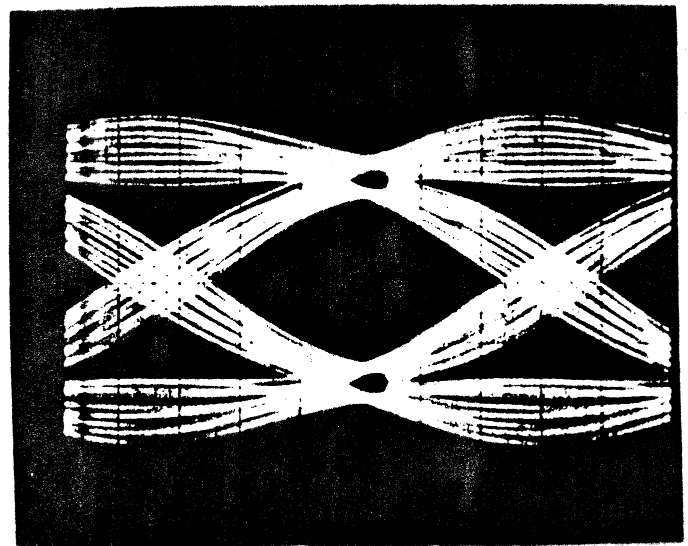
0 Frequency 5 MH_z

SPECTRA

CHANNEL-CODE COMPARISON TEST



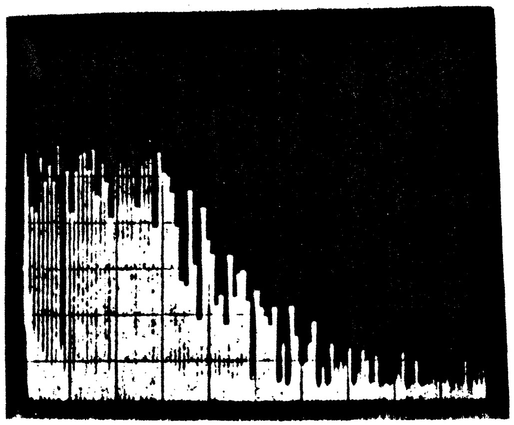
SPECTRUM



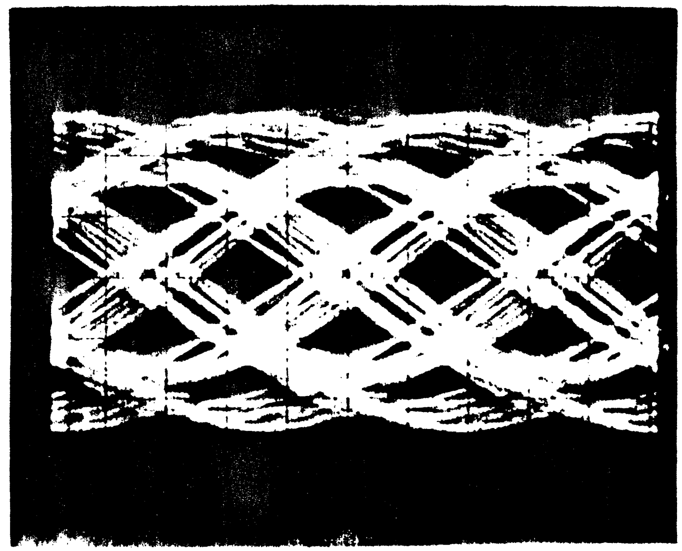
EYE

CELL

NRZI CODE

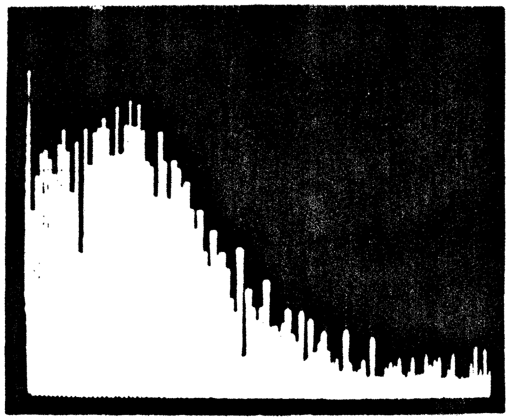


SPECTRUM

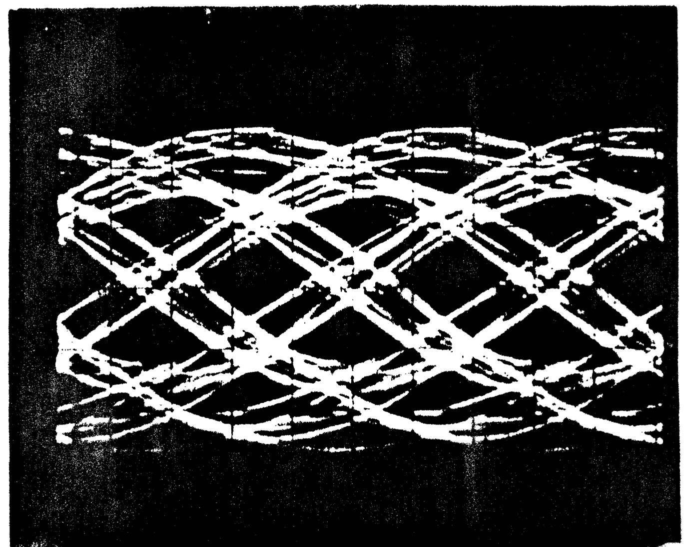


EYE

MILLER
MFM CODE
DELAY MODULATION

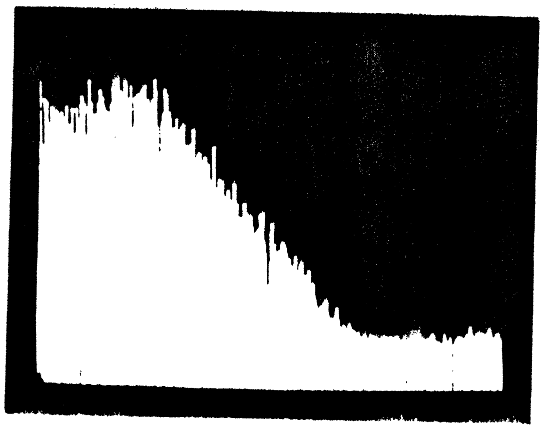


