Non-Linear Distortions in Magnetic Recording

Alexander Taratorin
IBM

Institute for Information Storage Technology
Santa Clara University

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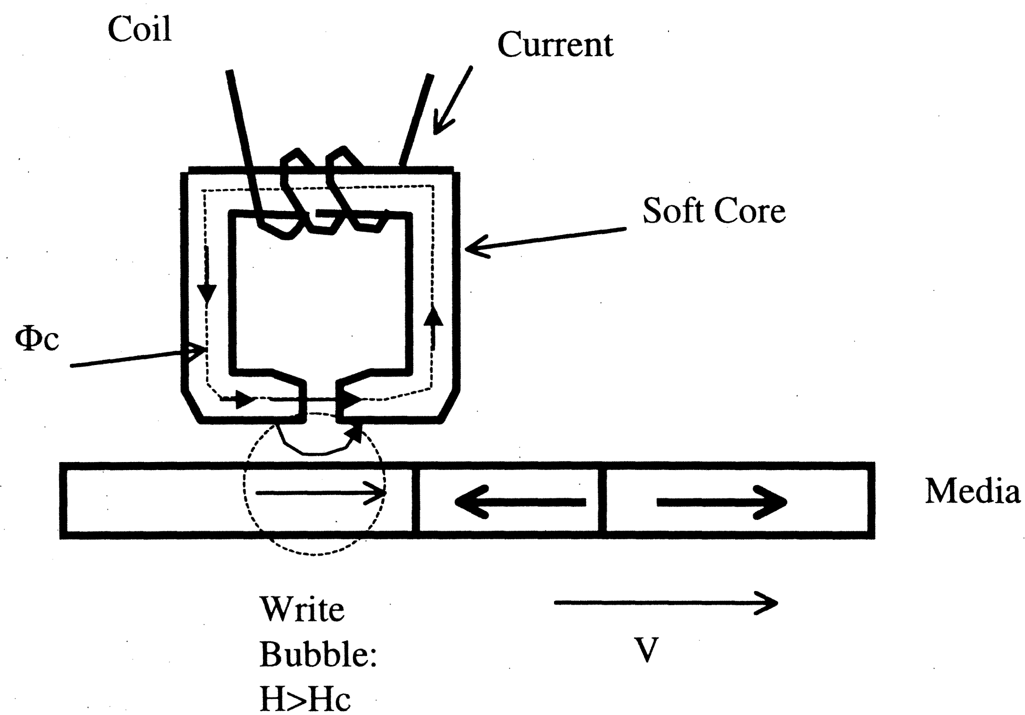
Recording process: Writing Head

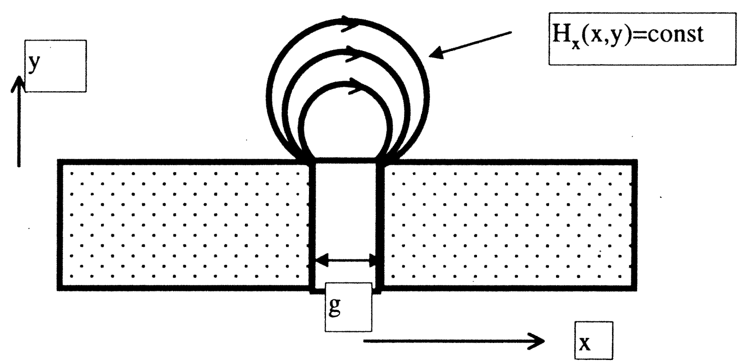


Karlqvist Field Approximation

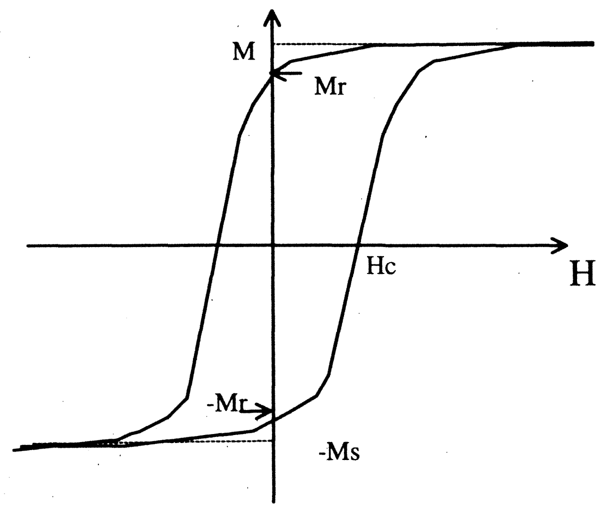
- Head Gap is small compared with gap depth and pole dimensions
- Distribution $H_x(x,y)$ is given by circular lines passing through the gap corners

$$H_x(x,y) = \frac{H_g}{\pi}\left(\tan^{-1}\left(\frac{x+g/2}{y}\right) - \tan^{-1}\left(\frac{x-g/2}{y}\right) \right)$$

$$H_y(x,y) = -\frac{H_g}{\pi}\ln\left(\frac{(x+g/2)^2 + y^2}{(x-g/2)^2 + y^2} \right)$$



Recording Medium: Hard Magnetic Material



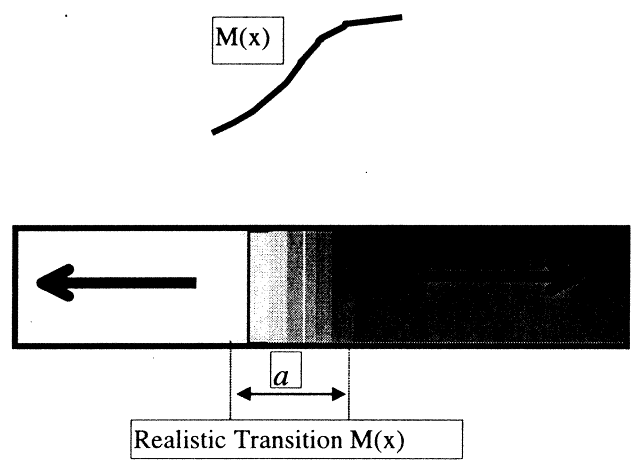
- Hysteresis Loop of the Magnetic Material
- Recording: Field H exceeds Coercivity, after the field is removed, magnetization returs to the remanence level

Transitions: Williams-Comstock Model

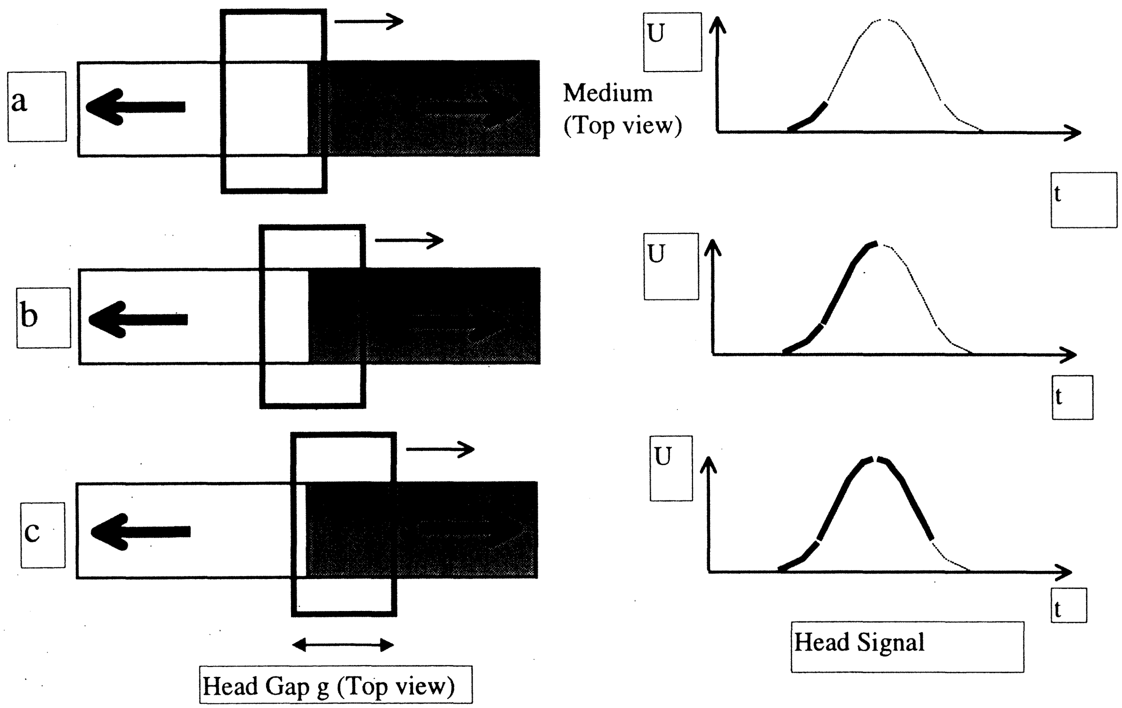
$$\left.\frac{dM}{dx}\right|_{x=x_0} = \frac{dM}{dH}\left(\frac{dH_{head}}{dx} + \frac{dH_d}{dx}\right)$$

- Magnetic transition is not ideal, it has finite extent(transition parameter (a), determined by medium hysteresis squareness (dM/dH), head field gradient (dH_{head}/dx) and medium demagnetization fields (dH_d/dx)

$$M(x) = \frac{2M}{\pi}\tan^{-1}\left(\frac{x}{a}\right)$$

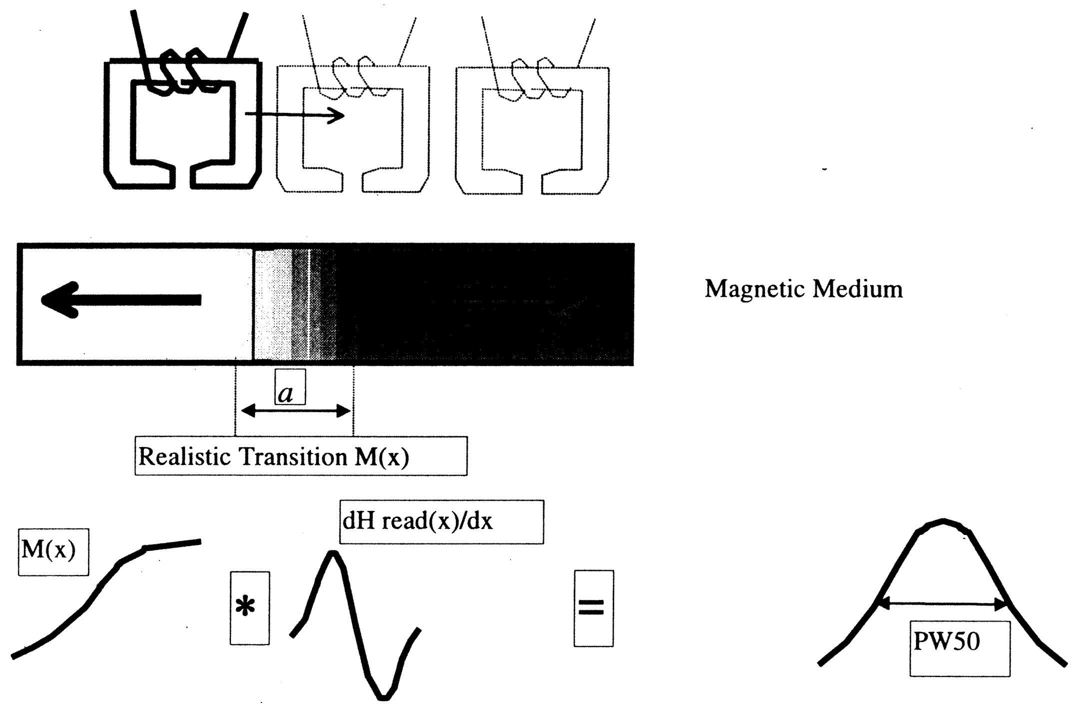


Read-Back process: Linear Superposition



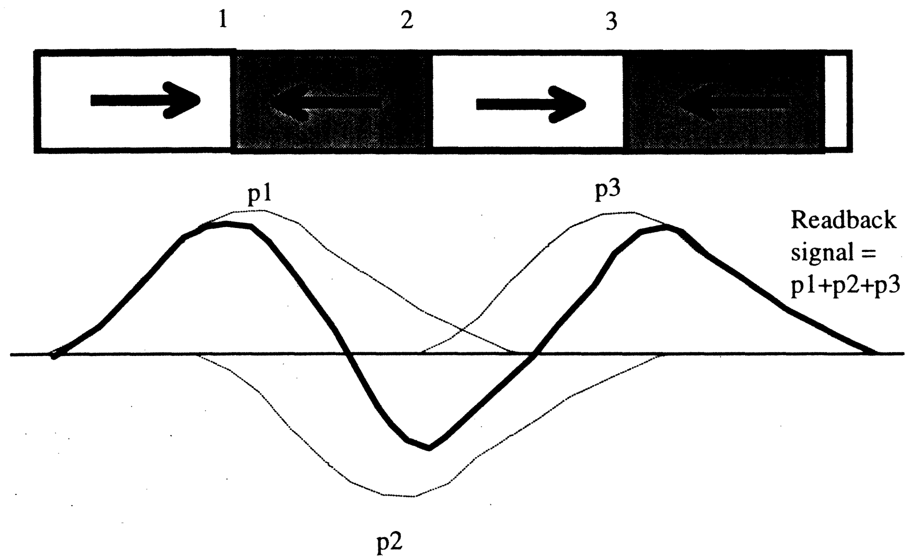
- Head reacts on the changes of medium magnetization
- Even if the transition is given by ideal step, head integrates the read-back signal (head response)

Read-Back Process



- Read-back signal is given by the convolution of the medium magnetization with the derivative of the reading head response (i.e. head read-back signal from the ideal step transition)

