Analog Recording Systems and Noise

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NOISE IN ANALOG RECORDING SYSTEMS

THE PHYSICAL ORIGINS OF TAPE, HEAD AND ELECTRONICS NOISE WILL BE REVIEWED. EXPRESSIONS FOR THE NARROW-BAND AND WIDE-BAND SIGNAL TO TAPE NOISE RATIOS WILL BE DISCUSSED. COMPARISONS WILL BE MADE BETWEEN THE THEORETICAL AND ACTUAL SIGNAL TO NOISE RATIOS OF AUDIO AND INSTRUMENTATION DIRECT RECORDERS, VIDEO FREQUENCY MODULATED AND PULSE CODE MODULATED RECORDERS.

NOISE IN ANALOG RECORDING SYSTEMS
JOHN MALLINSON

DISTINCTION BETWEEN:

INTERFERENCE
REPEATABLE

- CROSS-TALK ADJACENT TRACKS WRITE HD TO READ HD
- INCOMPLETE ERASURE
- FEED THROUGH
- 60 Hz, ETC.

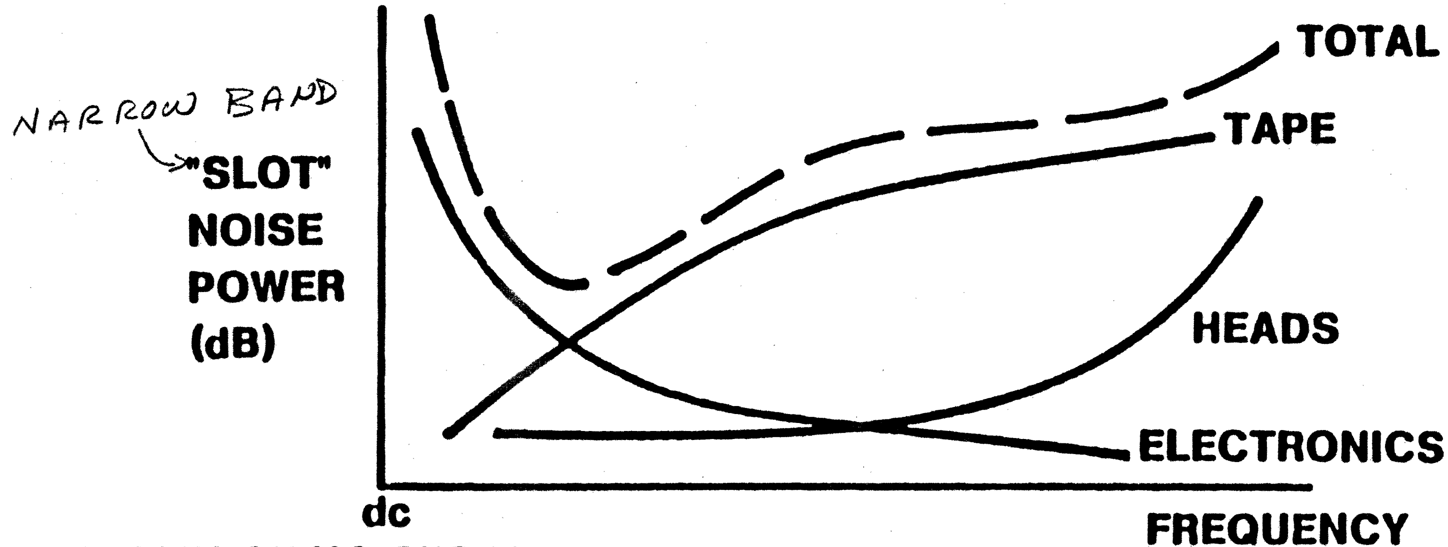
DISTORTION
PEAK SHIFT
BIT SHIFT

- AMPLITUDE SPECTRUM NOT FLAT
- PHASE SPECTRUM NOT LINEAR

NOISE
NON DETERIMINISTIC

- ELECTRONICS
- HEADS
- TAPE/DISC

THREE MAIN SOURCES OF NOISE



NOISE ADD POWER

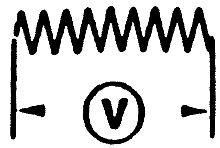
ORIGIN OF NOISES IS ALWAYS SOME UNCERTAINTY ABOUT A PHENOMENON:

ELECTRONICS:	**ELECTRON (NOISE) STATISTICS IN FIRST STAGE REPRODUCE PRE-AMPLIFIER**
RESISTORS:	**ELECTRON STATISTICS**
HEADS:	**DOMAIN WALL/ANGLE STATISTICS** DITHERING
TAPES:	**TAPE PARTICLE POSITION OR ORIENTATION STATISTICS**

RESISTORS — **JOHNSON NOISE** / **NYQUIST THEOREM**

R = IMPEDANCE, REAL PART

R

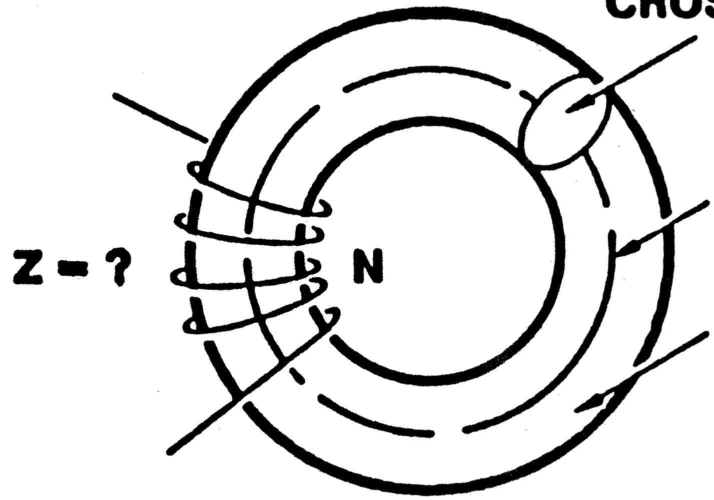


$T^{\circ}K$

$V = \sqrt{4kTR\ \Delta f}$ RMS **VOLTS**

$k =$	**BOLTZMAN'S CONSTANT** **($1.38\ 10^{-23}$ JOULES/DEGREE)**
$T =$	**ABSOLUTE TEMPERATURE**
$R =$	**RESISTANCE IN OHMS**
$\Delta f =$	**BANDWIDTH OF MEASUREMENT** (HERZ / CPS)