SPECTRUM

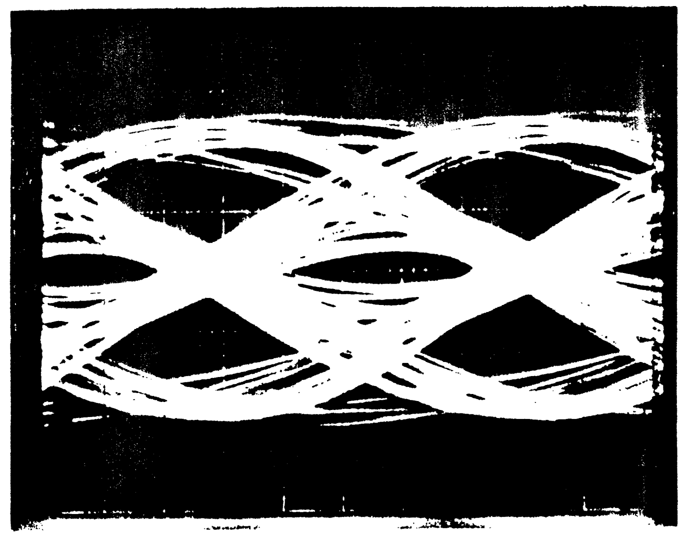


EYE

MILLER^2 CODE

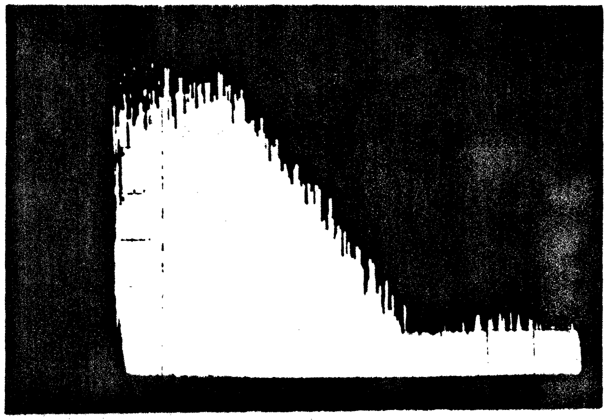


SPECTRUM

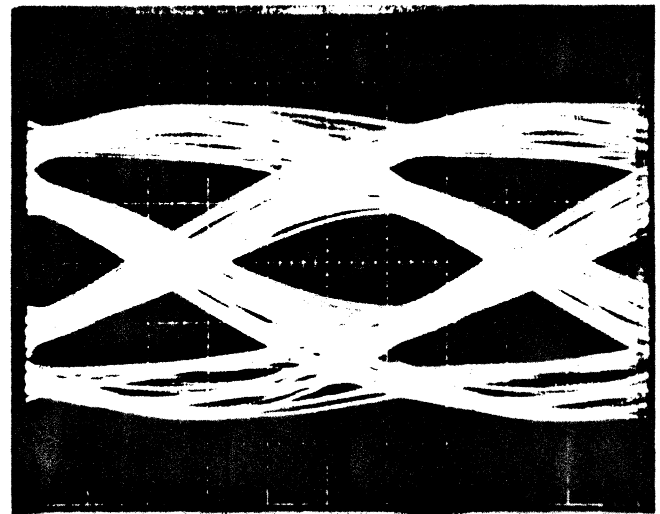


EYE

GCR --- 4/5 GROUP CODE RECORDING

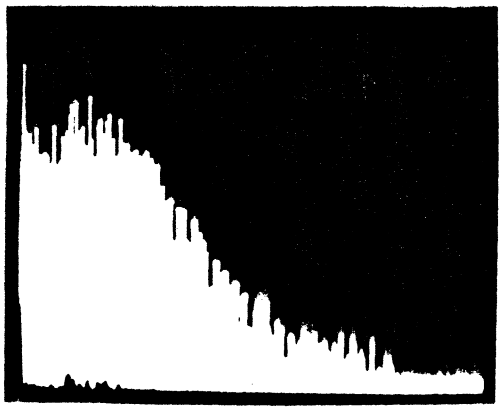


SPECTRUM

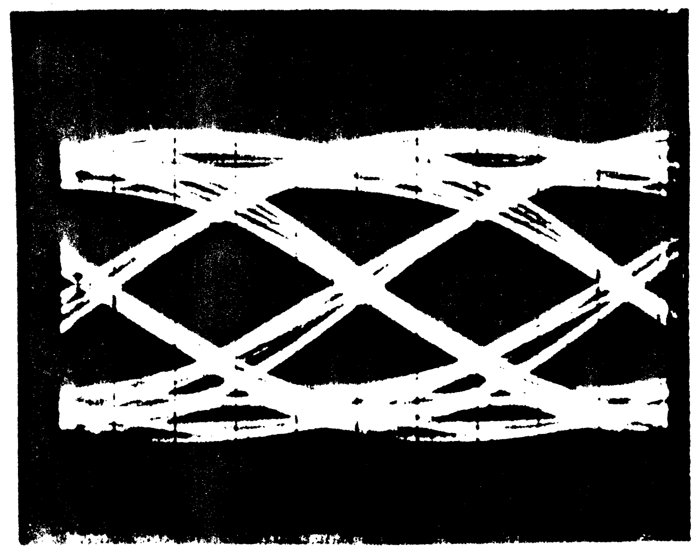


EYE

0,3 9/10THS CODE

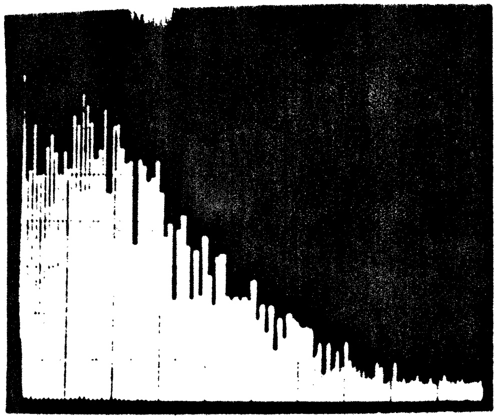


SPECTRUM