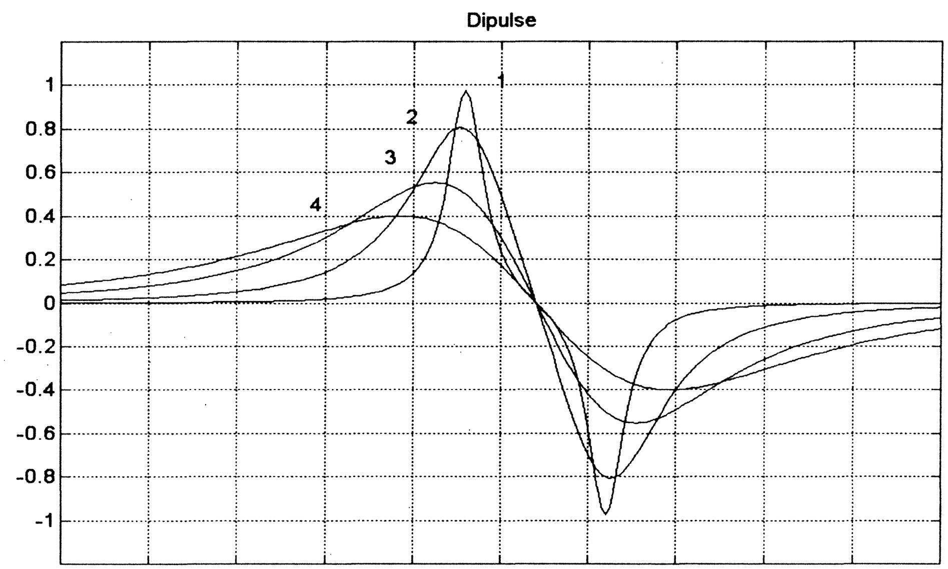
Inter-Symbol Interference (ISI)



$$f(x) = \frac{dH_{read}(x)}{dx} * \sum M_i(x) = \sum \frac{dH_{read}(x)}{dx} * M_i(x) = \sum p_i(x)$$

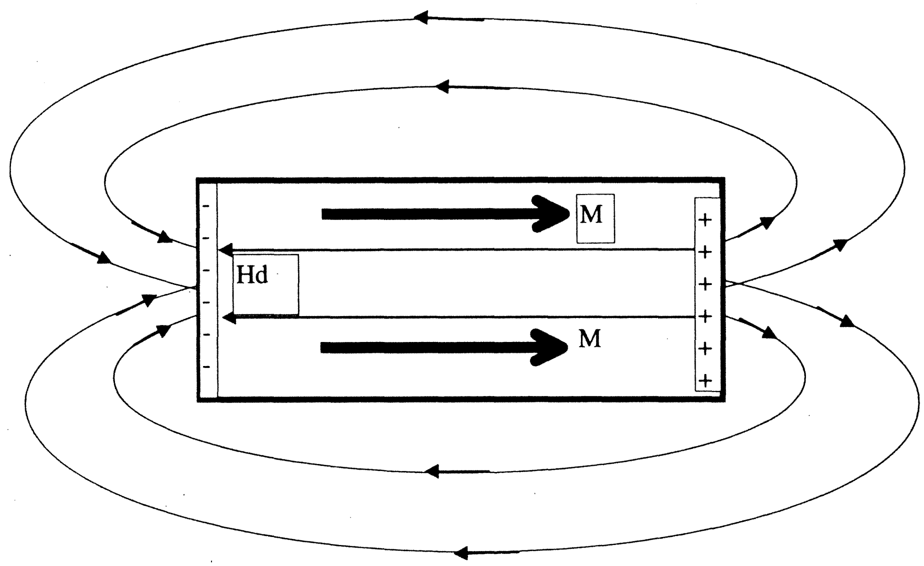
- Read-back signal from adjacent transitions equals to the sum of the read-back voltages from individual transitions (linear superposition)

Linear ISI: Amplitude Loss



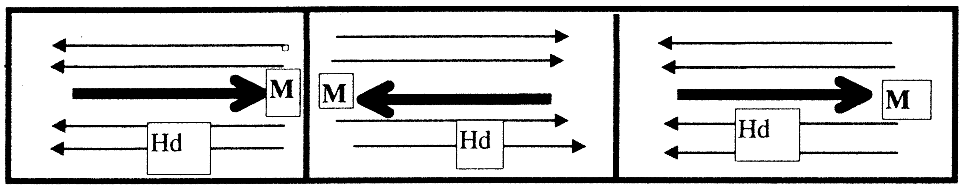
- Dipulse signal: 1 - PW50/T=0.3, 2-PW50/T=1; 3-PW50/T=2, 4-PW50/T=3;

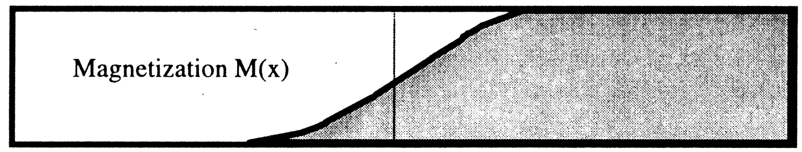
Demagnetization Field

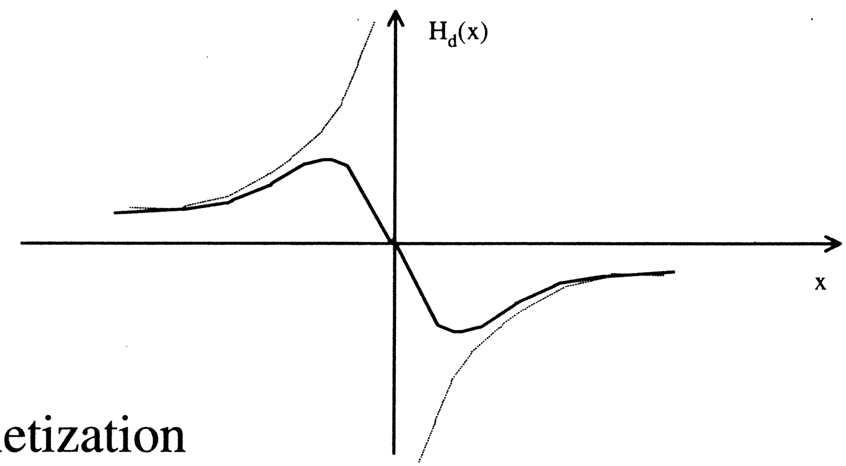


- Static magnetic fields, directed approximately opposite to the direction of the magnetization
- Demagnetization fields exist only inside a magnetic material
- They are generated by any discontinuity of magnetization

Demagnetization fields







- Always opposite to the magnetization
- Infinitely sharp transition: Hd is infinity in the transition center
- Realistic transitions: Hd equals to zero in the transition center

Demagnetization fields

- Far from transition center (no head imaging)

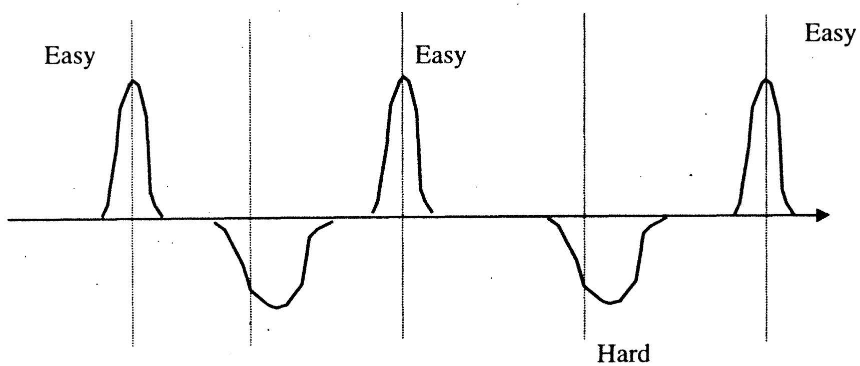
$$H_d(x) = -\frac{M_r \delta}{\pi x}$$

with head imaging:

$$H_d(x) = -\frac{4 M_r \delta \ d^2}{\pi \ x^3}$$

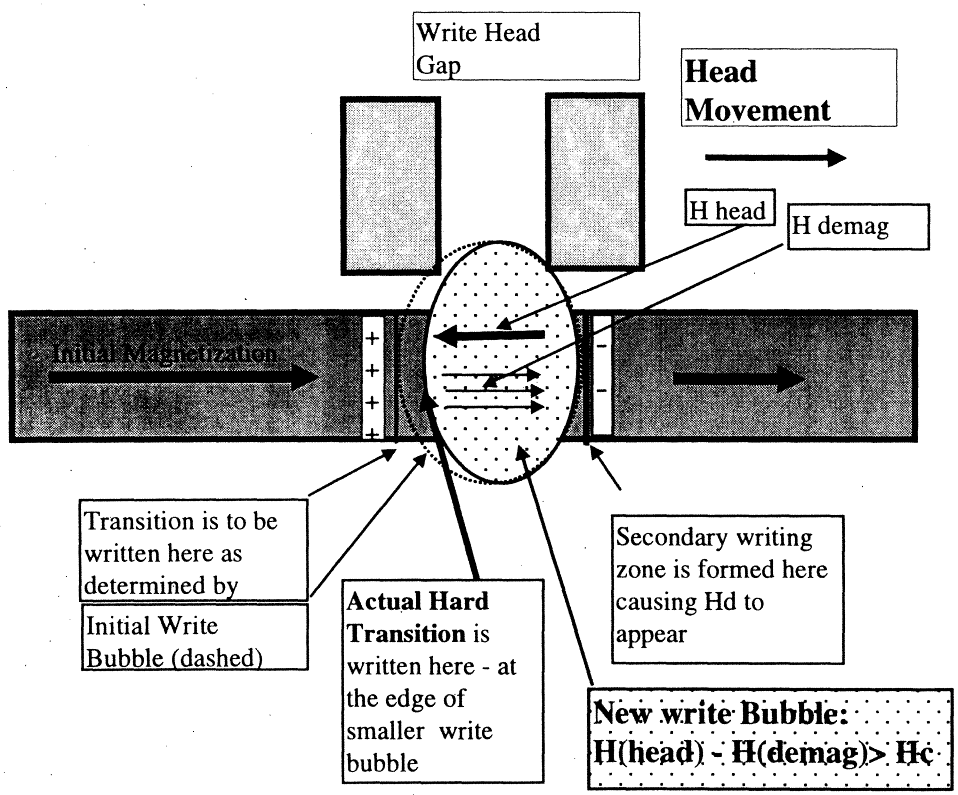
- No head imaging: drops as 1/x
- With head imaging: drops as $1/x^3$
- Proportional to the medium magnetic moment

Hard Transition Shift



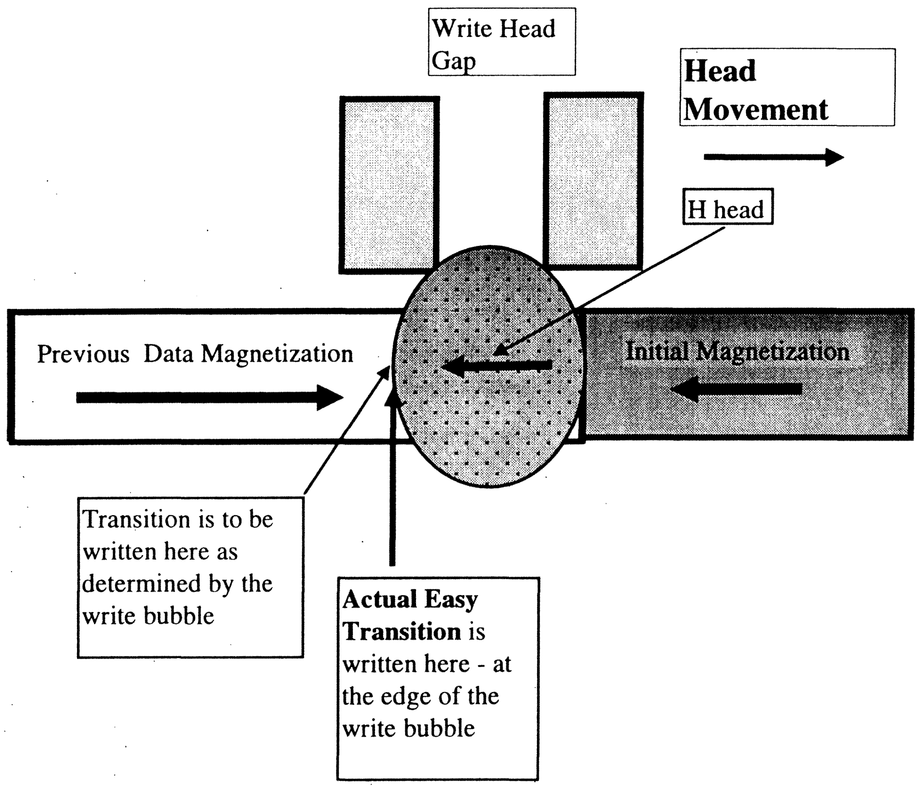
- Square wave recorded on DC-erased medium
- Easy Transitions are written along with medium magnetization
- Easy Transitions are not distorted
- Hard Transitions are written against medium magnetization
- Hard Transitions are delayed
- Hard Transitions may have different shape

Writing of Hard Transition



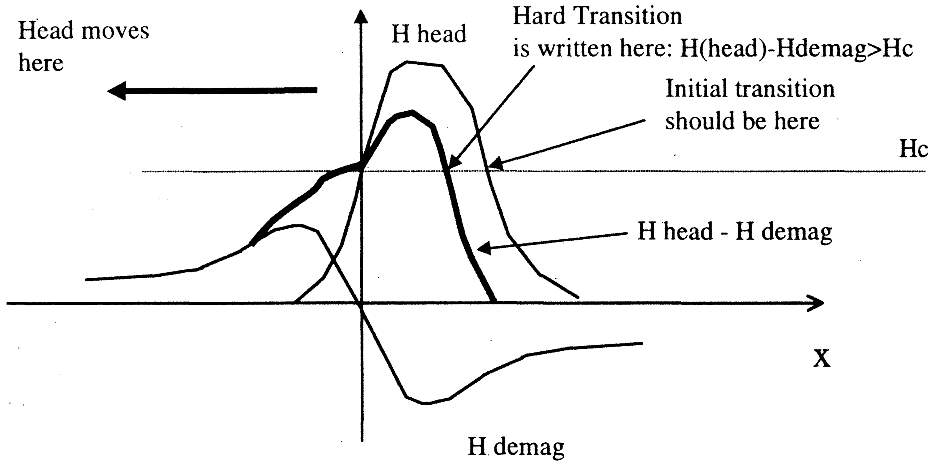
Writing of Easy Transition

- No demagnetization field, write bubble is not affected

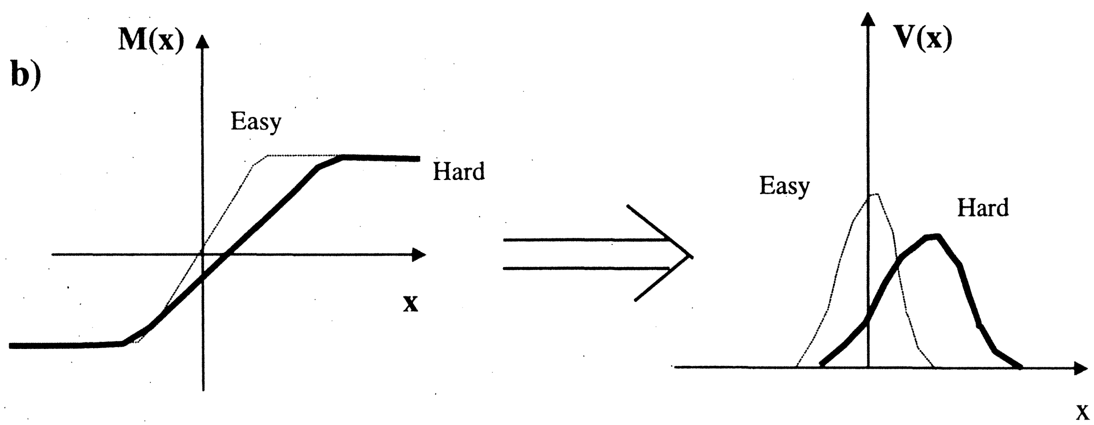


Hard Transition Shift and Magnetic Fields

a)



b)