ELECTRICAL IMPEDANCE OF A TOROID



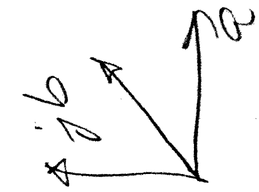
CROSS SECTION
AREA A

AV. PATH LENGTH, L

PERMEABILITY $\mu^* = \mu_R - j\mu_I$

COMPLEX
REAL
IMAGINARY
$\sqrt{-1}$

$a + jb$



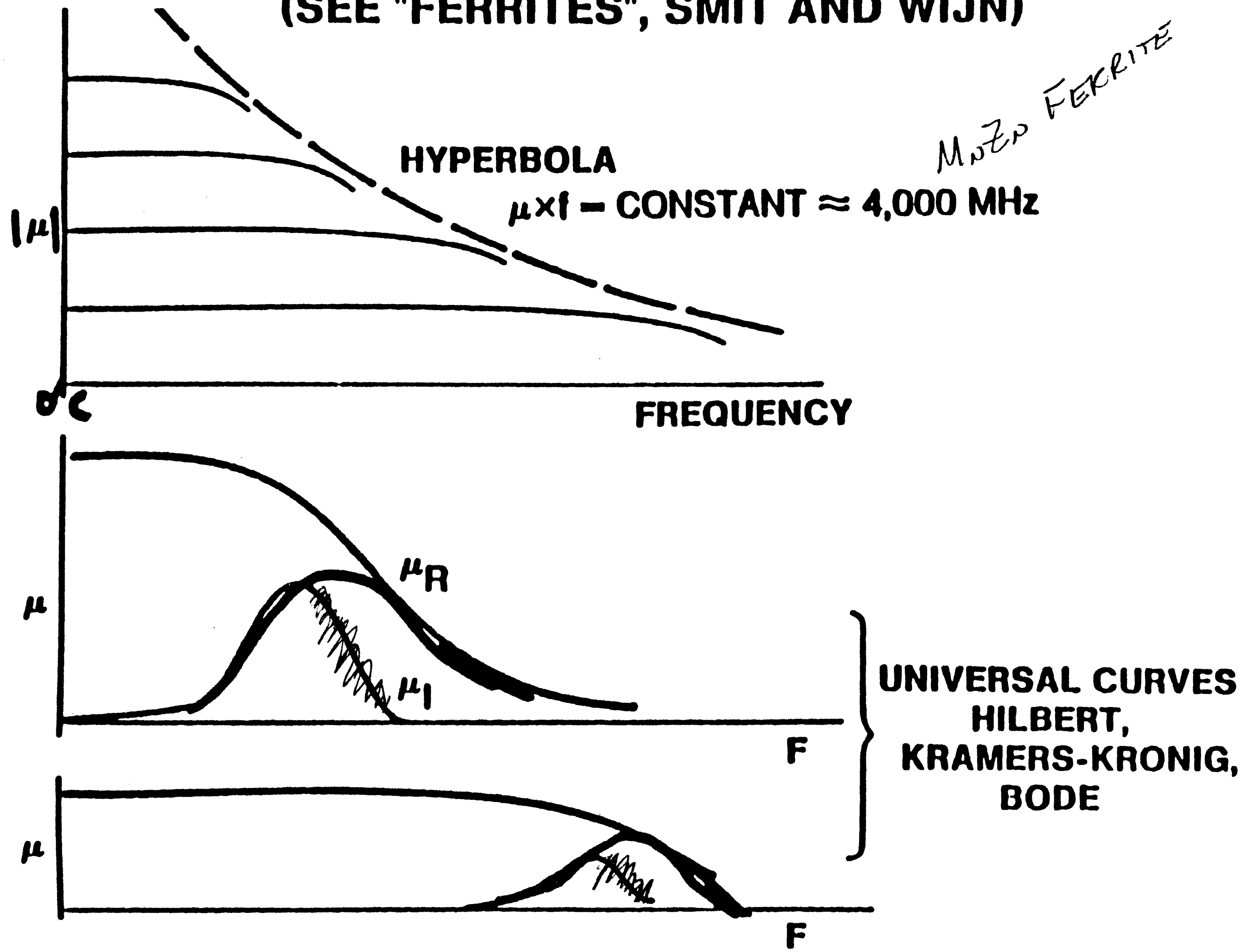
INDUCTANCE, $L^* = \left(0.4\,\pi\,10^{-8}\right) N^2 A \dfrac{\mu^*}{L}$

$$\text{IMPEDANCE} = j\omega L^* \approx j\omega \frac{N^2 A}{L}\mu_R + \omega \frac{N^2 A}{L}\mu_I$$

PURE INDUCTANCE
STORES ENERGY
∴ NOISELESS

RESISTANCE
DISSIPATES ENERGY
∴ NOISY

COMPLEX PERMEABILITY OF FERRITES
(SEE "FERRITES", SMIT AND WIJN)



IF PARTICLE:

POSITIONS ARE RANDOM

DIRECTIONS OF MAGNETIZATION ARE RANDOM

THEN, TO FIND THE TOTAL NOISE POWER, WE SIMPLY ADD THE POWERS

IF E_1 AND E_2 ARE TWO SIGNALS,

AVERAGE

$$\overline{(E_1+E_2)^2} = \overline{E_1^2} + \overline{E_2^2} + \overline{2E_1E_2}$$