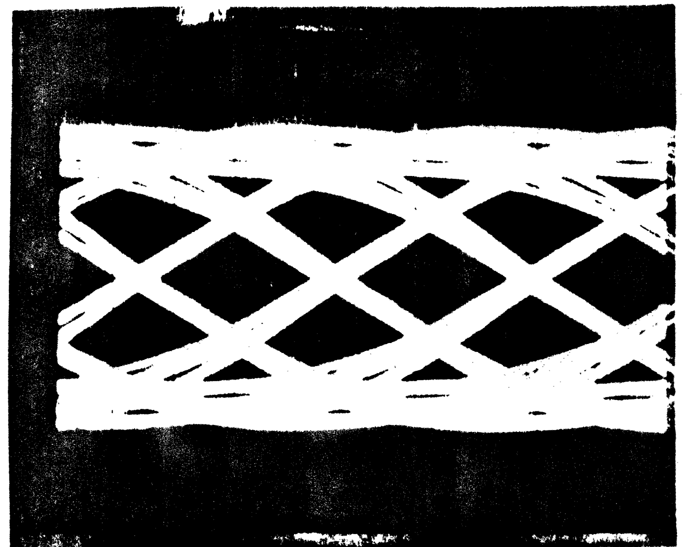


EYE

1,7 RLL CODE

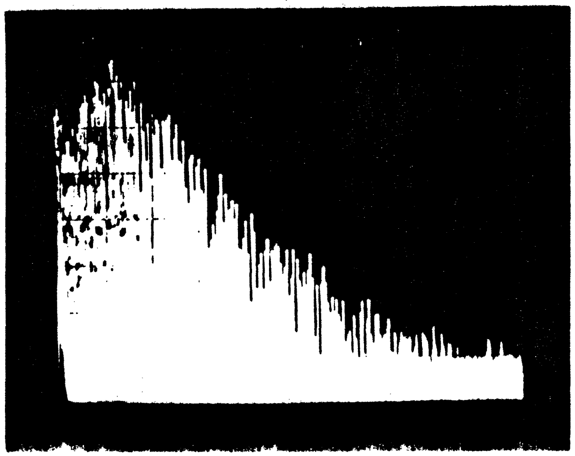


SPECTRUM

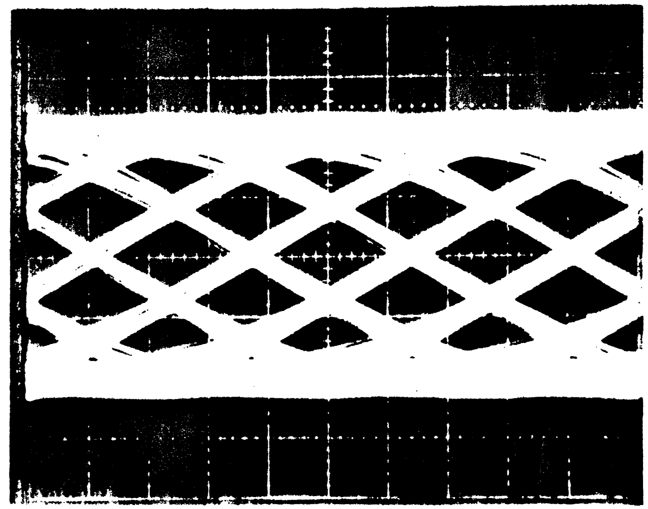


EYE

2,7 RLL CODE



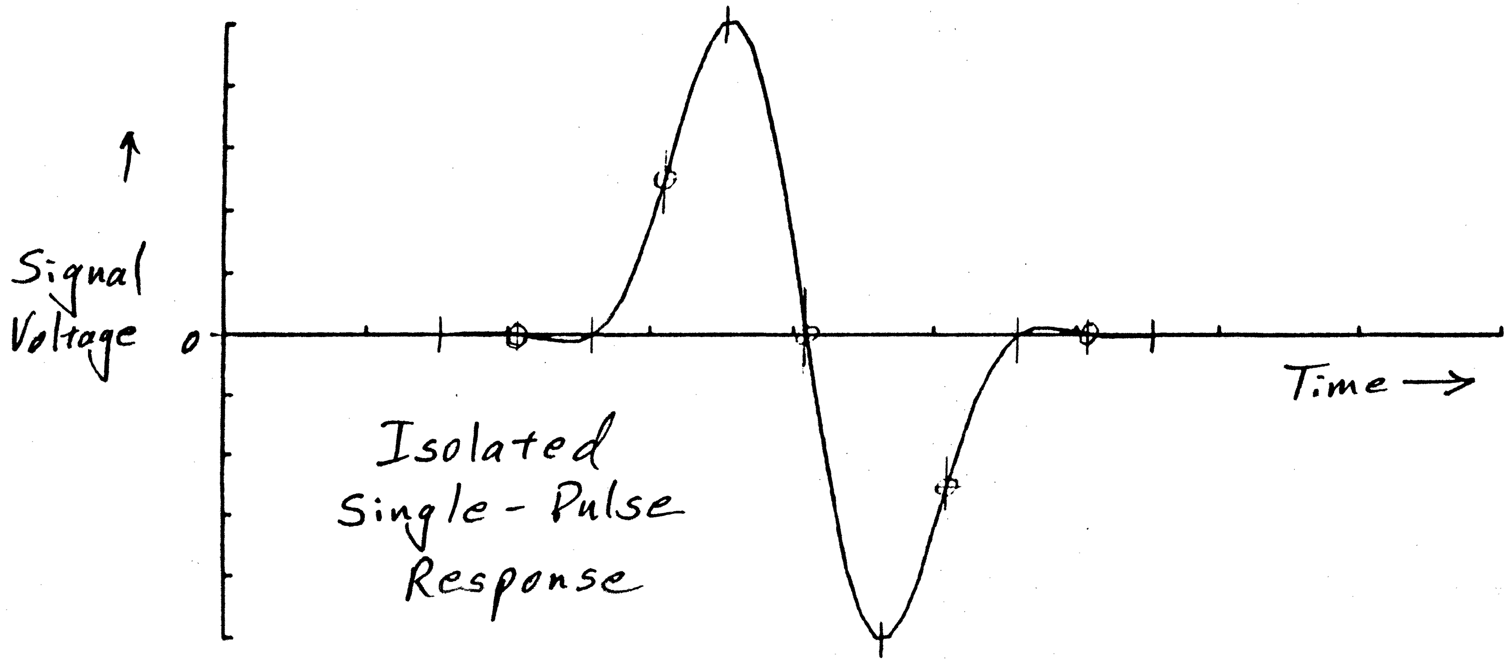
SPECTRUM

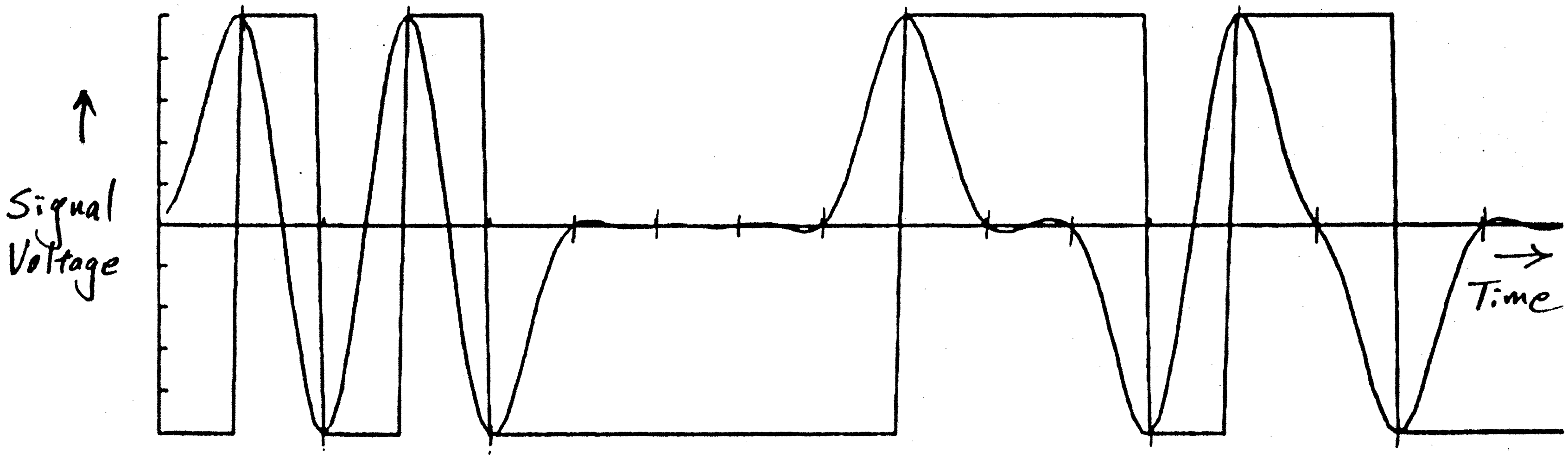


EYE

3,11 RLL CODE

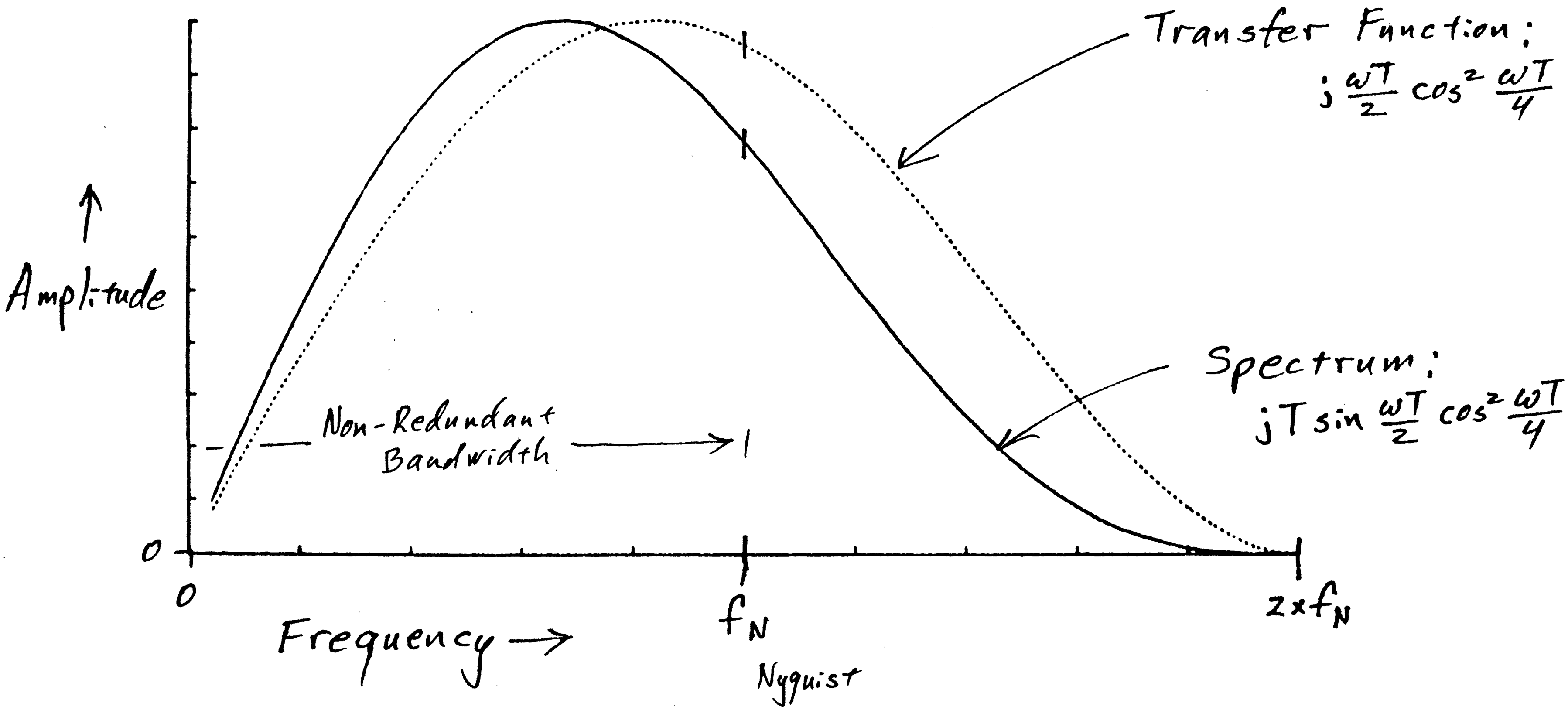
PSEUDO-TERNARY NRZI CHANNEL



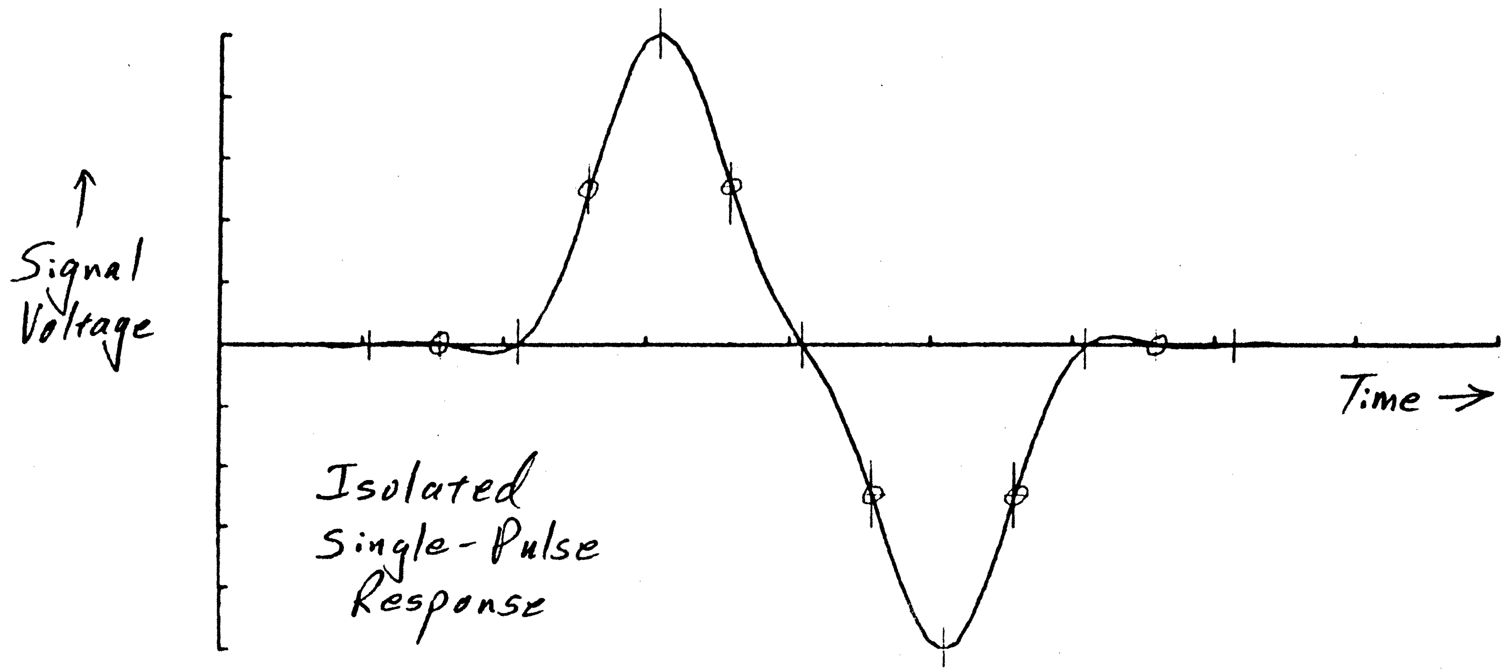