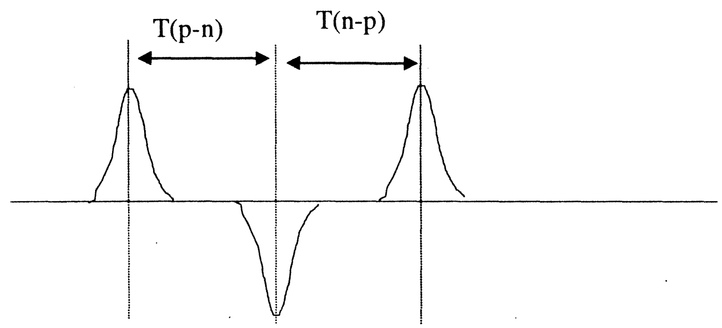
Transition Shift

- Transition is written when $H_h(x_0)=H_c$
- Shift: $H_h(x_0+\bullet\ )=H_c+H_d$
- $H_h(x_0+\bullet\ )= H_h(x_0)+\bullet\ \ d\,H_h/dx|_{x=\,x0} = H_c+H_d$
- $\bullet\ =\ -H_d\ /\ (d\,H_h/dx|_{x=\,x0})$
- Higher density (H_d) - larger transition shift
- Poor writing (e.g. poor gradient) - larger transition shift
- Theoretical equation:

$$\Delta = \frac{M_r \delta (d + \delta / 2)}{\pi Q H_c r} F(d, \delta, r)$$

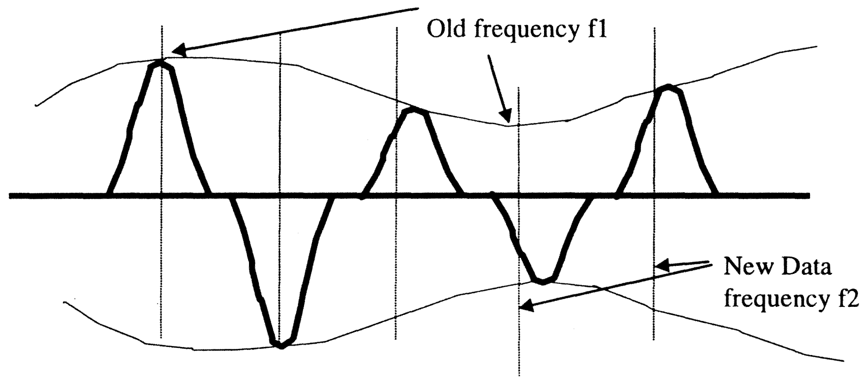
M_r is remanence medium magnetization, δ is the medium thickness, d is head-medium separation, *Hc* is the coercive field of the medium, *r* is the actual size of the head write bubble and *Q* is a numerical factor depending on the head geometry. Function $F(d,\delta,r)$ depends on head imaging and can be anything from unity to $F(d,\delta,r)=(d+\delta/2)^2/r^2$.

Asymmetry Test



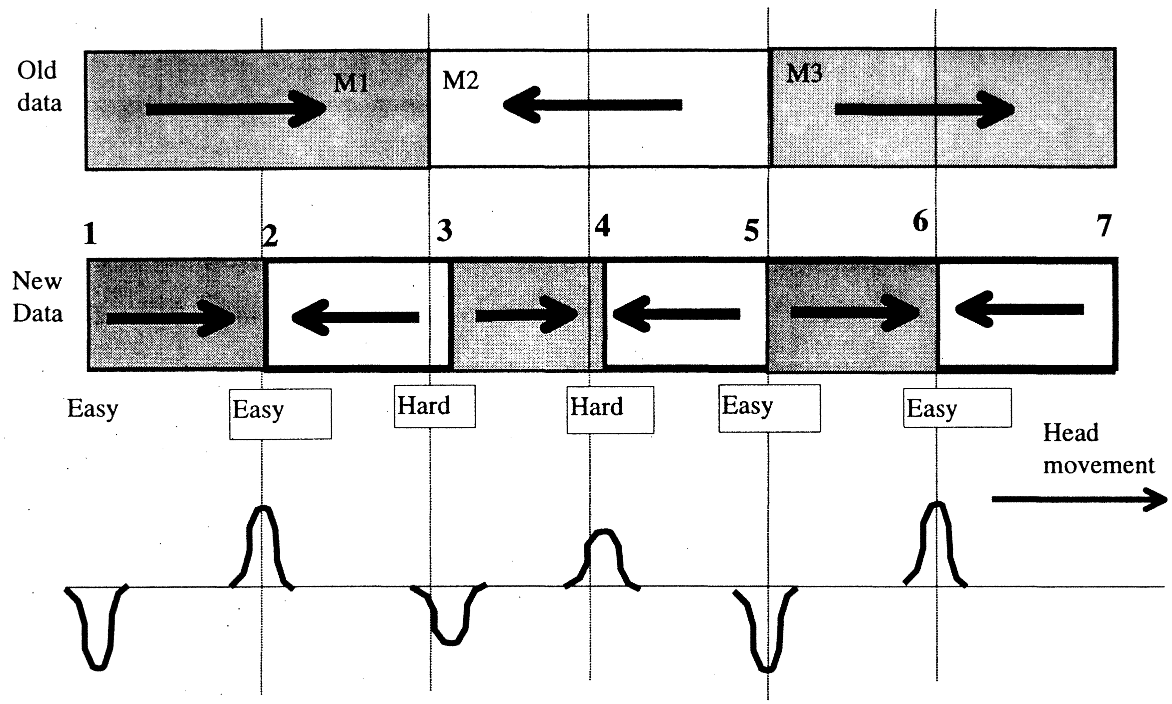
- Write Isolated Transitions on DC-erased medium
- Measure distances between peaks positive-negative-positive
- Asymmetry = Average(T(p-n) - T(n-p))
- T(p-n)=T+Δ and T(n-p)=T-Δ. Therefore:
- **Asymmetry = 2Δ**

Overwrite Test



- A pattern with low frequency f_1 is written and its average amplitude A1 is measured
- A pattern with higher frequency f_2 is written on the same track above the old pattern
- A residual signal at frequency f_1 is measured using a bandpass filter or a spectrum analyzer. This pattern has amplitude A2
- The overwrite ratio is calculated as 20log(A2/A1). This value reflects the "ability" of a new data to "suppress" old data which is previously written on the magnetic medium. Typical overwrite values should be kept below -30 dB.

Origin of Overwrite: Hard Transition Shift



- New pattern with 2f frequency is written on top of 1f pattern
- Sequence of 2 easy and 2 hard transitions, - old frequency is transformed into the sequence of hard/easy pulses

Overwrite ratio =2: Theoretical analysis

Assume that the hard transition has shape *h(t)* and the easy transition has shape *e(t)*. Transitions of the old pattern are written with period *4T* (the distance between positive and negative transitions is 2T) and transitions of the overwrite pattern are written with period *2T*. All transitions in the old pattern are easy and, therefore, the period of the old signal is given by:

$$f(old) = e(t) - e(t - 2T) \quad (5.5)$$

The corresponding period of the overwrite pattern is given by:

$$f(ow) = h(t - \Delta) - h(t - T - \Delta) + e(t - 2T) - e(t - 3T) \quad (5.6)$$

where Δ is the corresponding hard transition shift. When Fourier transform is calculated, each timing shift results in the additional phase of the signal, therefore:

$$F\{f(old)\} = E(\omega) - E(\omega)e^{i\omega 2T}$$
$$F\{f(ow)\} = H(\omega)e^{i\omega\Delta} - H(\omega)e^{i\omega(T+\Delta)} + E(\omega)e^{i\omega 2T} - E(\omega)e^{i\omega 3T} \quad (5.7)$$

Here ω is the frequency which for the old information pattern equals: $\omega_l = 2\pi/4T$, $E(\omega)$ is the spectrum of the easy transition, $H(\omega)$ is the spectrum of the hard transition. At frequency ω_l complex exponents are having integer number of pi, therefore they result in one or *i* and we obtain that the amplitudes of the old pattern A1 and of the overwrite pattern A2:

$$A1 = |H(\omega_1) + E(\omega_1)|$$
$$A2 = |(1 - i)(H(\omega_1)e^{i\omega_1\Delta} - E(\omega_1)| \quad (5.8)$$

If we assume that the shapes of the easy and hard transitions are approximately the same, the overwrite value equals:

$$OW = 20\log\left(\sqrt{1 - \cos(\frac{\pi}{2T}\Delta)}\right) \quad (5.9)$$

If the value of Δ is small, we can use approximation $\cos(x) \approx 1 - x^2/2$, therefore

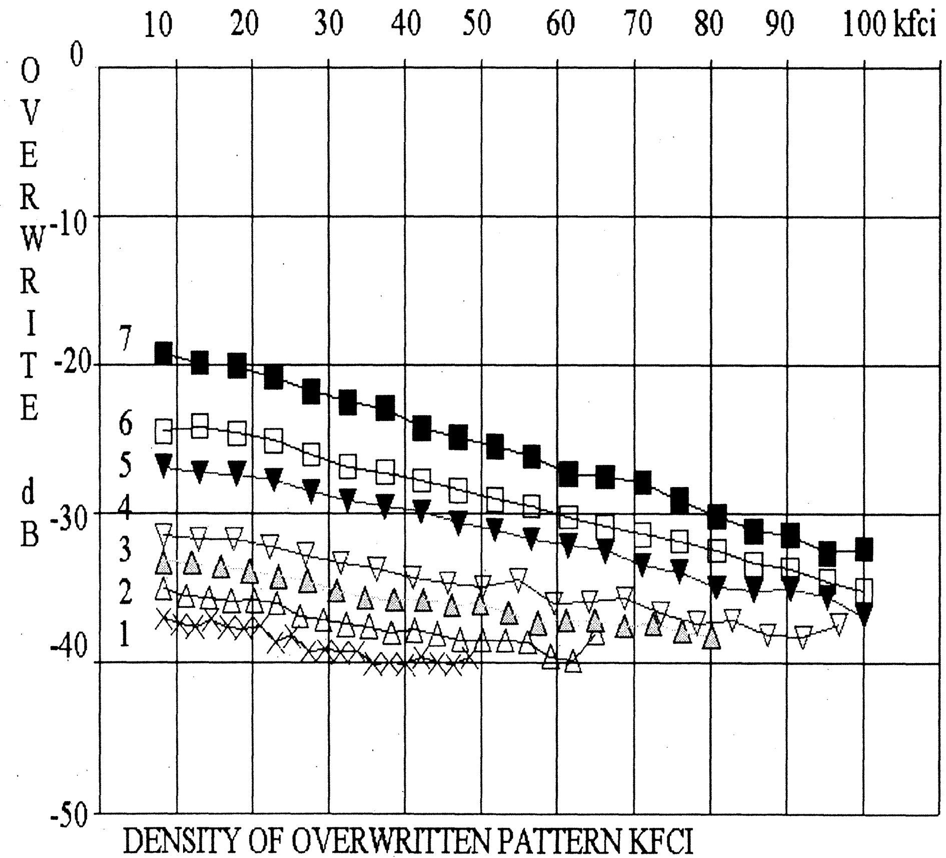
$$OW \approx 20\log\left(\frac{\sqrt{2}\pi}{4T}\Delta\right) \quad (5.10)$$

- For OW ratio 2 the derivation is analytically straightforward
- Overwrite is determined by the ratio of hard transition shift Δ to the period T of the overwriting pattern

$$OW \approx 20\log\left(\frac{\sqrt{2}\pi}{4T}\Delta\right)$$

- Meaning: timing modulation index (Δ /T)
- Example: T=10 ns, Δ =1ns, OW=20 dB
- Hard Transition shift should be minimized

Frequency dependence of Overwrite:Overwrite different LF pattern with the same HF pattern. Experiment demonstrates more than 10 dB difference between overwrite frequency ratio 10 and 2



HF pattern density (kfci):