IF E_1 AND E_2 ARE RANDOM $\overline{E_1E_2} = 0$

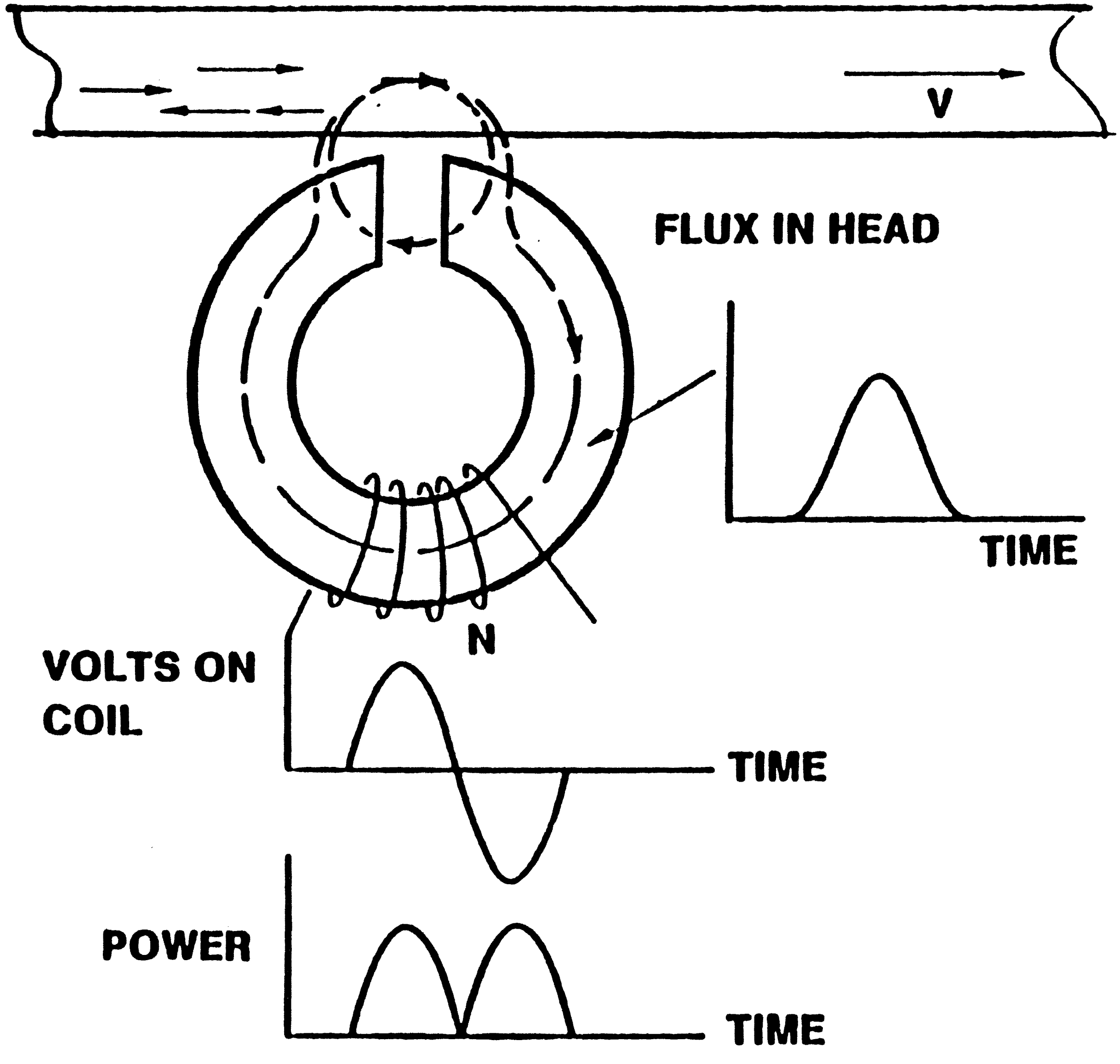
UNCORRELATED
INCOHERENT

THE NOISE POWER IS THE SUM OF THE SQUARES (NOT THE SQUARE OF THE SUM)