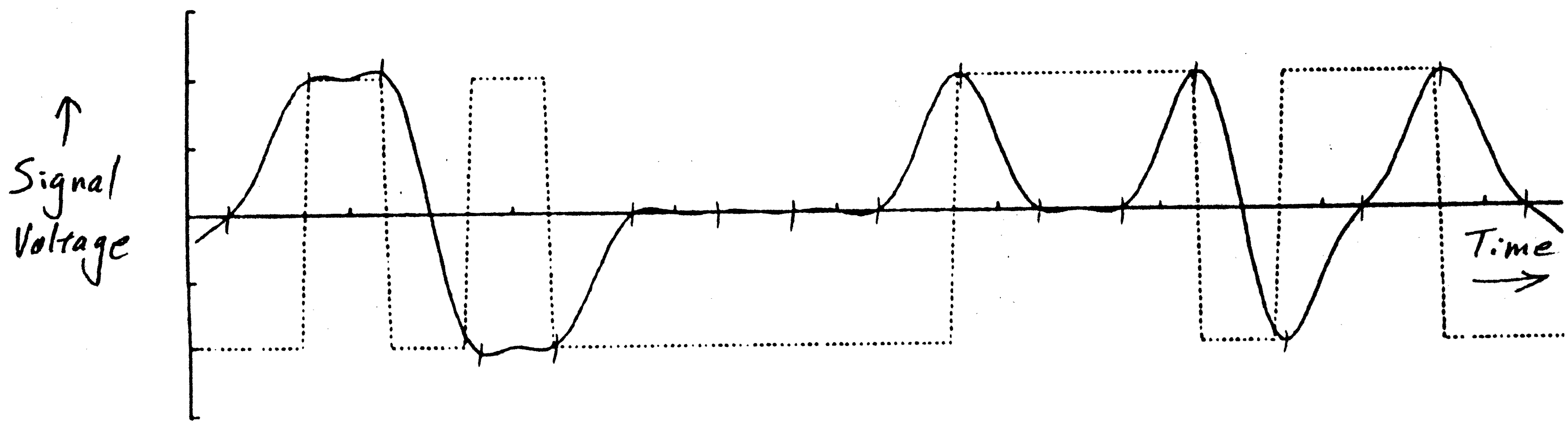
Pulse-Train Response

PSEUDO-TERNAR NRZI CHANNEL



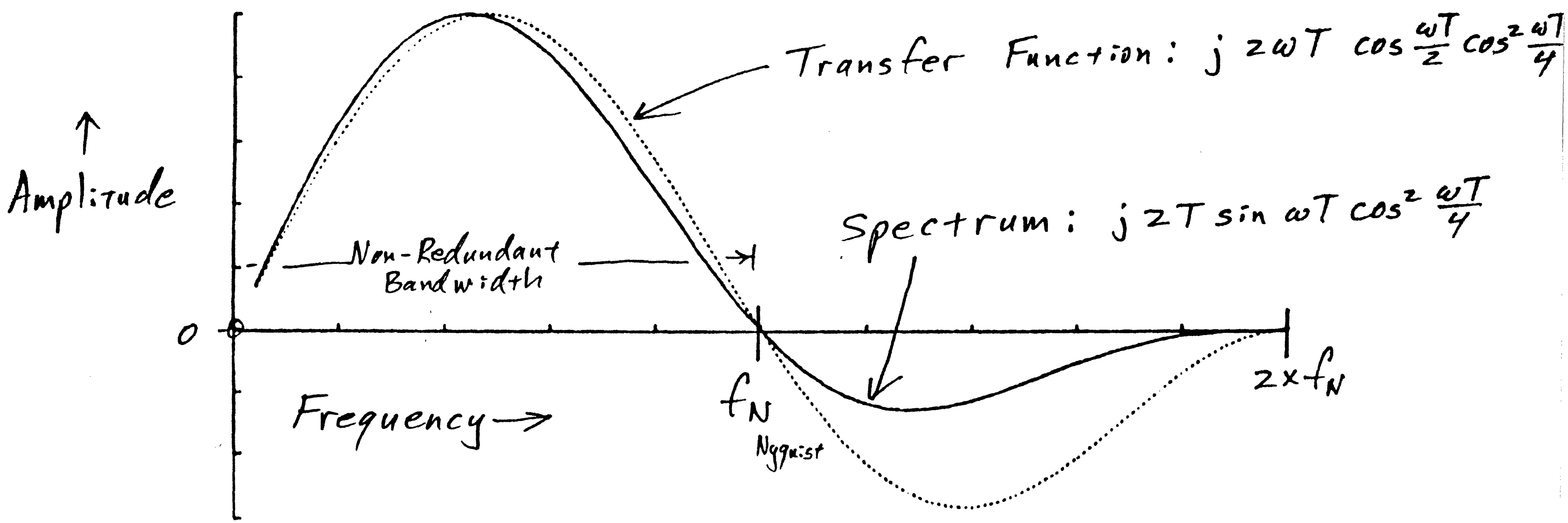
INTERLEAVED NRZI





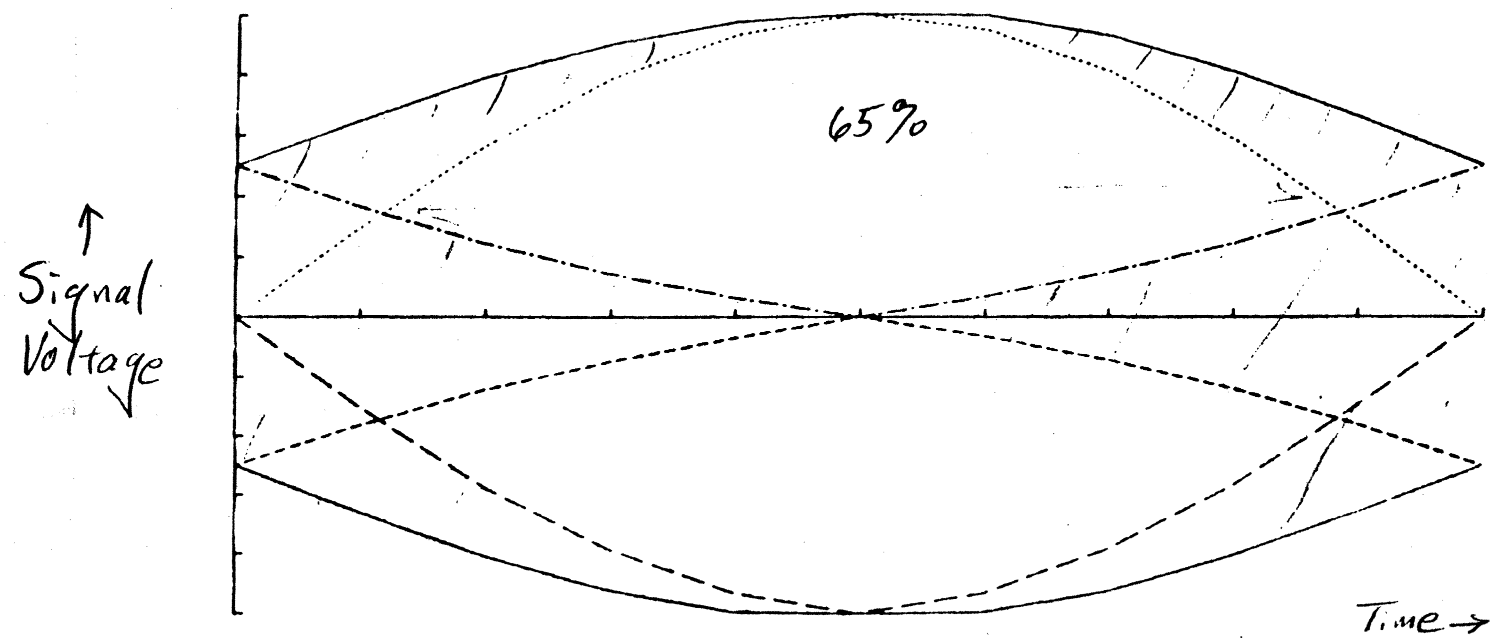
Pulse-Train Response

INTERLEAVED NRZI

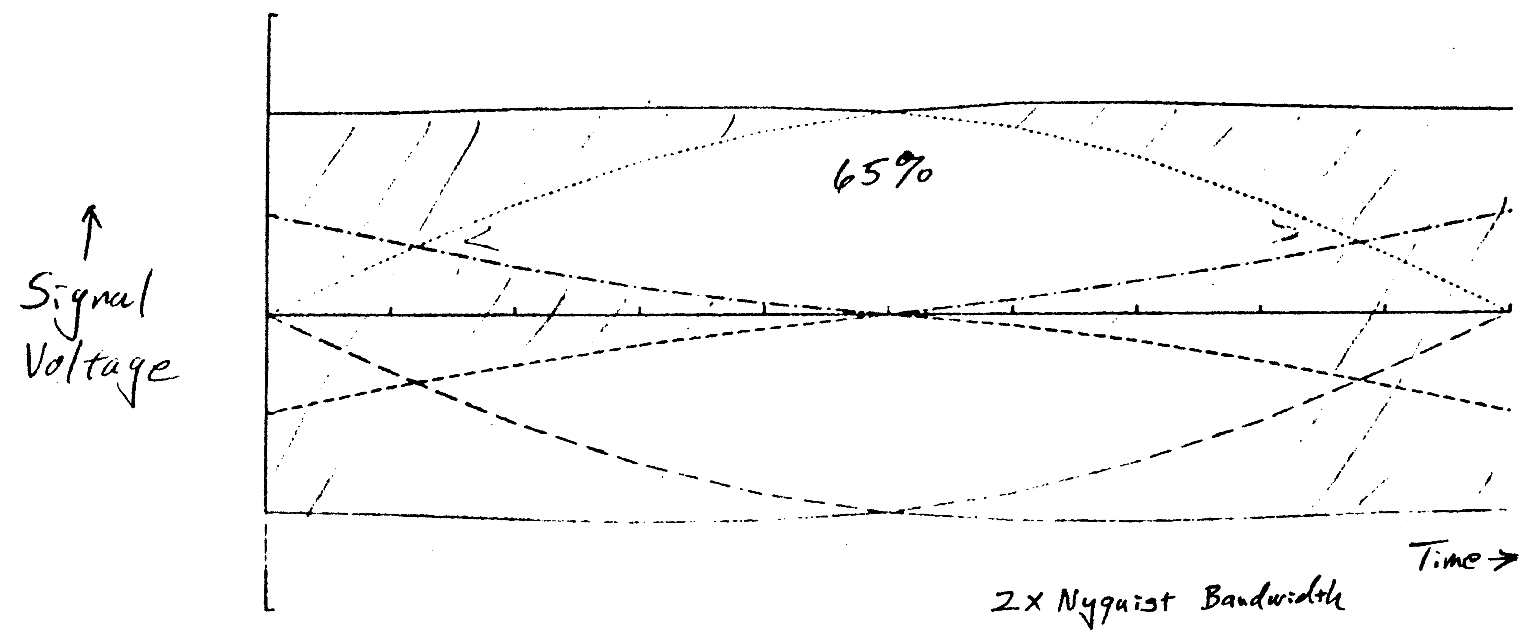


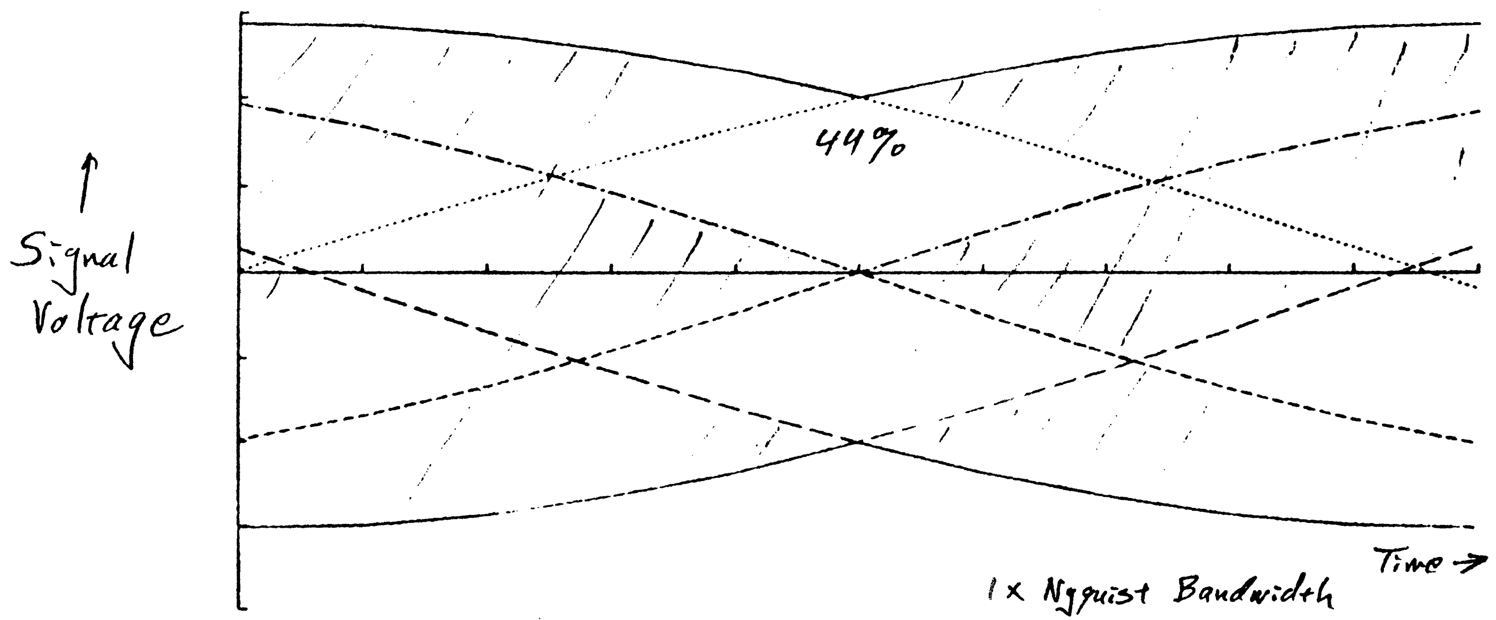
EYE PATTERN

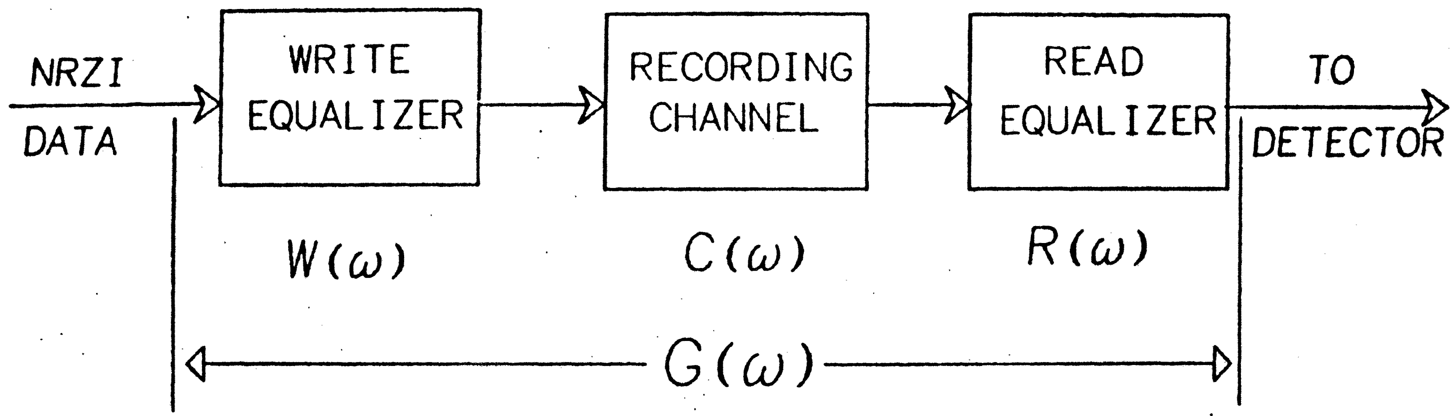