1-50

2-66

3 -83

4-100

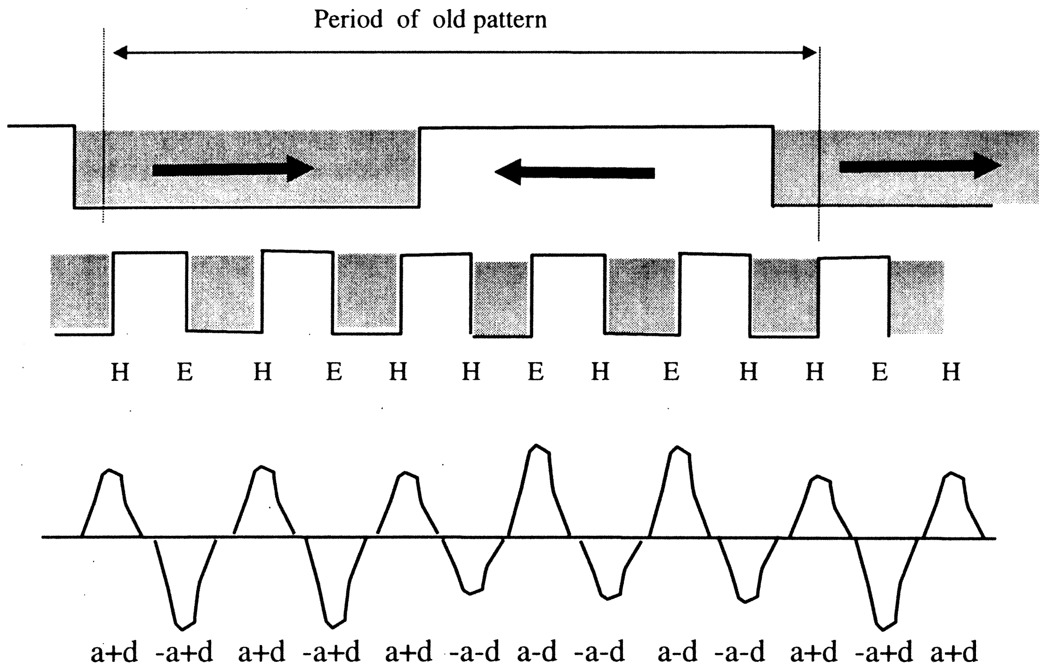
5-133

6-150

7-180

This is after edge trimming, I.e. effects of track width are eliminated

Overwrite for different frequency ratios. Theory



Easy = a-d Hard = a+d

- No simple rule: Sequence of Hard/Easy transitions (e.g.HEHEHHEHEH…)
- Use 'average' (a) and 'difference' (d) waveforms of hard and easy transitions. Analyze overwrite pattern

Overwrite for different frequency ratios. Theory

Let us use the following trick: imagine that average pulse of voltage *a(t)* is the average of easy and hard pulses, including hard transition shift and possible shape difference, and *d(t)* is their difference:

$$a(t) = \frac{h(t) + e(t)}{2}$$
$$d(t) = \frac{h(t) - e(t)}{2} \qquad (5.11)$$

Using (5.11), *h(t)=a(t)+d(t)* and *e(t)=a(t)-d(t)*. If we now write the sequence of easy and hard pulses in Figure 5.10 using sum and difference of *a(t)* and *d(t)* and alternate polarities we will see a wonderful picture. Average pulses, as it is expected, behave like undistorted sequence - they alternate +a -a +a -a etc. Difference pulses *d(t)* are exactly periodic with the period of the old pattern, indeed from Figure 5.10 we get:

+d+d+d+d+d-d-d-d-d-d ... etc.

This is a general rule which holds for any ratio of overwrite frequencies and allows us to analyze the overwrite signal.

Overwrite for different frequency ratios. Theory

, the sequence of the average pulses is not modulated by the old pattern and will have zero contribution at the frequency of the old pattern. Let the ratio of high frequency to low frequency signal be N, i.e. $f(old) = 2\pi / (2NT) = \pi / NT$. Assume that transitions of the low frequency pattern are easy and, therefore, one period of the old signal is given by the function:

$$f(old) = e(t) - e(t - NT) \tag{5.12}$$

As a general rule, the corresponding period of the overwrite pattern is modulated by the period of the old pattern and its erroneous part is given by:

$$f(ow) = \sum_{m=0}^{N-1} d(t - mT) - \sum_{m=N}^{2N-1} d(t - mT) \tag{5.13}$$

Only this signal is of interest because alternating average signal will not create harmonic at overwrite frequency. When the Fourier transform is calculated at overwrite frequency of π/NT, we get:

$$F\{f(old)\} = \left| E(\frac{\pi}{NT}) - E(\frac{\pi}{NT}) e^{i\frac{2\pi}{2NT}NT} \right| = 2\left| E(\frac{\pi}{NT}) \right|$$

$$F\{f(ow)\} = \left| D(\frac{\pi}{NT}) \right| \cdot \left| \sum_{m=0}^{N-1} (e^{-im\frac{\pi}{N}} - e^{-i(m+N)\frac{\pi}{N}}) \right| = \frac{\left| D(\frac{\pi}{NT}) \right|}{\sin(\pi / 2N)} \tag{5.14}$$

Overwrite for different frequency ratios. Theory

If we assume that the shapes of the easy and hard transitions are approximately the same, the difference between easy and hard transition is only in the timing shift Δ and

$$\left|D(\frac{\pi}{NT})\right| = \left|0.5E(\frac{\pi}{NT})\{\exp(-i\frac{\pi}{NT}\Delta)-1\}\right| = \frac{\left|E(\frac{\pi}{NT})\right|}{\sqrt{2}}\sqrt{1-\cos(\frac{\pi}{NT}\Delta)} \qquad (5.15)$$

the overwrite value equals:

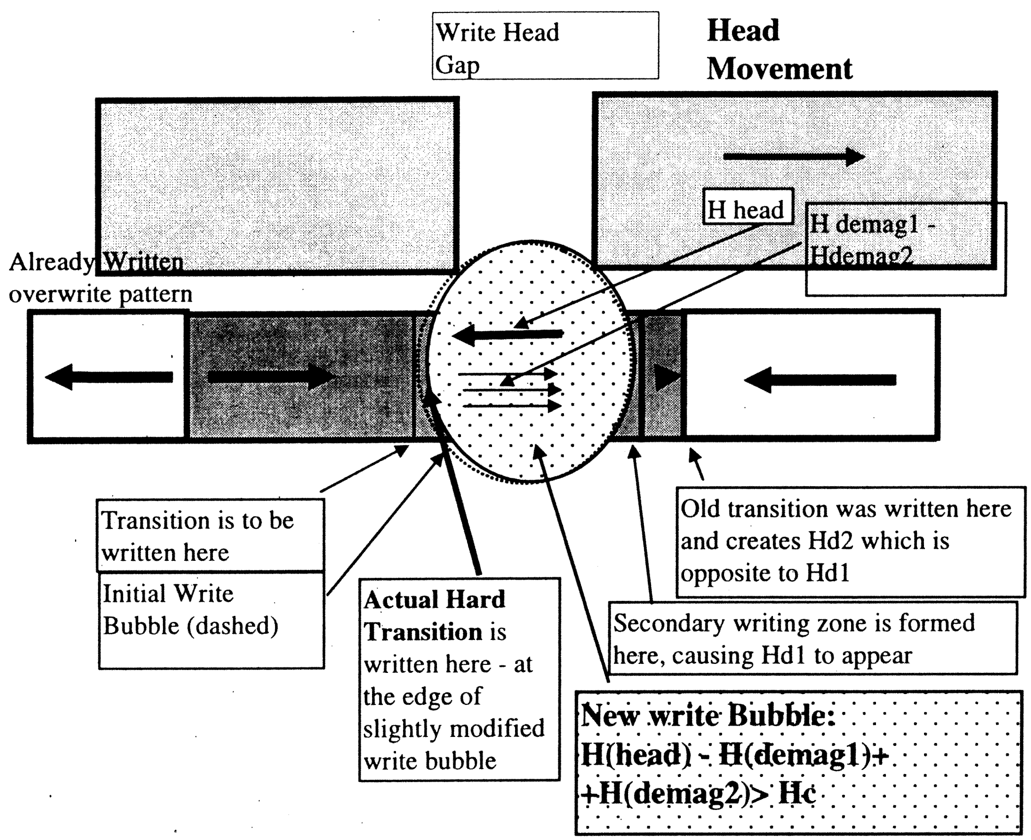
$$OW = 20\log\left(\frac{1}{\sqrt{2}}\frac{\sqrt{1-\cos(\frac{\pi}{NT}\Delta)}}{\sin(\frac{\pi}{2N})}\right) \qquad * \qquad (5.16)$$

According to (5.16) the value of overwrite should be almost independent on overwrite ratio. Indeed, when Δ is small, cos(x) is approximately $1-x^2/2$ and, since $\sin(\pi/2N)$ is decreasing with increasing N almost as $\pi/2N$, we get:

$$OW = 20\log\left(\frac{\Delta}{T}\right) \qquad (5.17)$$

Theoretical prediction: OW value should not depend strongly on the frequency ratio!

Overwrite : Proximity Effect



When a new transition of the HF pattern is written in the proximity of the old transition of the LF pattern, the demagnetization field of the old transition reduces the effective value of HTS. This effect is statistical and becomes negligible at low density

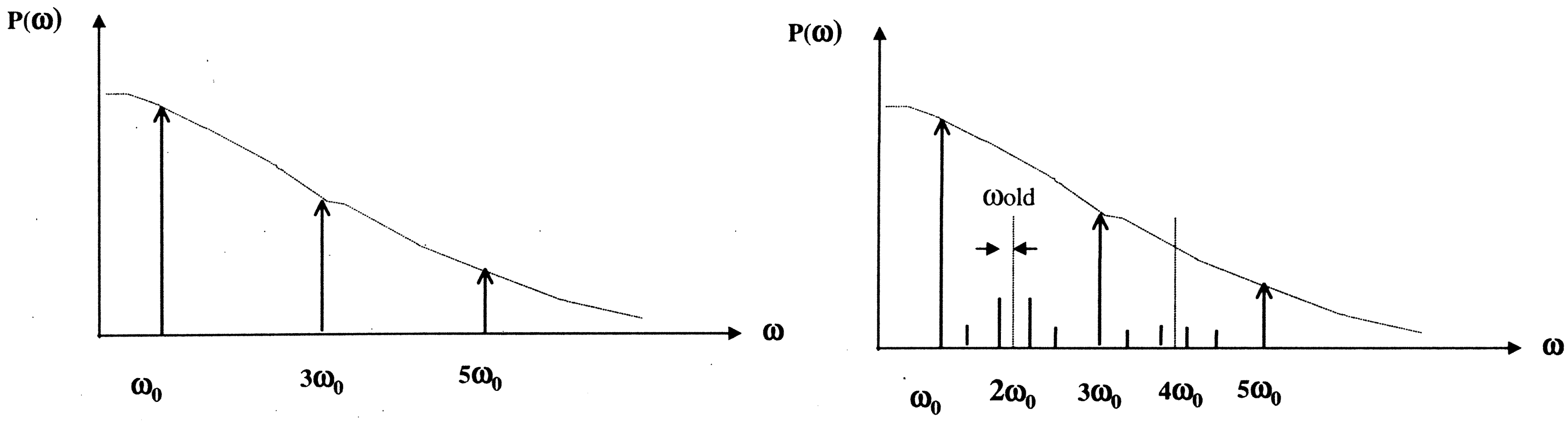
Overwrite including Proximity effect

$$OW = 20\log_{10}\left(\frac{\Delta}{T}\Psi(\omega)\right)$$

Where Δ is the value of HTS, T - period of the HF pattern, $\Psi(\omega)$ - a function, describing attenuation of HTS caused by transitions of old pattern (decreasing the effective value of HTS at high densities of the LF pattern)

- $\Psi(\omega)$ depends on the density of the LF pattern. This function should not depend on the density of the overwriting (HF) pattern.
- Proximity effect explains only part of the Overwrite degradation

Spectrum of the Overwrite Signal



- Left: without overwrite, right - when old information is overwritten
- Overwrite causes appearance of side bands around even harmonics of the signal at frequencies:

$$2\,k\,\omega_0 \pm n\,\omega_{old}$$

Overwrite: References

- Hard Transition shift and overwrite are discussed in:
- N.Bertram *Theory of Magnetic Recording*, Cambridge University Press, 1994.

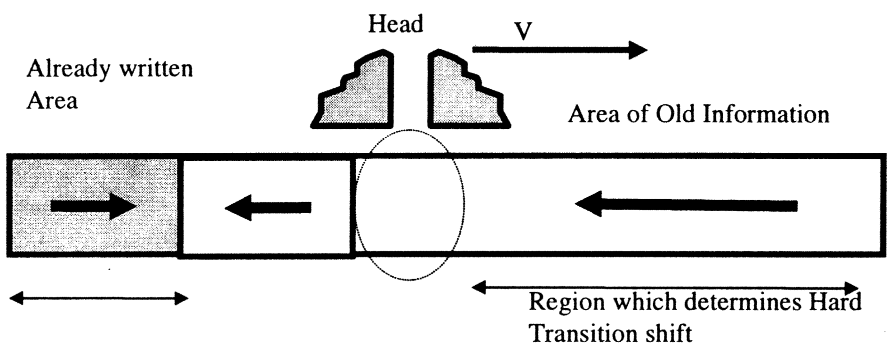
- G.Lin, Y.Zhao and H.N. Bertram "Overwrite in Thin Film Disk Recording Systems" - *IEEE Trans. Magnetics*, vol. 29, 6 pp. 4215-4223 - original paper describing relation between overwrite and Hard transition shift.

- Proximity effect was studied by Y.S.Tang and X. Tsang in "Non-Linear Transition Shifts in Magnetic Recording due to Interpattern Proximity Effects" - Journal of Applied Physics, 74,5, pp.3546-3550, 1993

- The dependence of overwrite on frequency is studied by J.Fitzpatrick and X.Che "The dependence of overwrite on proximity Effect" - presented at Intermag-96, Seattle, WA, april 1996, *IEEE Trans. Magnetics*, 1996 (Proceedings of Intermag 96 issue)

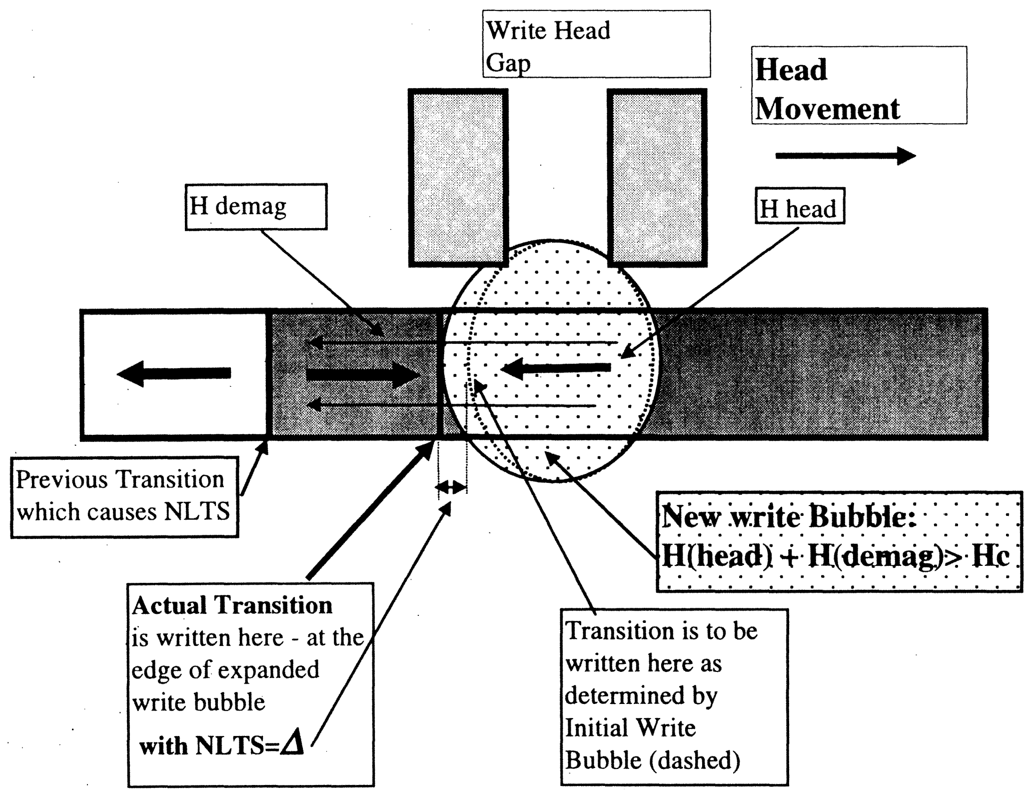
- The spectrum of overwrite signal was obtained by Y.S.Tang and C. Tsang "Theoretical Study of the Overwrite Spectra due to Hard Transitions effects" - *IEEE Trans. Magnetics*, vol. 25, 1, pp.698-702, 1989.