TAPE NOISE

SHOULD BE DOMINANT IN A PROPERLY DESIGNED RECORDING SYSTEM

EACH PARTICLE PRODUCES A PULSE OF POWER



HEAD NOISE VERY LOW COMPARED TO MEDIA NOISE

REASON - MEDIA STORES INFO

WINCHESTER 325 μ" = 6 MICRON

TOTAL TAPE NOISE POWER
(FROM AN UNEQUALIZED SYSTEM)
(See "Physics of Recording, MEE)

$$P = \int_{-\infty}^{\infty} E_N^2(k)\,dk = 4\pi\mu^2 nWV^2 \left\{ \frac{d\left(a+\frac{d}{2}\right)}{a^2(a+d)^2} \right\}$$

WHERE:

$E_N^2(k)$	= NOISE POWER DENSITY,
k	= WAVENUMBER $\left(\frac{2\pi}{\lambda}\right)$,
μ	= PARTICLE MAGNETIC MOMENT, (Bipole)
n	= NO. OF PARTICLES/UNIT VOLUME,
W	= TRACK WIDTH,
V	= HEAD/TAPE VELOCITY,
d	= COATING THICKNESSES, $\left(\frac{\Delta}{d}\right)$
a	= HEAD/TAPE SPACING

TOTAL TAPE NOISE POWER
(Continued)

20∫10 = V
10L10 = P

NOTE THAT THE TOTAL NOISE POWER:

1) **INCREASES WITH μ (=M_s×VOL)**

2) **INCREASES WITH n**

3) **INCREASES WITH W**

4) **INCREASES WITH V^2**

(3 and 4:) **DIFFERENCE BETWEEN COHERENT AND INCOHERENT**

5) **DECREASES WITH a** (d)

6) **ALMOST INDEPENDENT OF d** (Δ)

KNOWNING THE TOTAL NOISE POWER DOES NOT GIVE US THE NOISE POWER DENSITY, $E^2(k)$.

THE NOISE POWER DENSITY OR SPECTRUM

$$NPS(k) = E_N^2(k)\,\Delta k$$

$$= 4\pi\mu^2 nWV^2\, k(1-e^{-2kd})e^{-2ka}\,\Delta k$$

NOTE THAT:

1) INCREASES WITH μ

2) INCREASES WITH n

3) INCREASES WITH W

4) INCREASES WITH V^2

5) INCREASES WITH $k = \frac{2\pi}{\lambda}$

6) INCREASES WITH d

7) DECREASES WITH a

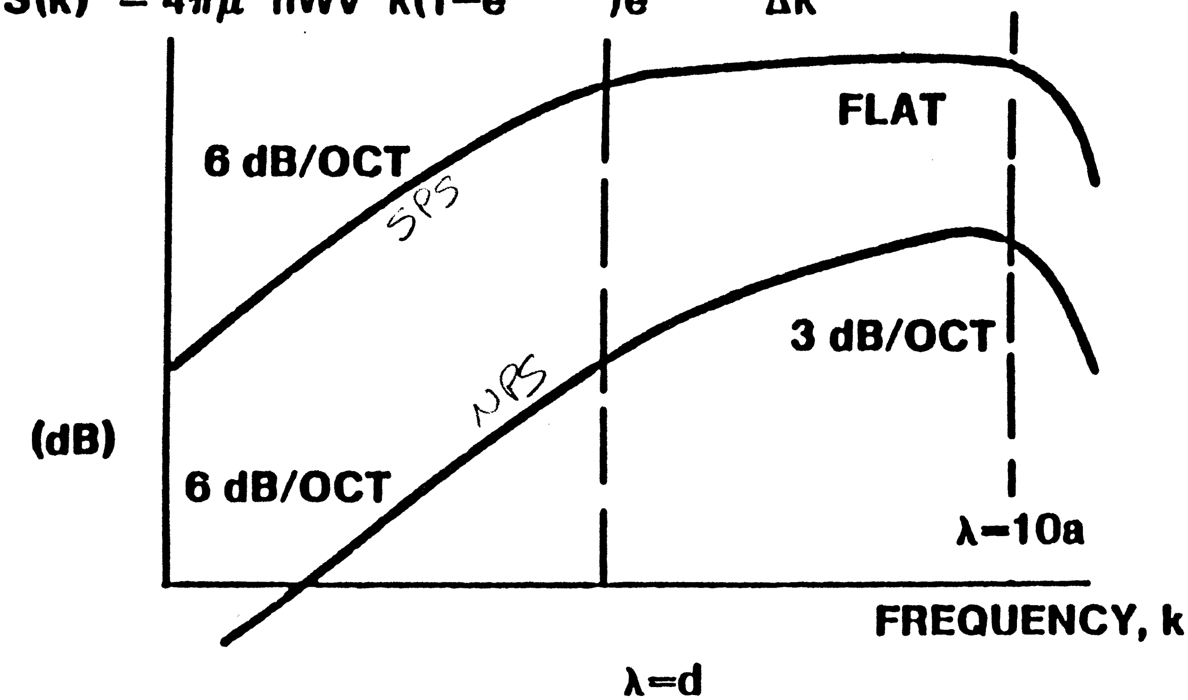
COMPARE NPS(k) WITH THE WALLACE SPECTRUM FOR THE COHERENT SIGNAL

MAGNETIZATION THICKNESS LOSS SPACING LOSS

$$SPS(k) = \frac{1}{4}\left[4\pi\mu nWV(1-e^{-kd})e^{-ka}\right]^2$$

MEAN SQUARE OF SINE WAVE $= \frac{1}{2}$, (TWO SIDED SPECTRA)

$$NPS(k) = 4\pi\mu^2 nWV^2 k(1-e^{-2kd})e^{-2ka}\,\Delta k$$



NARROW BAND OR SLOT SIGNAL TO NOISE RATIO

$$\text{SNR SLOT} = \frac{SPS(k)}{NPS(k)}\Delta k$$

$$= \pi \frac{nW(1-e^{-kd})^2}{k(1-e^{-2kd})}\Delta k$$

NOTE THAT:

1) INDEPENDENT OF μ

2) INDEPENDENT OF V

3) INDEPENDENT OF a

4) INCREASES WITH n

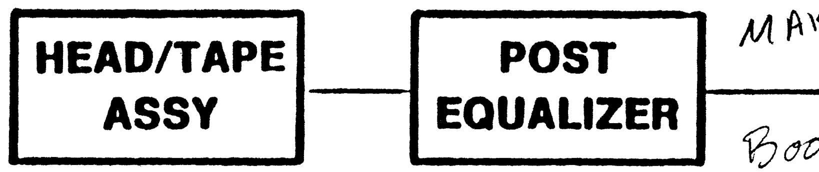
5) INCREASES WITH W

6) DECREASES WITH kd

7) DECREASES WITH k

IN ORDER TO HAVE A DISTORTION LESS SYSTEM THE OUTPUT MUST BE "EQUALIZED"