PSEUDO-TERNARY NRZI



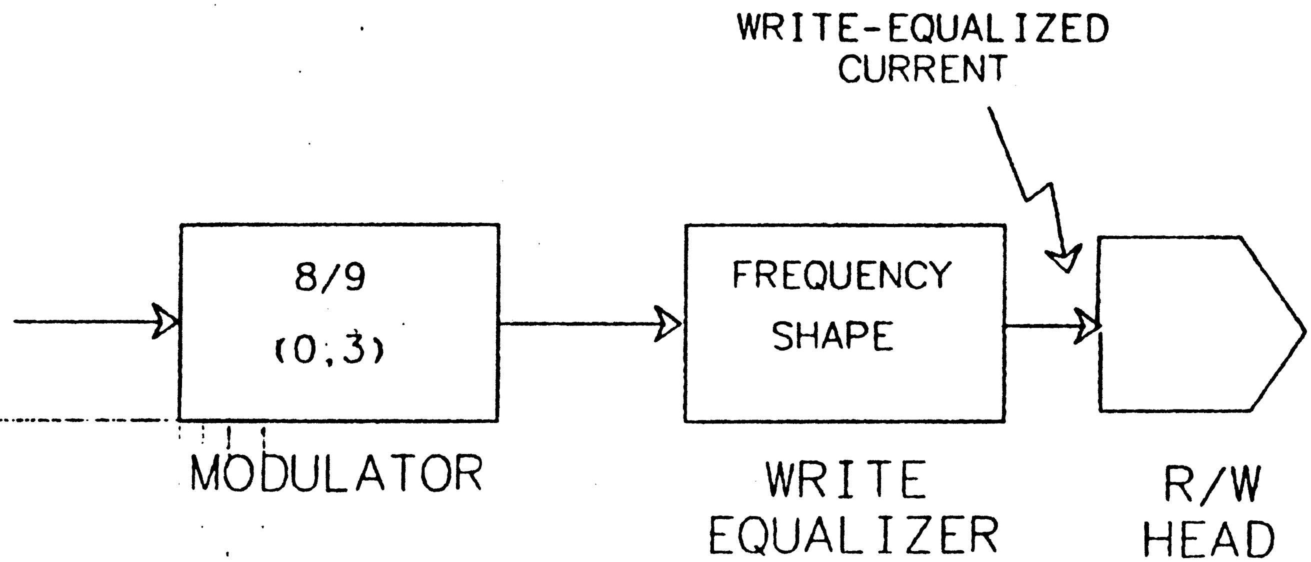
EYE PATTERNS
INTERLEAVED NRZI





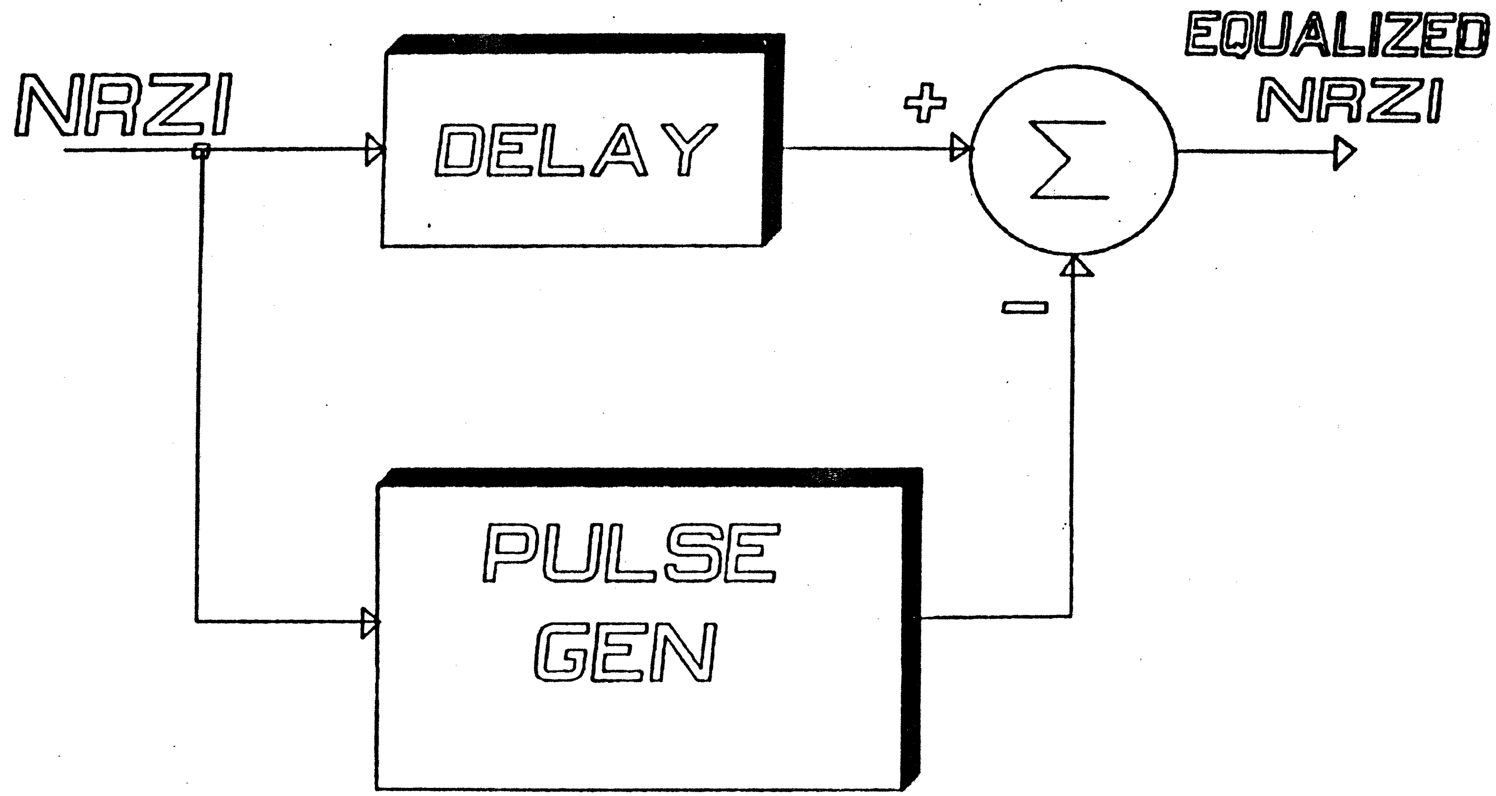


EQUALIZATION STRATEGY

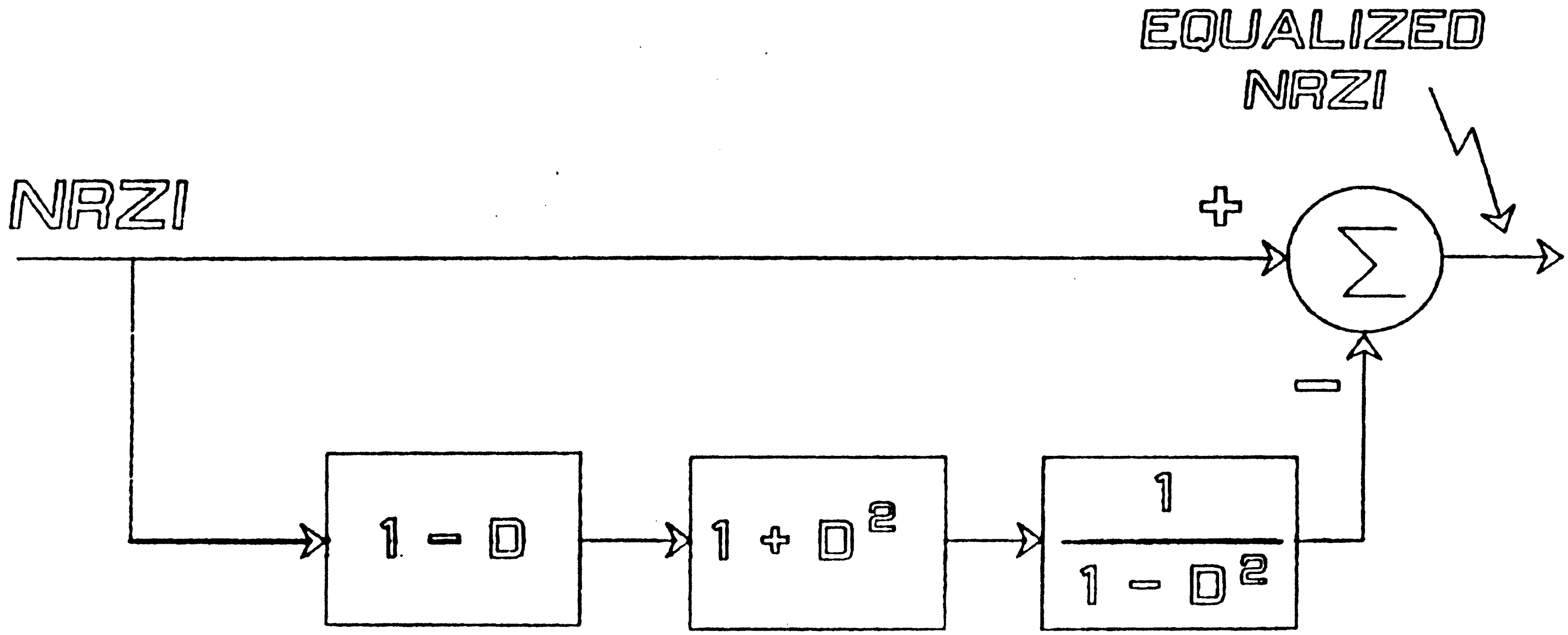


3480 WRITE ELECTRONICS

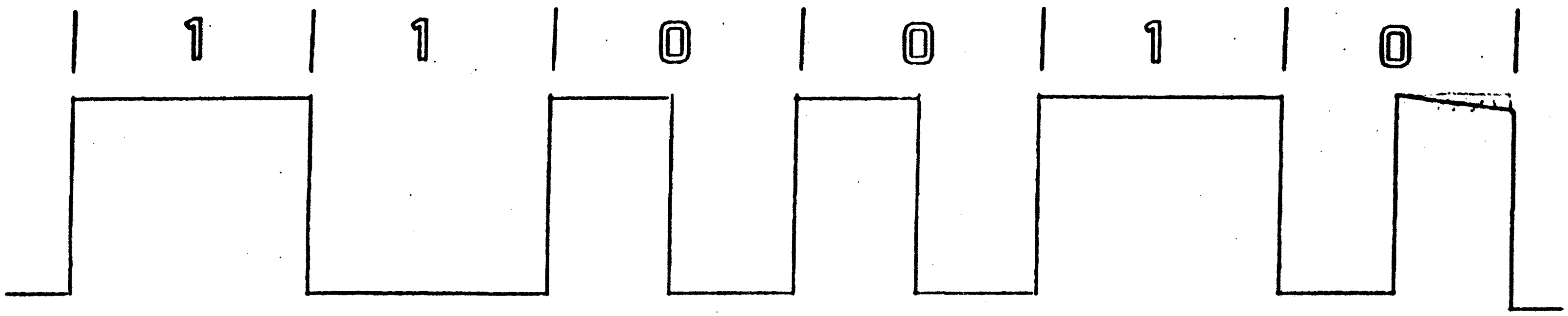
"Write Equalization in High-Linear-Density Magnetic Recording," R.C. Schneider, IBM J. Res. Develop., V 29, No. 6, Nov. 1985