Non-Linear Transition shift (NLTS)



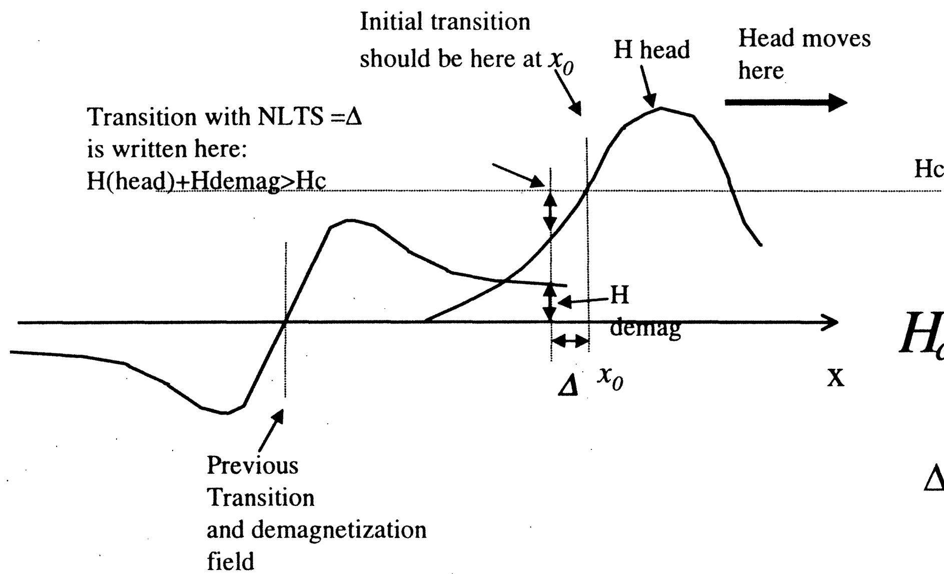
- Origin of NLTS is of the same physical nature as the origin of Hard transition shift. The only difference is that NLTS is caused by preceeding transitions of the currently written pattern, while HTS is determined by the old information.

NLTS: Demagnetization field of the previous transition



- Demagnetization field of the previous transition coincides with the head field direction and expands the write bubble. Transition is written "early". NLTS is typically stronger than HTS since the size of write bubble is larger than the distance between transitions

NLTS: Magnetic fields and equations



$$H_{demag} + H_h(x_0+\Delta) > H_c\ ,$$

$$\Delta = \frac{H_{demag}}{\left(\frac{dH_h}{dx}\Big|_{x=x_0}\right)}$$

- NLTS is proportional to the magnitude of the demagnetization field and inversely proportional to the head field gradient at the transition location

The transition is written at the location $x_0+\Delta$, at which holds:

$$H_{demag} + H_h(x_0+\Delta) > H_c \,, \tag{6.1}$$

where x_0 is the location of the ideal transition without NLTS, Δ is the amount of NLTS.

Assuming that the value of NLTS is small, we can use Taylor series expansion around x_0 and obtain that the value of Δ is proportional to the value of the demagnetization field:

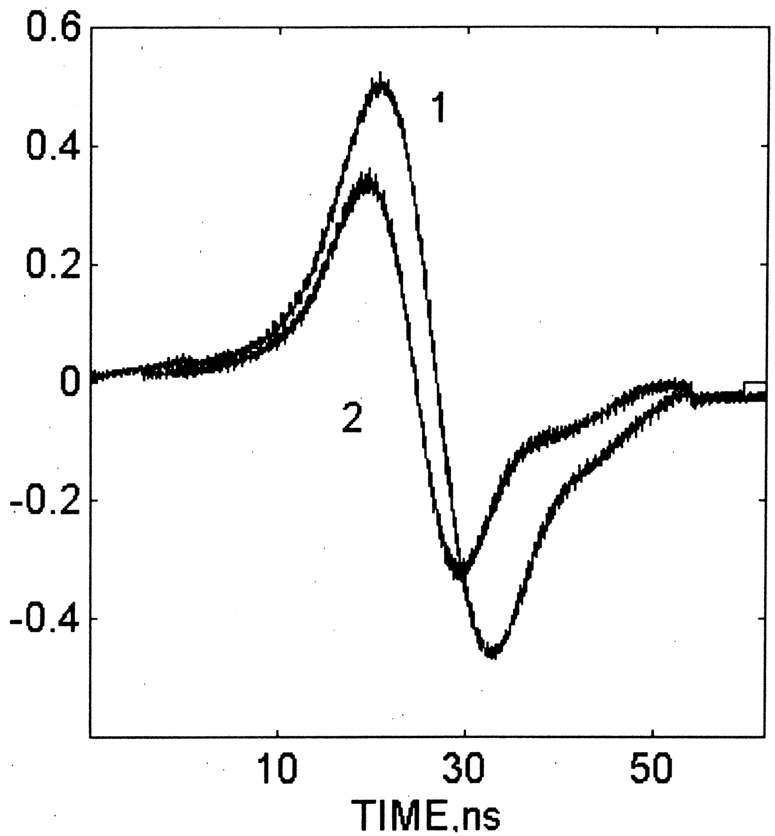
$$\Delta = \frac{H_{demag}}{\left(\frac{dH_h}{dx}\Big|_{x=x_0}\right)} \tag{6.2}$$

The theoretical expression which allows us to estimate the value of NLTS is similar to the equation which was given in Chapter 5 to calculate the value of a Hard transition shift:

$$\Delta = \frac{M_r \delta (d + \delta / 2)}{\pi Q H_c B} F(d, \delta, B) \tag{6.3}$$

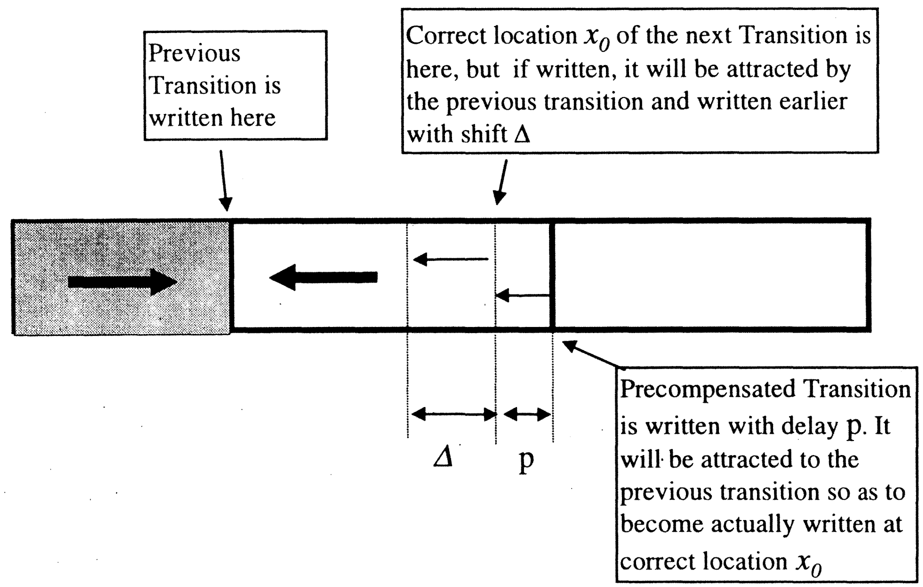
where M_r is remanence medium magnetization, δ is medium thickness, d is head-medium separation, Hc the coercive field of the medium, Q is a numerical factor depending on the head geometry and B is the distance between transitions. Function $F(d, \delta, B)$ depends on head imaging and can be unity to $F(d,\delta,B) = (d+\delta/2)^2 / B^2$. The dependence of NLTS on the distance between transitions is usually described by some power of distance: $\Delta = N(B) \approx K / B^W$, where the power p is experimentally measured. Typical values of W are in the range of 1.5 to 2.5.

NLTS: Effect on Read-Back signal



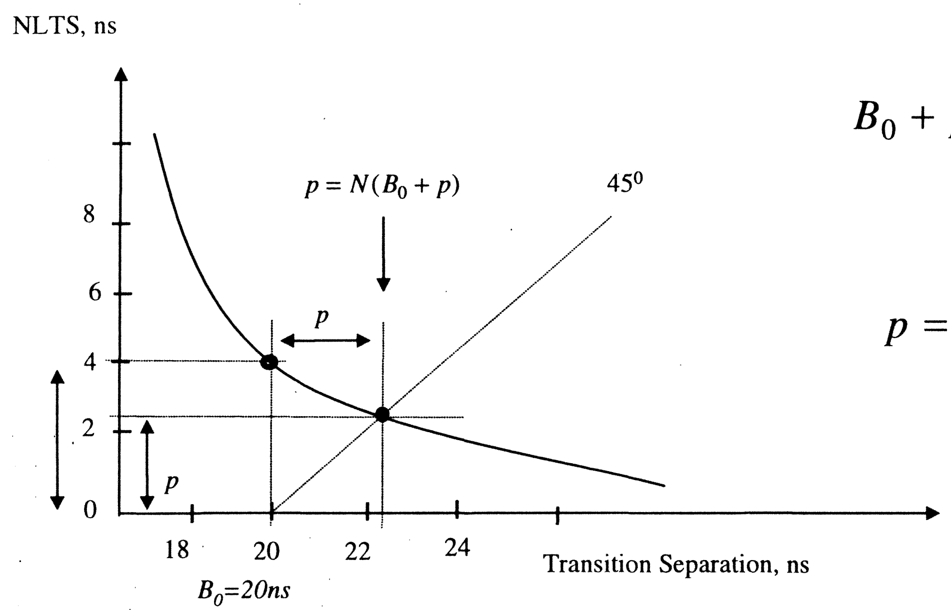
- 1 - as expected from linear superposition
- 2 - 25% of NLTS
- Amplitude loss - mainly due to stronger ISI
- Second transition is moved early
- These distortions are catastrophic for PRML channels - samples are wrong and Maximum Likelihood detector makes a lot of errors.

NLTS: Write Precompensation



- Delay transition during write process if another transition was written one clock early
- Total shift of the second transition should be eliminated

Precompensation parameter

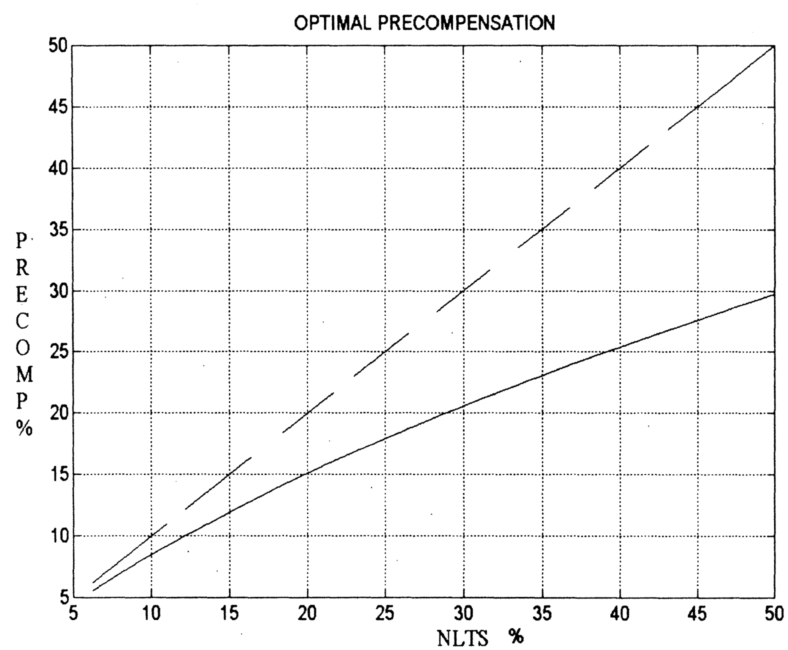


$$B_0 + p - N(B_0 + p) = B_0$$

$$p = N(B_0 + p)$$

- Optimal Precompensation is smaller than the NLTS value

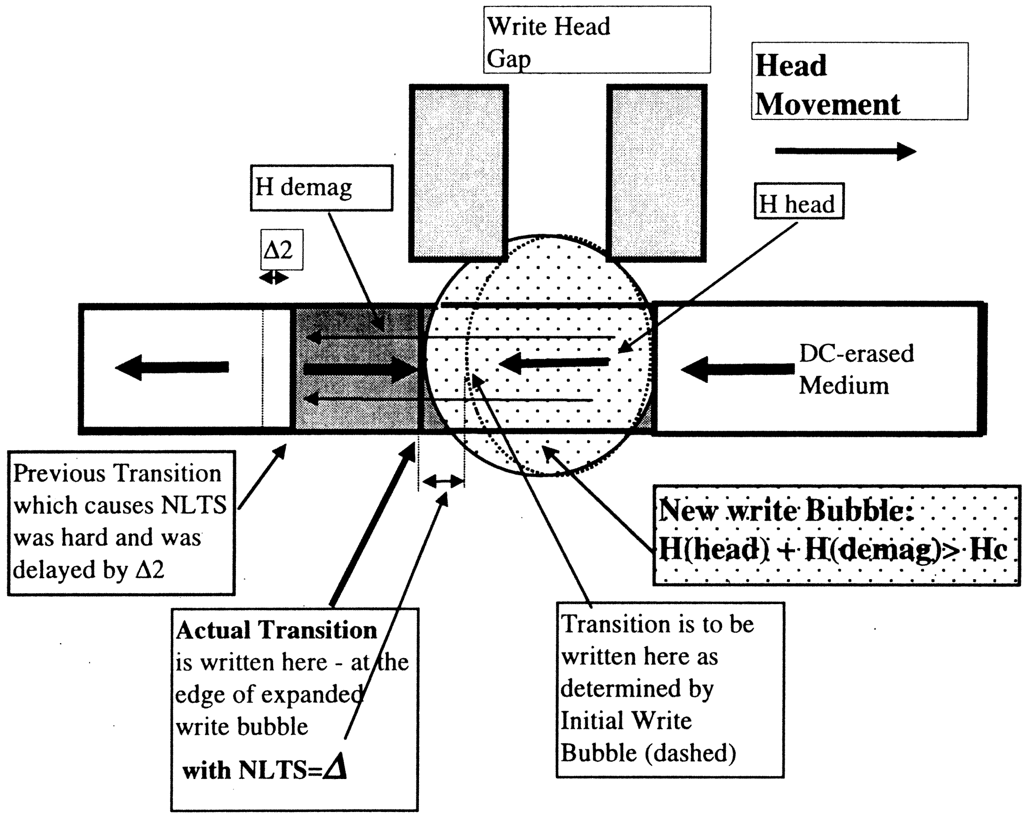
Optimal precompensation and NLTS



NLTS and Hard Transition Shift: Hard/Easy Dibit

- First transition is written late due to HTS ($\Delta 2$)
- Second transition is easy, shifted early by NLTS
- Resulting shift:

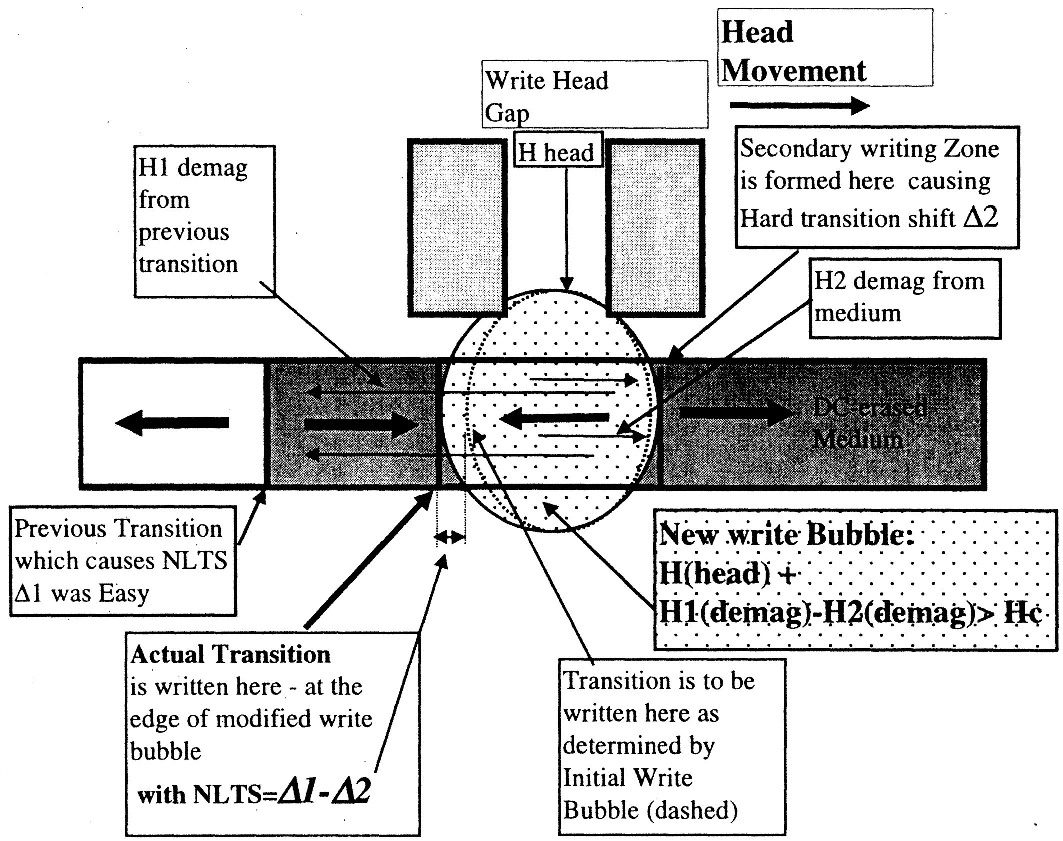
$$\Delta_{H/E} = N(B - \Delta_2)$$



NLTS and HTS: Easy/Hard Dibit

- First transition is easy, not affected
- Second transition is pulled early by NLTS and late by HTS
- Total shift:

$$\Delta_{E/H} = \Delta_1 - \Delta_2$$



NLTS and HTS: Easy/Hard Dibit

The resulting write bubble is determined by the balance of two demagnetization fields and the actual transition will be written at the location, where:

$$H(head) + H1(demag) - H2(demag) > Hc \qquad (6.6)$$

Similar to the analysis presented in section 6.1, if both demagnetization fields are small enough, the resulting shift of the transition:

$$\Delta = \frac{H1_{demag} - H2_{demag}}{\left(\frac{dH_h}{dx} \big|_{x=x_0} \right)} \qquad (6.7)$$

or, equivalently:

$$\Delta_{E/H} = \Delta_1 - \Delta_2 \qquad (6.8)$$

where Δ_1 is the value of NLTS without the hard transition shift and Δ_2 is the value of the hard transition shit. Therefore, for an Easy/Hard (E/H) dibit transition, NLTS and the hard transition shift have opposite directions and resulting transition shift will be smaller than for AC-erased medium.

Hard/Easy and Easy/Hard Dibits: Summary

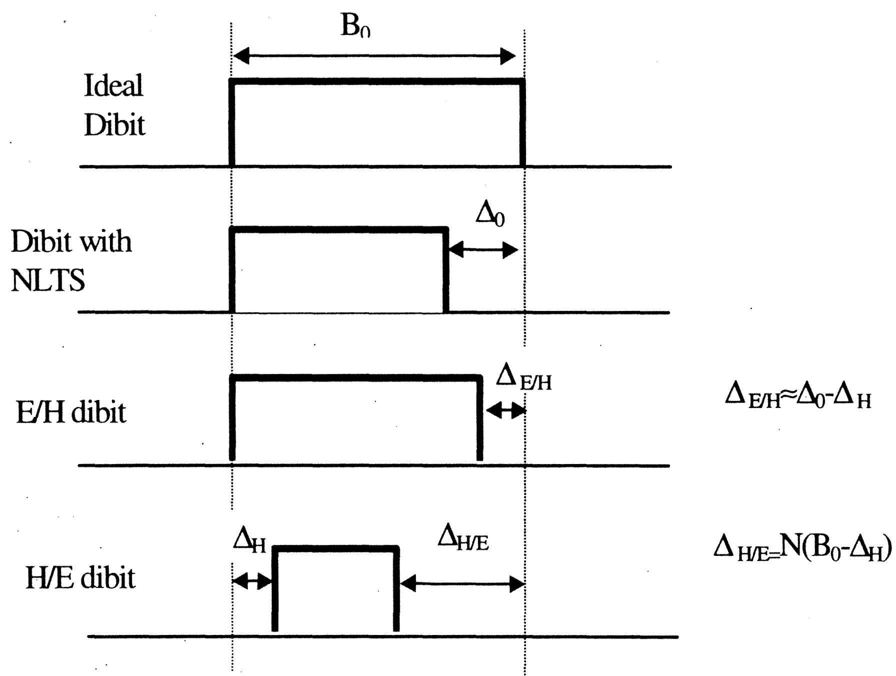
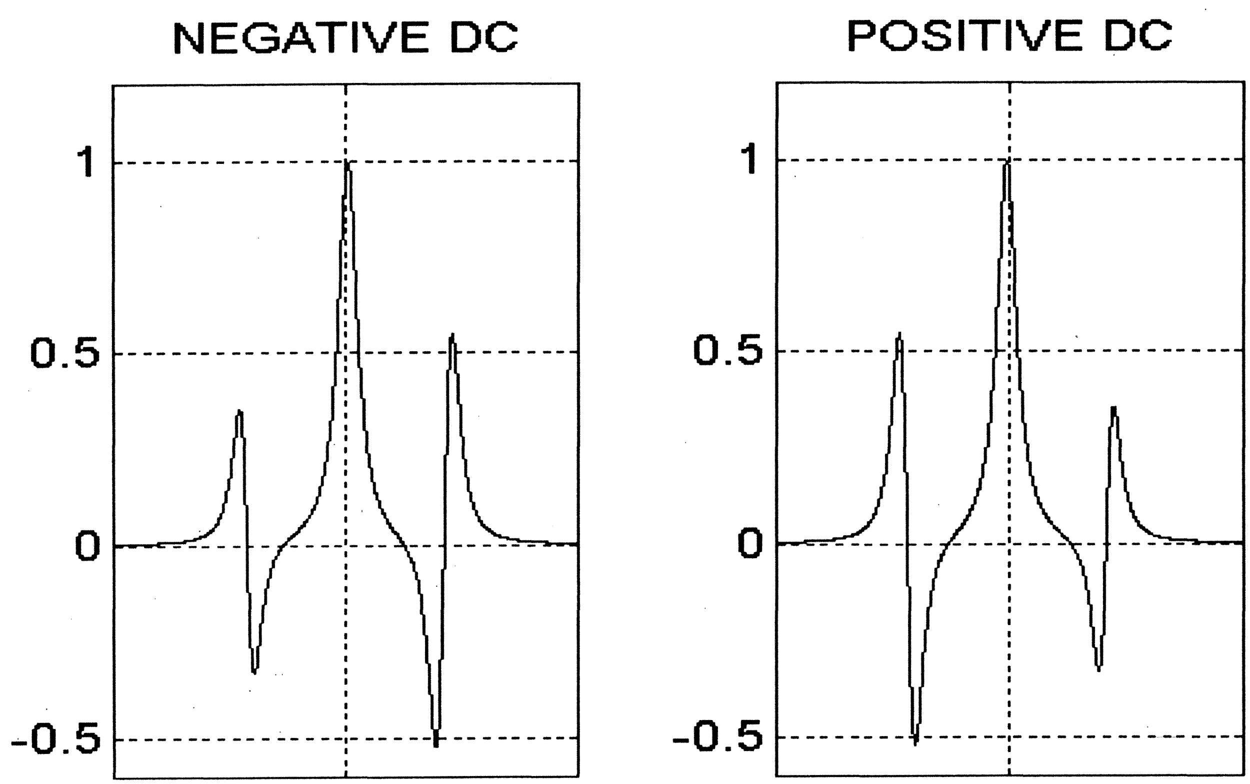
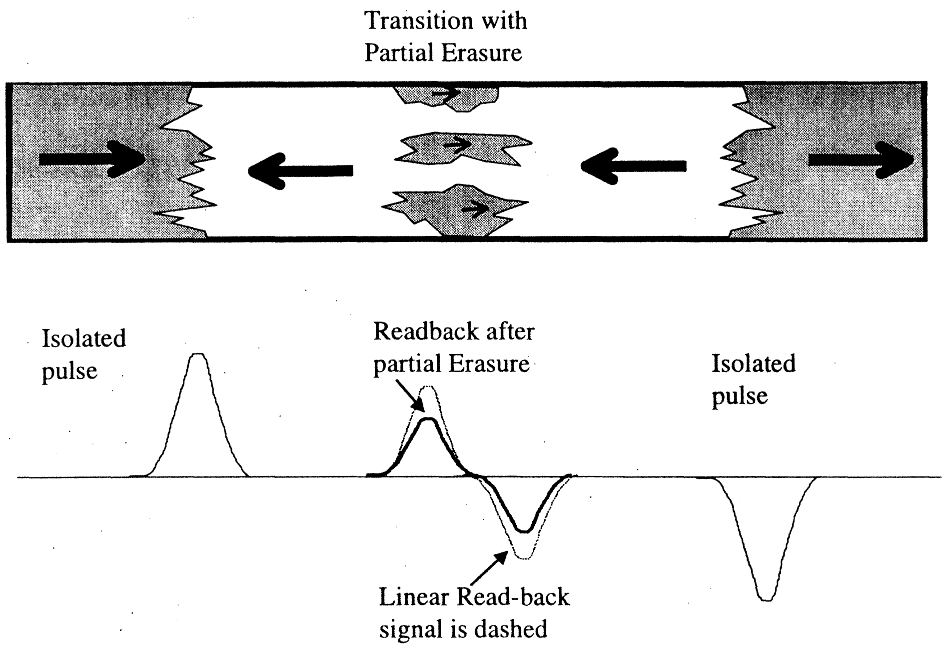


Figure 6.10 Interactions of NLTS with Hard Transition Shift

Hard/Easy and Easy/Hard Dibits: Read-back



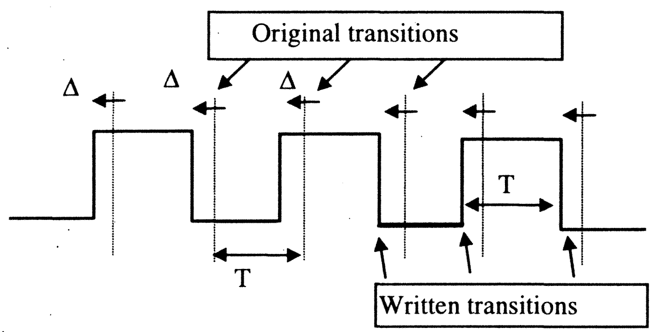
Amplitude Loss (Partial Erasure)



- Transition percolation causes amplitude loss
- Read-back signal: $V_{PE}(x) = (1 - \alpha)V(x)$

Spectral Measurement of Partial Erasure

- Assumption: while PE and NLTS coexist at high density, if a square wave pattern is written, all transitions are shifted equally and, therefore, NLTS does not interfere with measurements