THE REQUIRED EQUALIZATION IS JUST THE RECIPROCAL OF THE WALLACE SPECTRUM



MAKE FLAT ACROSS BAND

BOOST LOWS/HIGHS

SPS(k) $\qquad$ $\frac{1}{SPS(k)}$

OVERALL TRANSFER FUNCTION IS

$$SPS(k) \cdot \frac{1}{SPS(k)} = 1$$

WIDEBAND SIGNAL TO NOISE RATIO

$$SNR_{WIDE} = \left[\int_{k_{min}}^{k_{max}} \frac{k(1-e^{-2kd})\,dk}{\pi nW(1-e^{-kd})^2} \right]^{-1}$$

$$= \pi nW\, W \left[\int_{k_{min}}^{k_{max}} k \, COTH \frac{kd}{2} \, dk \right]^{-1}$$

$$\approx 2\pi nW \left[k_{max}^2 - k_{min}^2 \right]^{-1}$$

$(kd >> 1)$

HIGH DENSITY SYSTEMS

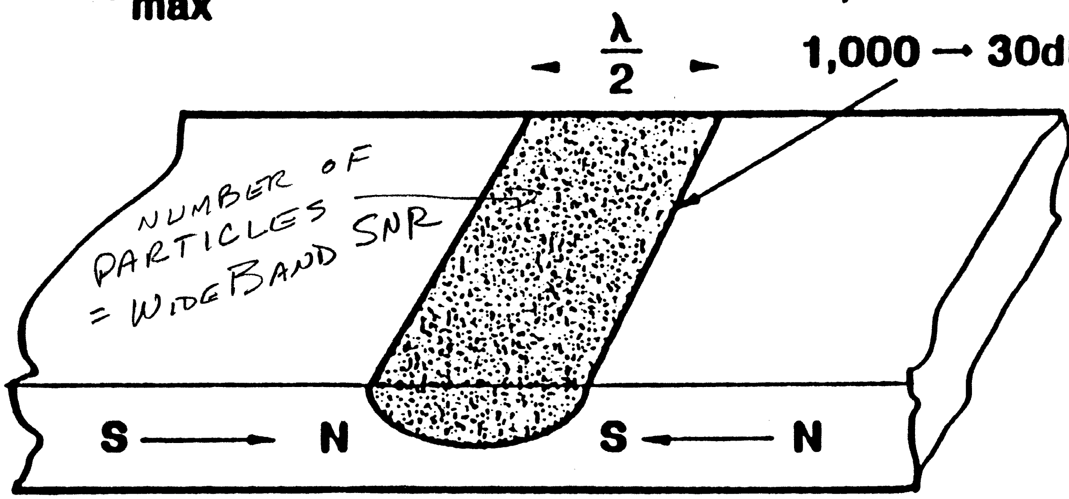
$$\approx 2\pi nW \, k_{max}^{-2} = \frac{nW\lambda_{min}^2}{2\pi}$$

WHY IS IT THAT:

$$\text{SNR} \propto \frac{nW}{k_{max}^2} \propto nW\lambda_{min}^2 \;???$$

10,000 → 40dB

1,000 → 30dB



90% 1/3λ
80% 1/4λ

THE REPRODUCE HEAD ONLY SENSES A VOLUME OF TAPE, 1/2 A WAVELENGTH LONG AND ABOUT 1/5 λ DEEP, AND THE TRACKWIDTH WIDE:

VOLUME $\propto W\lambda^2$

∴ ALWAYS BETTER TO REDUCE W THAN REDUCE λ!!

COMPARISONS WITH REALITY

A PROFESSIONAL AUDIO RECORDER

A.C. BIAS	- 1% THIRD HARMONIC DISTORTION LEVEL - ABOUT 20% OF MAXIMUM SIGNAL
BANDWIDTH	40 Hz-15 kHz
SPEED	7.5 INCH/SECOND
TRACKWIDTH	80 mils
n (γ–Fe_2O_3)	10^{15} PARTICLES/CUBIC INCH
	SNR_{WIDE}(FLAT EQUALIZATION).
EXACT CALC.	54 dB
APPROX CALC.	55 dB
MEASURED	56-58 dB

AN INSTRUMENTATION RECORDER (A.C. BIAS)

BANDWIDTH	400 Hz - 1.5 MHz
SPEED	120 ips
TRACKWIDTH	50 mil
n	10^{15} (STANDARD $\gamma-Fe_2O_3$)

	SNR_{WIDE}	(WITH Fe PARTICLES)
EXACT CALC.	36 dB	48
APPROX CALC.	36 dB	48
MEASURED	34 dB	44

AN F.M. VIDEO RECORDER

IF SIGNAL $f(x) = a \cos k_s x$,
THEN F.M. IS $\cos [k_c x + \beta \int f(x)\, dx]$,

PEAK WAVENUMBER DEVIATION IS $a\beta$,

AND SNR $\approx \dfrac{3\pi n W (a\beta)^2}{2 k_c k_s^3}$.