WRITE EQUALIZER

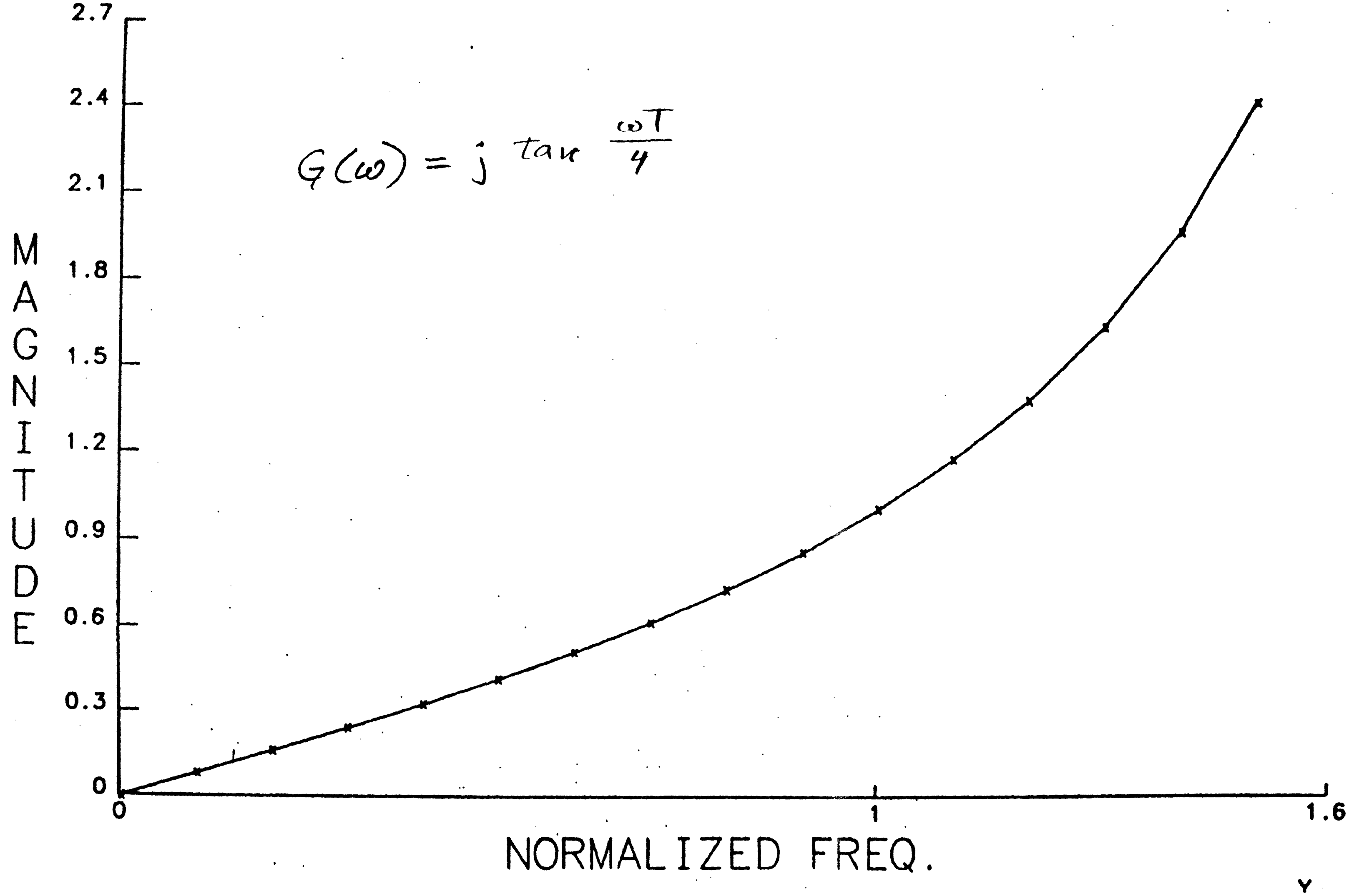


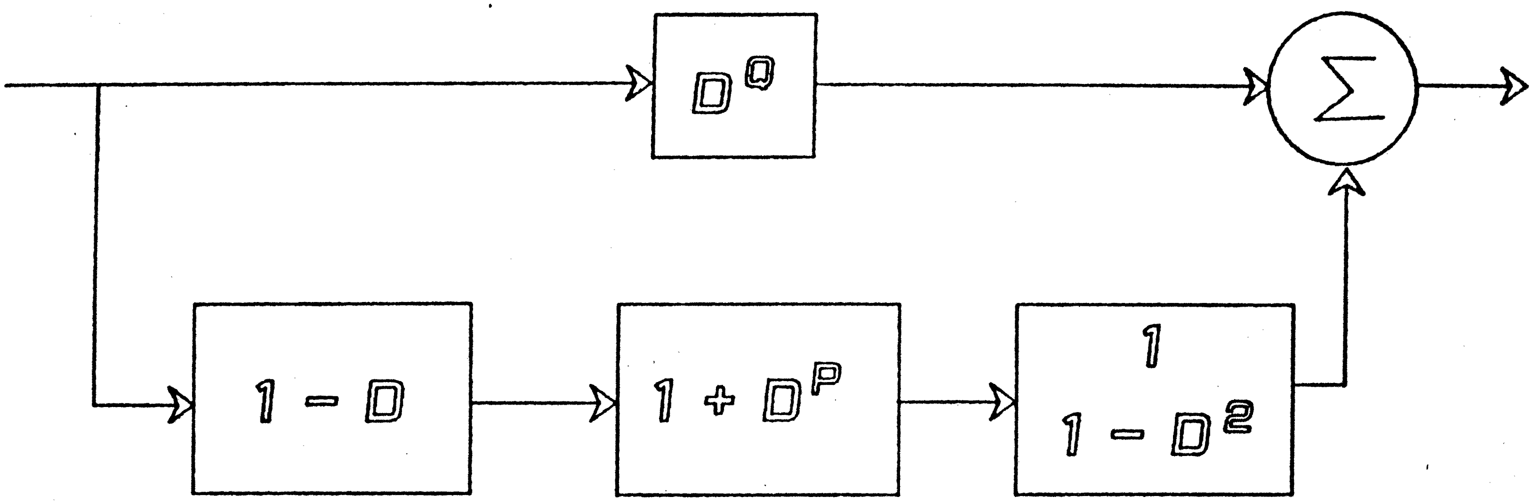
3480 WRITE EQUALIZER



EQUALIZED WRITE CURRENT

3480 WRITE EQUALIZER TRANSFER FUNCTION MAGNITUDE



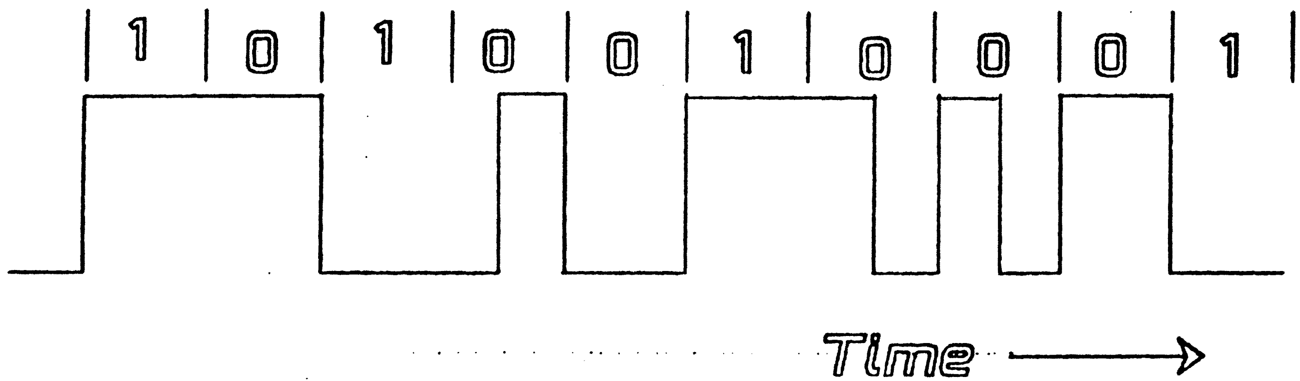


A MORE GENERAL WRITE-EQUALIZER

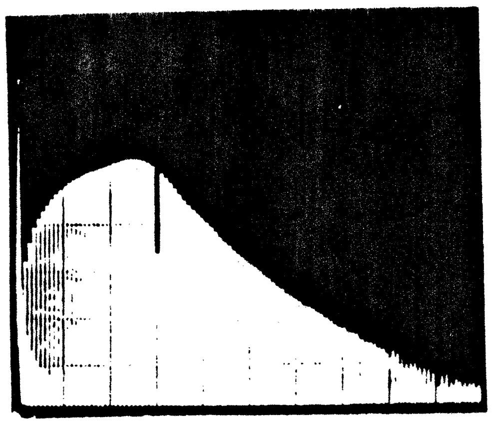
D = 1/2 CODE-BIT CELL