Spectral measurement of Partial Erasure

If a periodic pattern consisting of pulses of alternating polarity with distance between pulses T is written, the spectrum of this pulse sequence consists of odd harmonics at a fundamental frequency of $\omega_0 = 2\pi / 2T$. The shape of this spectrum repeats the shape $P(\omega)$ of continuous spectrum of an isolated transition *p(t)*. The Fourier transform of this readback signal is given by:

$$R_{HF}(\omega) = \omega_0 P(\omega) \sum_{k=odd} \delta(\omega - k\omega_0) \qquad (6.11)$$

Note that the spectrum amplitude is proportional to the pattern frequency $\omega_0 = \pi / T$. Let us write two patterns: low frequency (LF) and high frequency (HF) with different distances between transitions. Now it is easy to demonstrate that in general, at any odd harmonic k (periodic pattern does not contain even harmonics) we have:

$$R_{LF}(k\omega_{LF}) = \frac{1}{k} R_{HF}(\omega_{HF}), \text{ where } \quad \omega_{LF} = \frac{\omega_{HF}}{k} \qquad (6.12)$$

Let $k=3$. The first harmonic of this pattern equals:

$$R_{HF}(\omega_0) = \omega_0 P(\omega_0) \qquad (6.13)$$

Spectral Measurement of Partial Erasure

Let us now compare what happens if we write a pattern with a lower frequency, for example $\omega_0 / 3$. In this case we will look at the third harmonic of the pattern which equals exactly ω_0:

$$R_{LF}(\omega_0) = \frac{\omega_0}{3} P(\omega_0) \tag{6.14}$$

As we see, $R_{LF}(\omega_0) = R_{HF}(\omega_0)/3$. Since this pattern is low frequency, it will not contain NLTS and partial erasure. Therefore, if we measure $3R_{LF}(\omega_0)$ and compare this value to $R_{HF}(\omega_0)$, we can easily estimate amplitude loss:

$$3R_{LF}(\omega_0)(1-2\alpha) = R_{HF}(\omega_0) \tag{6.15}$$

A factor of 2α appears, since in a high frequency pattern each transition has partial erasure from its two neighbors: one to the right and one to the left. Therefore,

$$\alpha = \frac{1}{2} - \frac{R_{HF}(\omega_0)}{6R_{LF}(\omega_0)} \tag{6.16}$$

Partial Erasure measurement: Summary

- Define LF pattern as 100100100… in NRZI encoding, i.e. each “1” is a transition and each “0” is no transition.
- Define NRZI HF pattern as 11111….
- Perform the overwrite test for the frequency ω_0 of the HF pattern (Refer to Section 5.3), i.e. :
  1. Write the LF pattern and measure the amplitude V(LF) on the output of the band-pass filter at ω_0 (or use a spectrum analyzer)
  2. Write the HF pattern and measure its amplitude V(HF) at ω_0.
  3. If steps 1,2 are done using a standard overwrite test, the overwrite ratio OW is calculated as OW=20log(V(HF)/V(LF)).

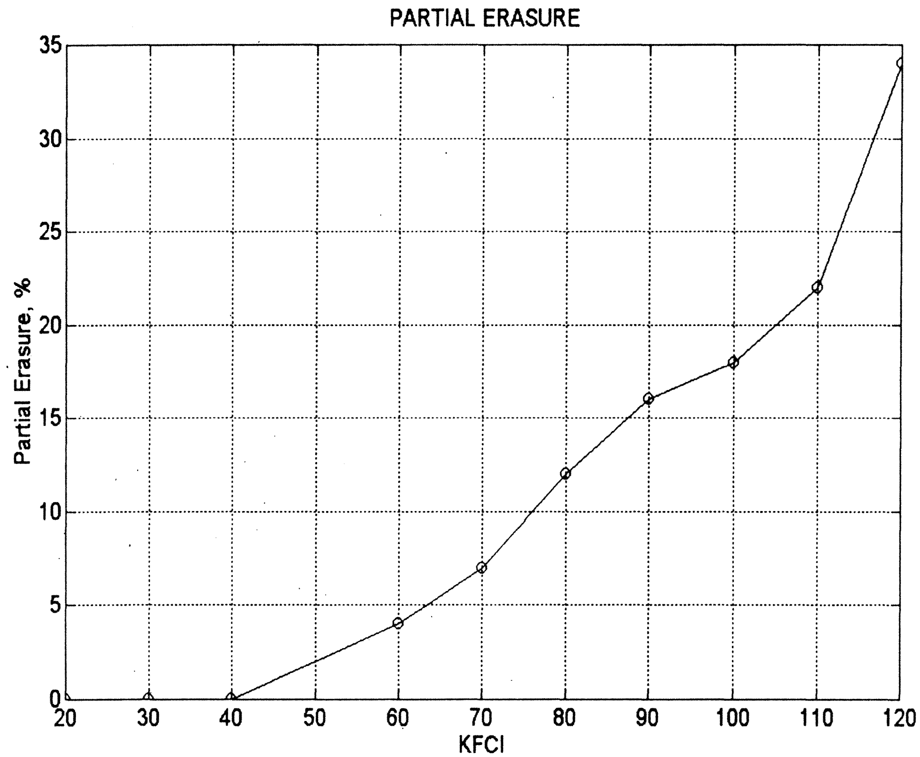
- Calculate amplitude loss as

$$\alpha = \frac{1}{2} - \frac{V(HF)}{6V(LF)} \qquad (6.17)$$

or, if OW value in dB is obtained,

$$\alpha = \frac{1}{2} - \frac{10^{\frac{OW}{20}}}{6}$$

Partial Erasure: Density Dependence



NLTS & Amplitude Loss: References

- A. Armstrong, H.Bertram & J.K. Wolf "Nonlinear Effects in High Density Magnetic Recording" - IEEE Trans. Magnetics, 27, 5, pp. 4366-4376, 1992 - A useful paper describing non-linearities and their models.

- H.Bertram, A. Armstrong & J.K. Wolf "Theory of Nonlinearities and Pulse
- Asymmetry in High Density Magnetic Recording" - IEEE Trans. Magnetics,
- 28, 5, pp. 2701-2706, 1992 - model calculations of NLTS.

- Interactions of NLTS with hard transition shift were first mentioned by C. Tsang, Y.S. Tang " Time Domain Study of Proximity Effect Induced Transition Shifts" - IEEE Trans. Magn. 27, p. 795-802, 1991.

- The most comprehensive paper describing precompensation, partial erasure and spectral measurements of partial erasure is by X.Che "Nonlinearity Measurements and Write Precompensation Studies for a PRML Recording Channel" - IEEE Trans. Magnetics, vol.31, 6, pp.3021-3026, 1995.

NLTS Measurements

- Spectral Elimination (5-th Harmonic) : write simple repetitive pattern, containing dibits and isolated transitions, measure specific harmonics using spectrum analyzer
- Pseudo-Random Sequences (Dipulse Extraction and Time Correlation) - write a special pseudorandom pattern, digitize it with high resolution and perform mathematical analysis (Fourier transform or correlation)

Harmonic Elimination

- Write a special pattern on the disk and measure the amplitude of a particular (e.g. 5-th) harmonic of this pattern $E(kw_0)$. The pattern is constructed in such a way that if the superposition of all pulses is linear, the corresponding harmonic is equal to zero.
- Write a different pattern consisting of transitions with a specified period on the disk and measure the amplitude of the same harmonics of this pattern $X(kw_0)$.
- Compute a value of NLTS, usually as

$$\delta = E(k\omega_0) / [k\omega_0 X(k\omega_0)]$$

Principle of Harmonic Elimination

Periodic pattern y(t), p(t) - isolated pulse

$$y(t) = p(t) - p(t - T_1) + p(t - T_2) - \ldots - (-1)^N p(t - T_N)$$

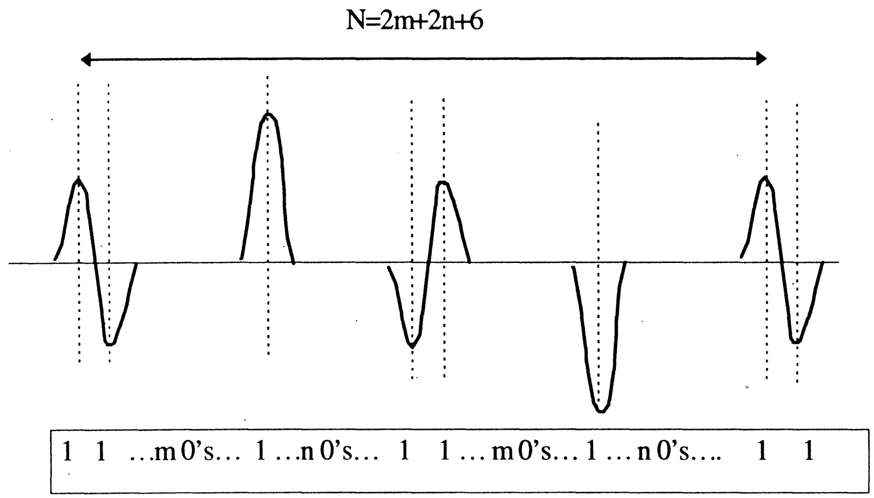
Fourier Transform:

$$Y(\omega) = P(\omega)\left[1 - e^{-i\omega T_1} + e^{-i\omega T_2} - \ldots - (-1)^N e^{-i\omega T_N}\right]$$

At k-th harmonic $Y(kw_0)=0$

$$k\omega_0 = k2\pi / NT$$

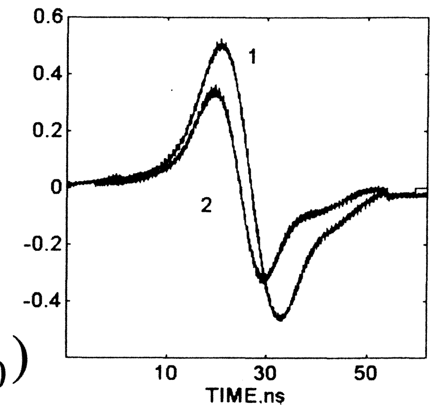
Example of Pattern



- 1100..(m 0's)100..(n 0's)1100..(m 0's)100(n 0's)
- A full period of this pattern equals 2m+2n+6.
- Example: m=n=6, full period N = 30

Error Signal from NLTS

■ Error signal from dibit with NLTS:

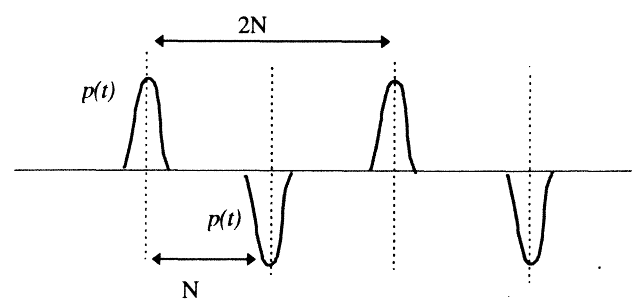


$$e(t) = p(t) - p(t-\Delta) \approx \Delta \frac{dp}{dt}$$

- Spectrum of Error signal:
- Reference signal:

$$E(k\omega_0) = \Delta k\omega_0 P(k\omega_0)$$

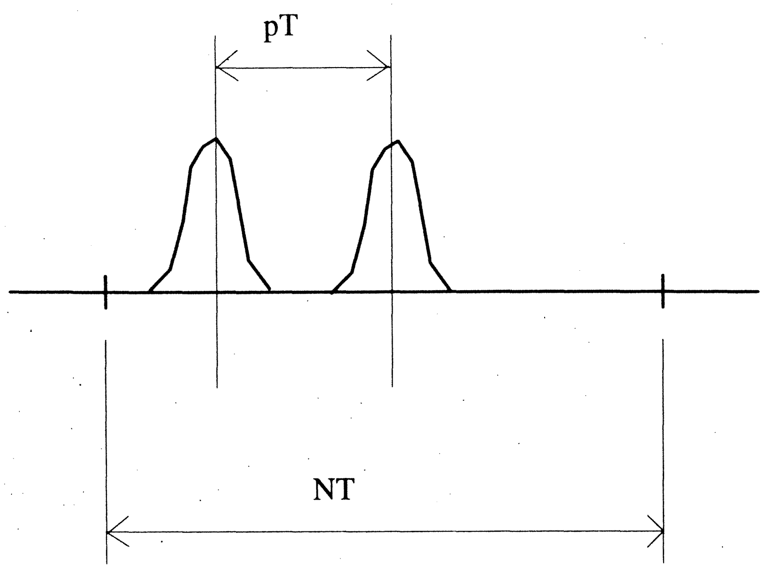
$$R(k\omega_0) = |P(k\omega_0)(1-\exp\{-i\pi\})| = 2P(k\omega_0)$$



■ NLTS value:

$$\Delta = \frac{1}{k\omega_0} \frac{E(k\omega_0)/2}{R(k\omega_0)/2} = \frac{1}{k\omega_0} \frac{E(k\omega_0)}{R(k\omega_0)}$$

Pairs of pulses eliminating k-th harmonic



$$Y(\omega) = P(\omega)(1 + e^{-i\omega pT})$$

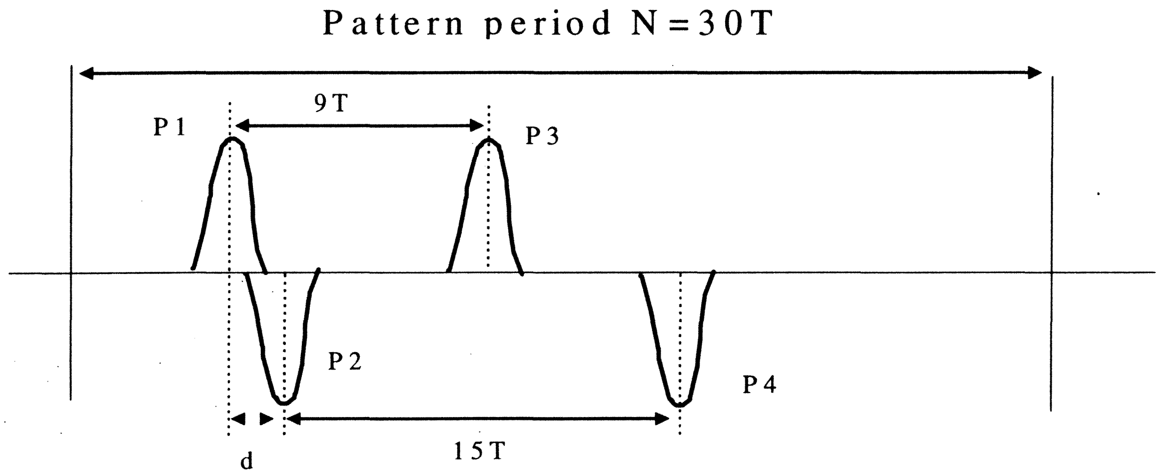
$$Y(k\omega_0) = P(k\omega_0)(1 + e^{-i2\pi \frac{kp}{N}})$$

$$\omega_0 = \frac{2\pi}{NT}$$

$$kp = \frac{2m+1}{2} N$$

- This pair of pulses will result in zero spectrum at:
- We can combine positive and negative pairs of pulses to create harmonic elimination patterns