IN TIME DOMAIN, $f = \dfrac{kv}{2\pi}$,

$$\text{SNR} = \frac{3nWV^2(\Delta f)^2}{8\pi f_c f_s^3}$$

OR SNR $= \dfrac{3nWV^2 m^2}{8\pi f_c f_s}$, $\left(m = \dfrac{\Delta f}{f_s}\right)$. MODULATION INDEX

AN F.M. VIDEO RECORDER (Continued)

A TYPE "C" PROFESSIONAL MACHINE:

n = 10^{15} PARTICLES/CUBIC INCH
W = $5\ 10^{-3}$ INCHES
V = 1000 IPS
Δf = 3 MHz/VOLT VIDEO INPUT (1 VOLT PEAK)
f_c = 9 MHz
f_s = 4.5 MHz.

$$\text{SNR} = 38\ \text{dB}\ \frac{\text{MEAN POWER}}{\text{MEAN POWER}} \left(\frac{\text{RMS}}{\text{RMS}}\right)$$

$$= 47\ \text{dB}\ \frac{\text{PEAK POWER}}{\text{MEAN POWER}} \left(\frac{\text{P–P}}{\text{RMS}}\right)$$

MEASURED VALUE IS 49-50 dB (PRE-EMPHASIS)

REFERENCES FOR SESSIONS
ANALOG SYSTEMS AND NOISE

[1] J. C. MALLINSON "MAXIMUM SIGNAL-TO-NOISE RATIO OF A TAPE RECORDER", IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-5, NO. 3, PP. 182-186, SEPTEMBER, 1969.

[2] J. C. MALLINSON, "ON EXTREMELY HIGH DENISTY DIGITAL RECORDING", IEEE TRANSACTIONS ON MAGNETICS, VOL. MAG-10, NO. 2, PP. 368-373, JUNE, 1974.

[3] J. C. MALLINSON, "THE SIGNAL-TO-NOISE RATIO OF A FREQUENCY-MODULATED VIDEO RECORDER", E.B.U. REVIEW-TECHNICAL, NO. 153, PP. 1-4, OCTOBER, 1975.

[4] J. C. MALINSON, "TUTORIAL REVIEW OF MAGNETIC RECORDING", IEEE TRANSACTIONS ON MAGNETICS, VOL. 64, NO. 2, PP. 196-208, FEBRUARY, 1976.

A PULSE CODE MODULATED SYSTEM
(PCM OR "DIGITAL")

— DISTORTION

TRUE NOISE CAUSES BIT ERRORS ONLY. ERRORS IN QUANTIZATION APPEAR AS NOISE. SUPPOSE THE PEAK SIGNAL IS 1 VOLT. SUPPOSE THERE ARE N BITS/WORD. THE QUANTIZING INTERVAL IS 2^{-N} (APPROX.).

THE RMS QUANTIZING ERROR IS $\frac{2^{-N}}{\sqrt{12}}$*

$$SNR = 2^{N}\sqrt{12} \qquad \frac{\text{PEAK SIGNAL}}{\text{RMS NOISE}}$$

$$= 2^{2N} .12 \qquad \frac{\text{POWER}}{\text{POWER}}$$

$$= (6N+10.8) \qquad \text{dB}$$

$$* \int_{-1/2}^{1/2} x^2\,dx = 2\left[\frac{x^3}{3}\right]_0^{1/2} = 1/12$$