P = 2(d + 1)

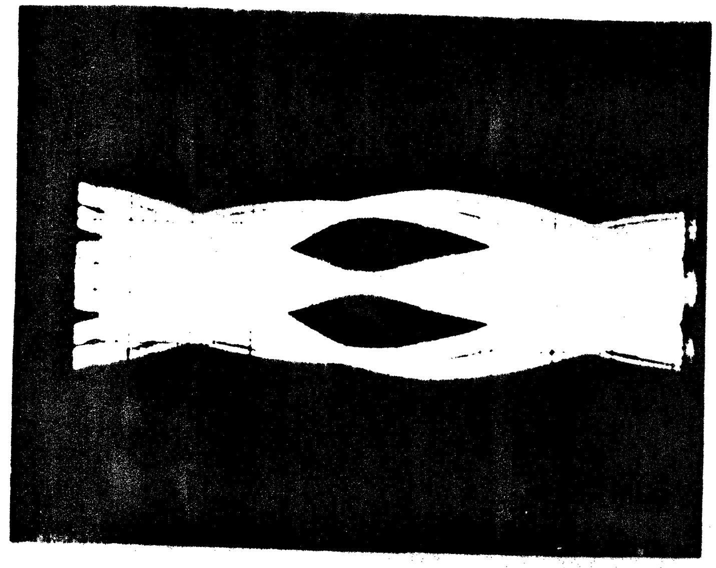
Q = ???



[1,k] WRITE-EQUALIZED CURRENT



SPECTRUM

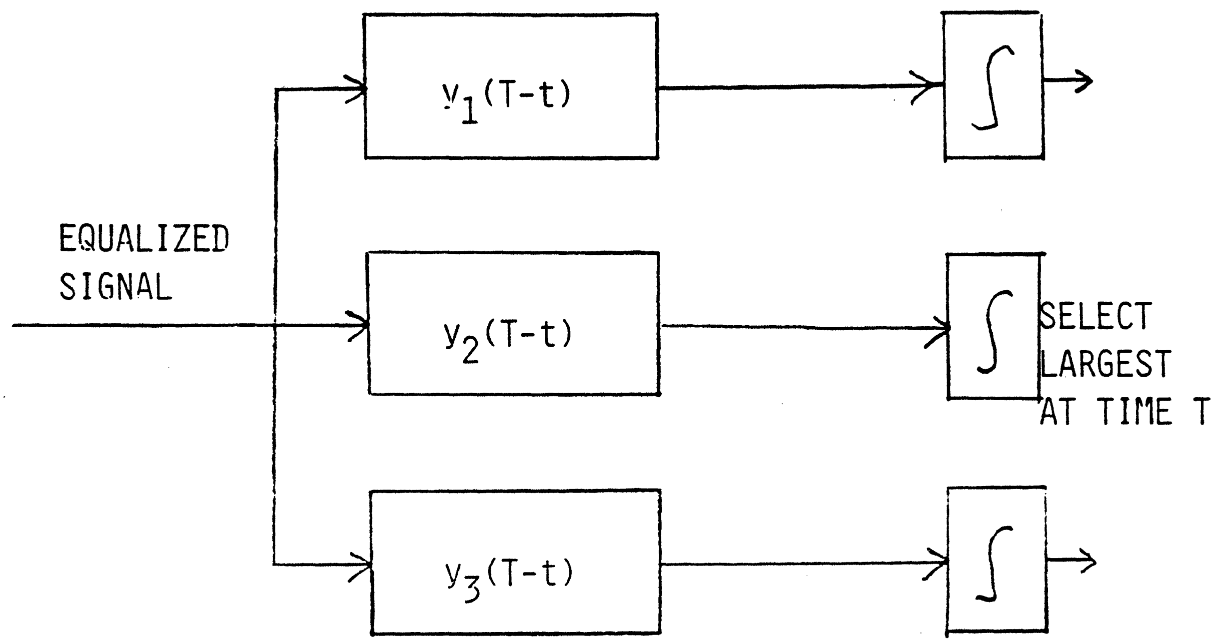


EYE

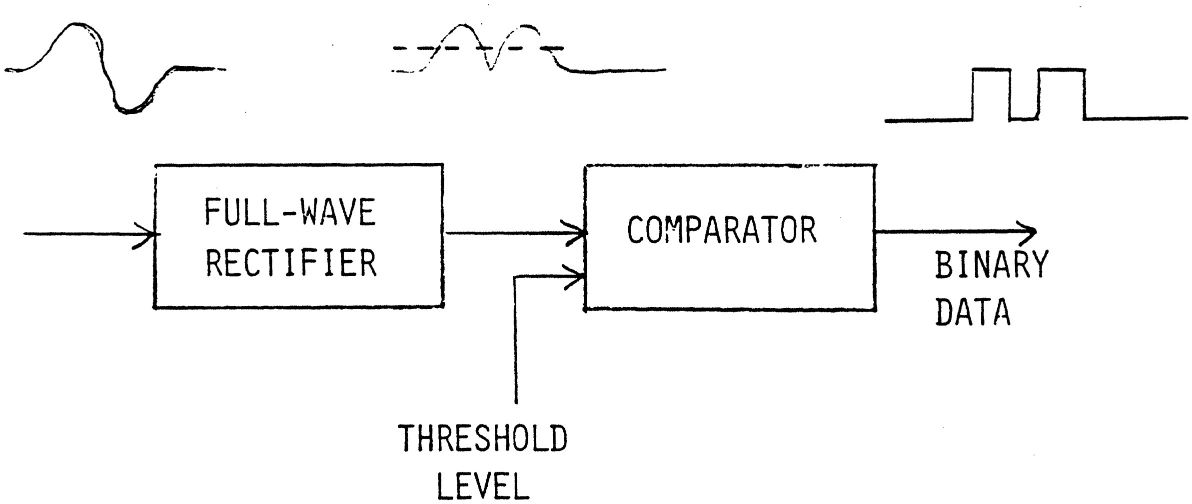
FREQUENCY MODULATION CODE

R.C. Schneider, "Write Equalization in High-Linear-Density Magnetic Recording," IBM J. Res. Dev., Vol. 29, Nov. 1985, pp. 563-8.

DATA DETECTORS

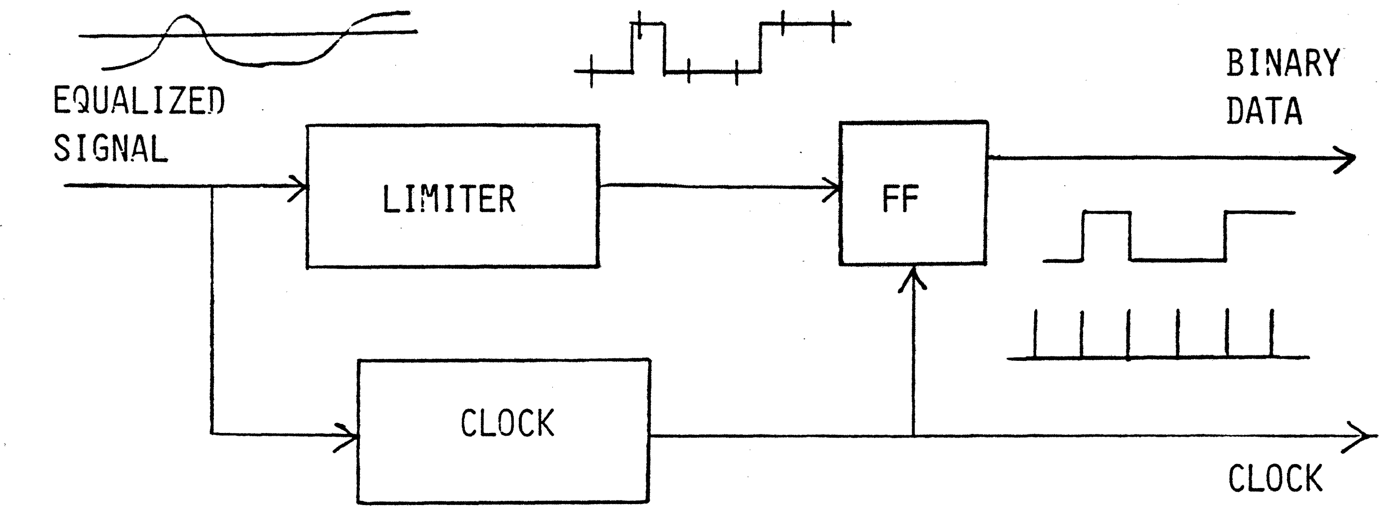


MATCHED FILTER DETECTOR

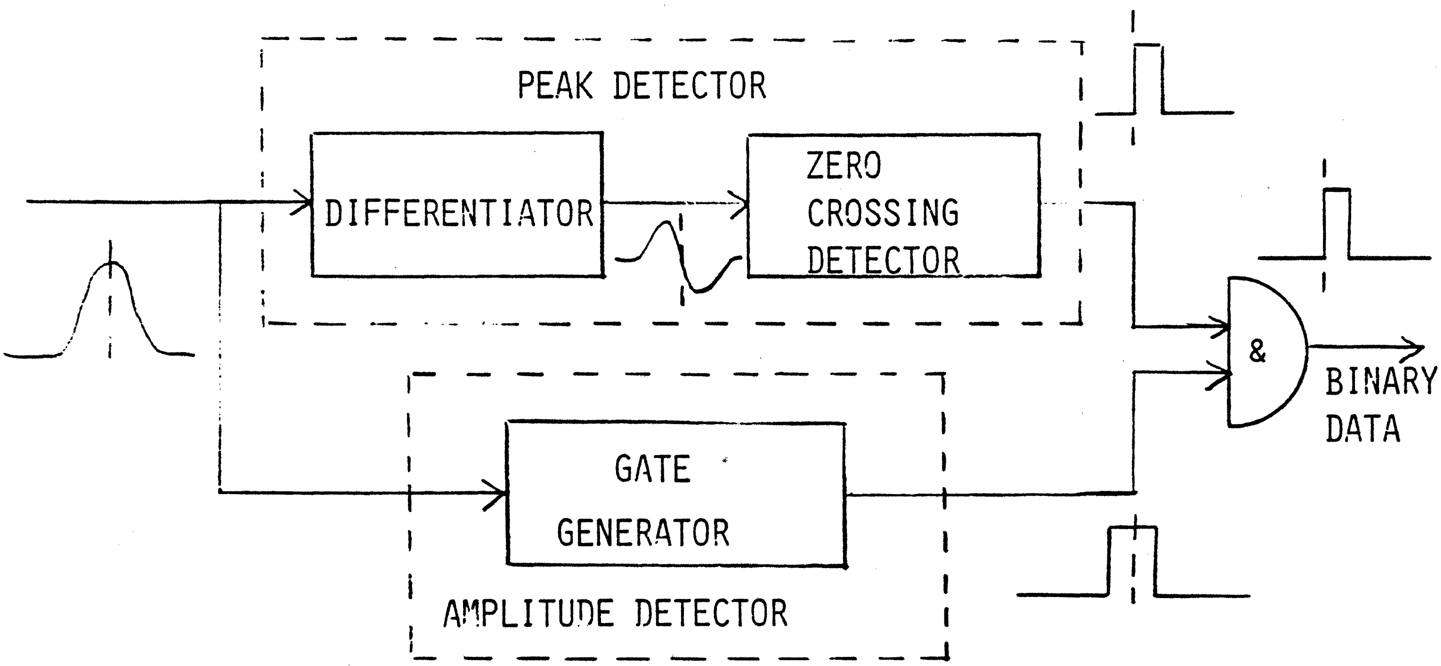


SIMPLE AMPLITUDE DETECTOR

DATA DETECTORS



SAMPLING DETECTOR



GATED PEAK DETECTOR

CLOCK RECOVERY

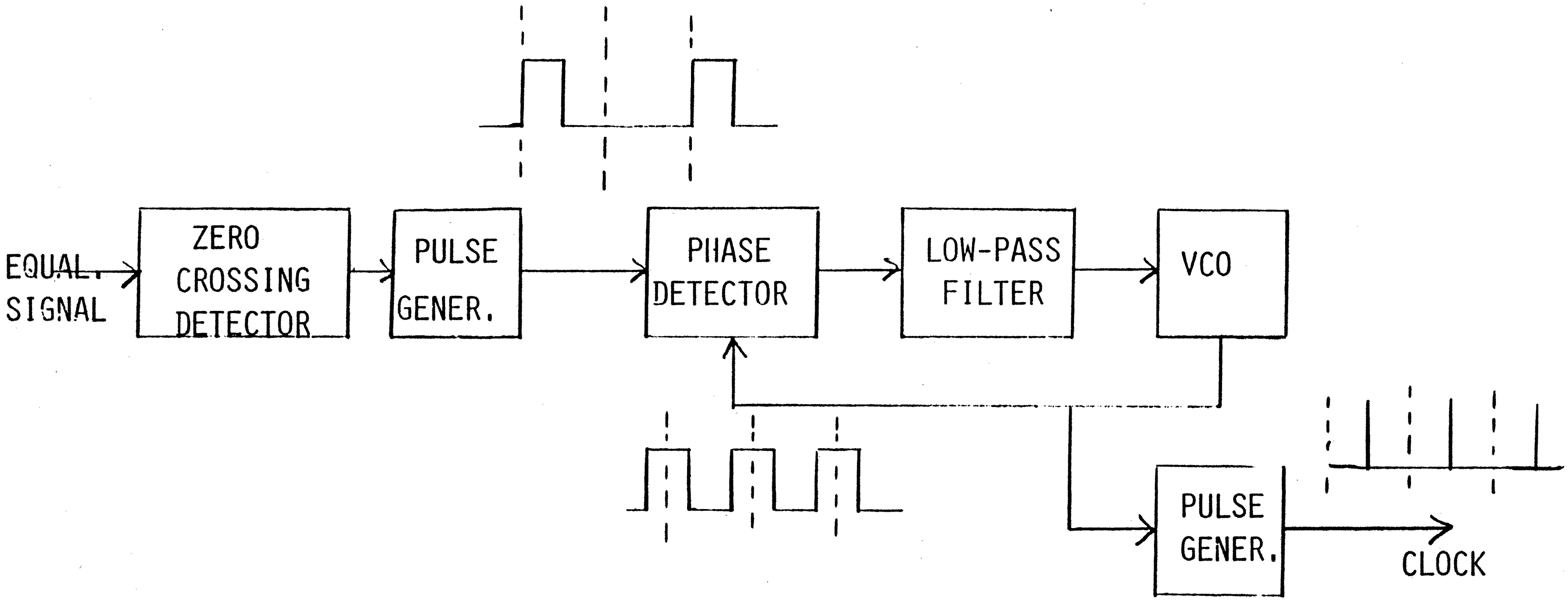
NRZI
- PARALLEL TRACKS, ODD PARITY
- SYNCHED NRZI, ENRZI

SELF-CLOCKING CODES
- DOUBLE FREQUENCY

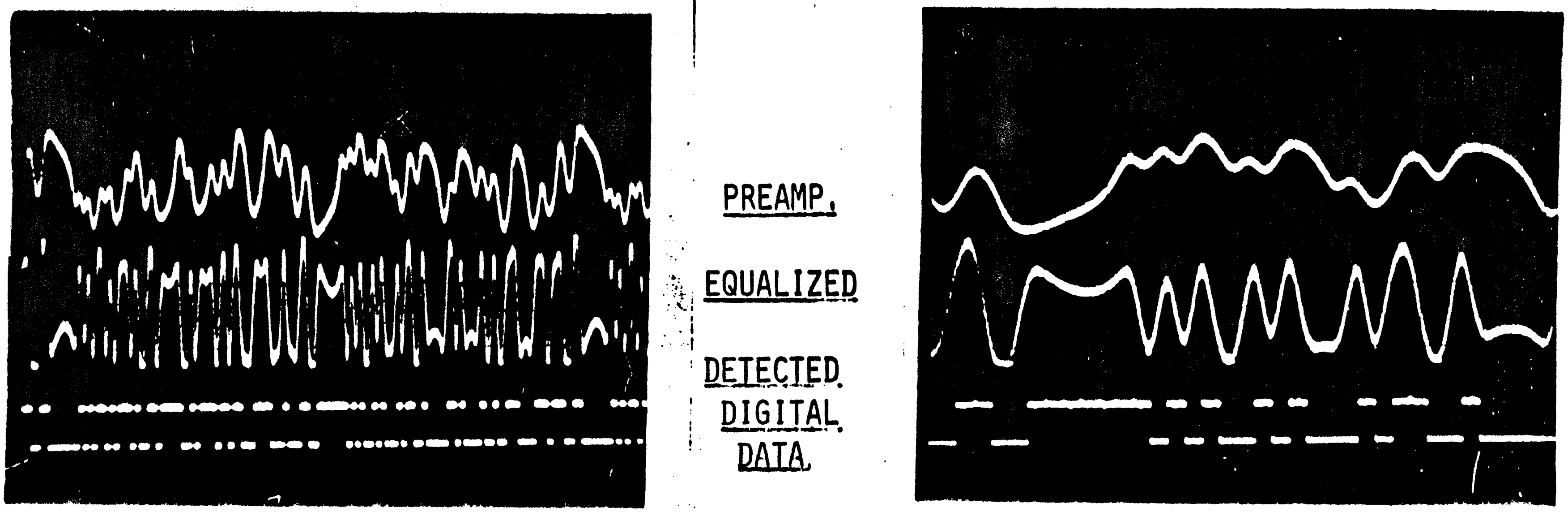
RUN-LENGTH-LIMITED CODES

FILLED CODES

PILOT TONES



CLOCK EXTRACTION BY PHASE-LOCKED LOOP



DIGITAL RECORDING WAVEFORMS AT 60 KFCI

BELL & HOWELL INSTRUMENTATION RECORDER
FERRITE HEADS, 50 MIL TRACK
DUPONT CROLYN VIDEO TAPE