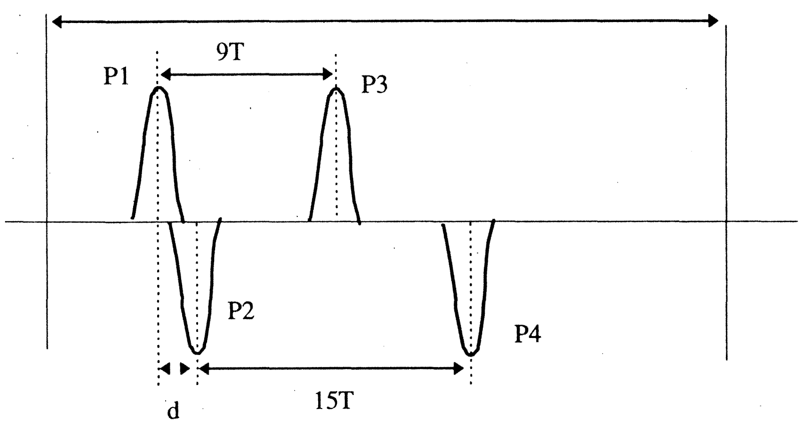
Simple Pattern for NLTS measurements

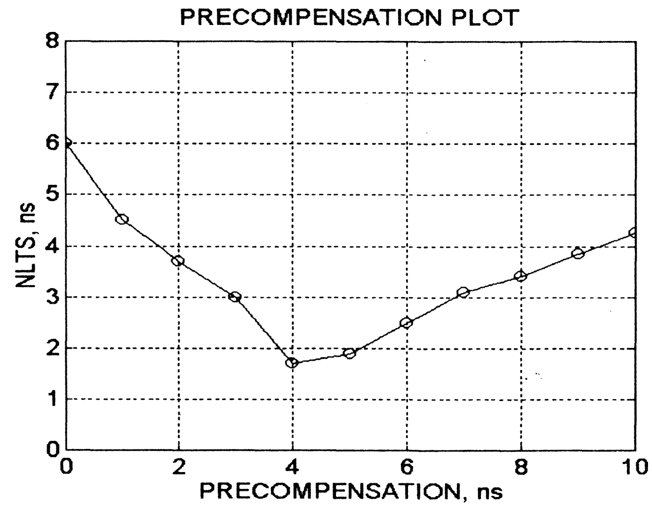


- This pattern conisist of: pair of positive pulses (P1 and P3, distance 9T) and pair of negative pulses (P2 and P4, distance 15T). P1 and P2 form dibit and pulse P2 is distorted by NLTS. Pattern period is 30T

$$\Delta = \frac{1}{k\omega_0}\frac{E(k\omega_0)}{R(k\omega_0)/2} = \frac{2}{k\omega_0}\frac{E(k\omega_0)}{R(k\omega_0)}$$

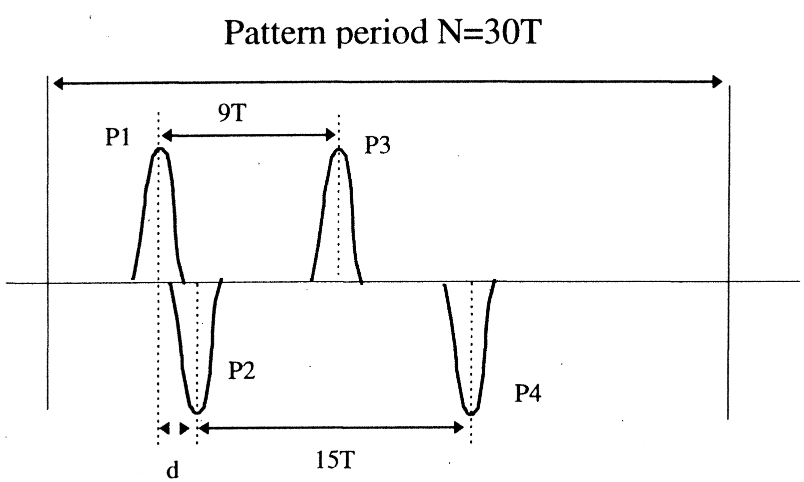
Precompensation Mode

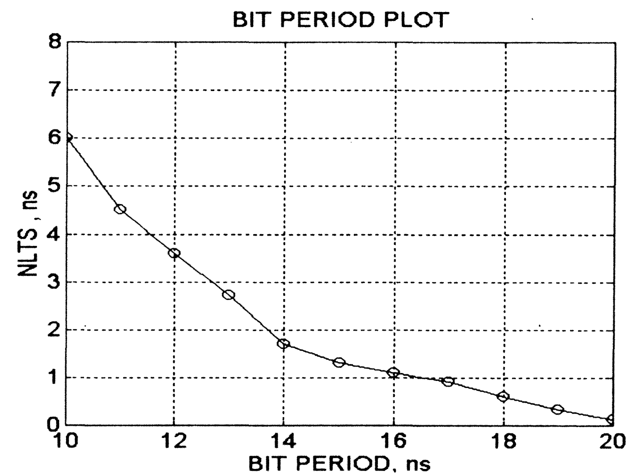




- Delay pulse P2 and Measure amplitude of 5-th harmonic for different delays.
- Minimum point - optimal precompensation for dibit

Bit Period Mode





- Delay pulses P2 and P4 by the same amount
- Measure 5-th Harmonic
- Effectively change bit distance between P1 and P2 while keeping elimination property between P2 and P4

Partial Erasure and 5-th Harmonic measurement

Let us consider what happens with the read-back signal for a pattern shown in Figure 7.4 when it contains amplitude loss α due to partial erasure. The dipulse signal distorted by both NLTS and PE is given by:

$$f(t) = (1-\alpha)p(t) - (1-\alpha)p(t - T + \Delta) \qquad (7.15)$$

The error signal (the difference between the ideal dipulse and the signal given by (7.15)) generated by this dipulse is:

$$e(t) \approx \alpha p(t) - \alpha p(t - T) + (1-\alpha)\Delta \frac{dp}{dt} \qquad (7.16)$$

The spectrum of the error signal is, correspondingly:

$$E(\omega) = P(\omega)\left(\alpha - \alpha e^{-i\omega T} + i\Delta(1-\alpha)\omega\right) \qquad (7.17)$$

At k-th harmonic $E(k\omega_0) = P(k\omega_0)\left(\alpha - \alpha e^{-ik\omega_0 T} + i\Delta(1-\alpha)k\omega_0\right)$.

Partial Erasure and 5-th Harmonic measurement

Eq. (7.17) is used to calculate plots shown in Figure 7.8. This figure is a dependence of the measured value of NLTS using 5-th harmonic on actual value of NLTS versus different amounts of partial erasure (0% to 50% with 5% steps)

As seen, both NLTS and partial erasure will affect spectral elimination results. For example if 20% NLTS and 20% amplitude loss are present in the signal, the spectral method will measure approximately 35% of NLTS. On the other hand, if NLTS is absent, the measured signal will be completely due to partial erasure.

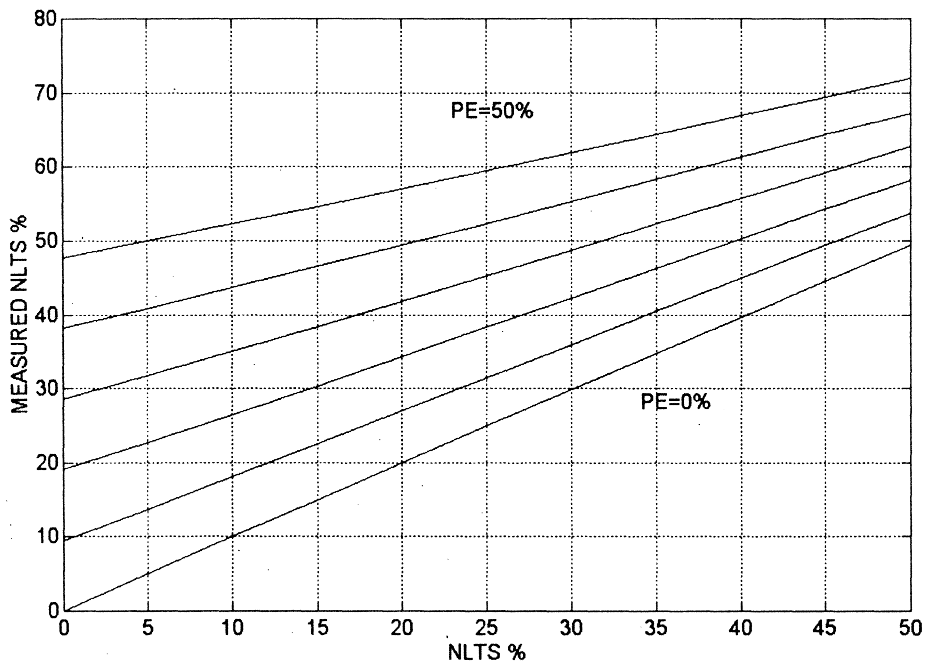
When dibit separation is proportional to the total length of the harmonic elimination pattern, k=5, N=30, we can obtain a simplified expression for (7.17), where:

$$E(k\omega_0) = P(k\omega_0)\left(\alpha - \alpha e^{-i\frac{\pi}{3}} + i\Delta(1-\alpha)k\omega_0 \right) \qquad (7.18)$$

To find an absolute value we find the squares of real and imaginary parts in (7.18) substituting $\cos(\pi/3) = 1/2$ and $\sin(\pi/3) = \sqrt{3}/2$. If we discard all cross-terms having products of either Δ^2 or α^2, assuming that their values are small, (7.18) approximately equals:

$$|E(k\omega_0)| = |P(k\omega_0)|\sqrt{\alpha^2 + \frac{\pi^2}{9}\Delta^2 + \frac{\pi}{3}\Delta\alpha} \qquad (7.19)$$

Influence of Partial Erasure on 5-th harmonic



Separating NLTS and Partial Erasure

$$Z = \left(\frac{E(k\omega_0)}{P(k\omega_0)} \right)^2$$

$$A = (1-\alpha)^2 (k\omega_0)^2$$

$$B = (2\alpha(1-\alpha)k\omega_0 \sin(k\omega_0 d)$$

$$C = \alpha^2 (1-\cos(k\omega_0 d))^2 + \alpha^2 \sin^2(k\omega_0 d) - Z$$

$$A\Delta^2 + B\Delta + C = 0$$

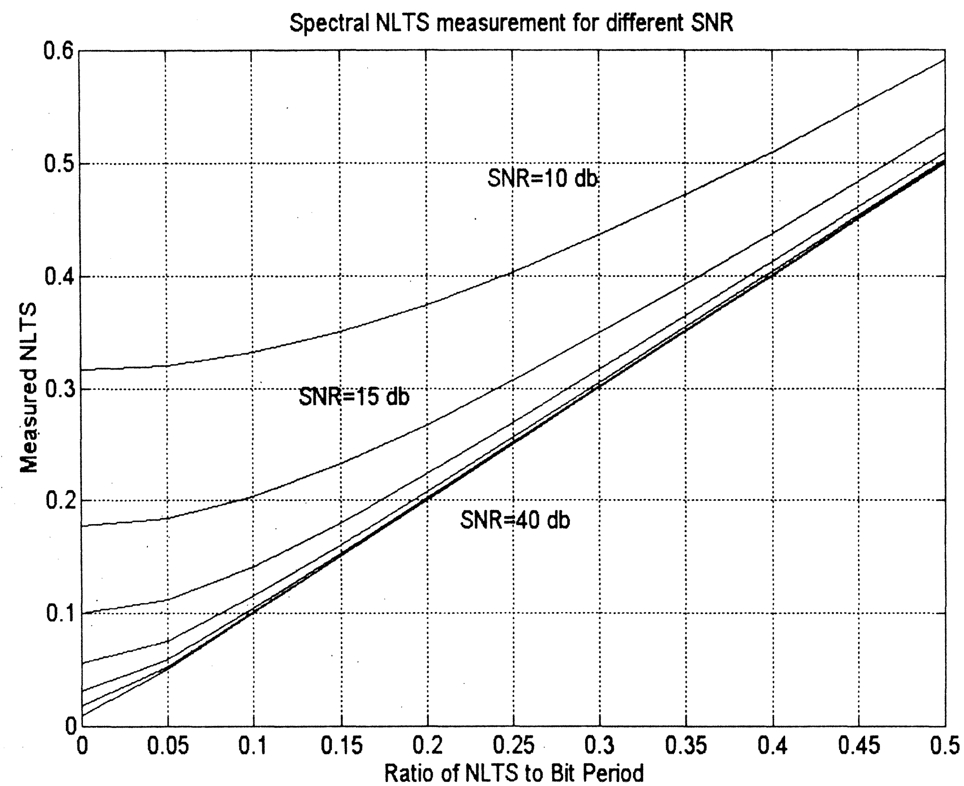
$$\Delta = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

Let d=T, k=5, ω_0 =2π/30T. The measured value of α=0.2. Amplitude of the error signal $E(k\omega_0)$ from a single dibit equals 6mV. Amplitude of the reference pattern consisting of isolated pulses with distance between pulses 15T equals 40mV, therefore $P(k\omega_0)$=20 mV. We find:

Z=0.098, A=0.7,B=0.29,C= -0.058

From here the estimated value of Δ=14.8%. At the same time, direct measurement will predict almost 29% of NLTS.

Influence of Noise on 5-th harmonic



Pseudo Random Sequences

- Write a pseudo-random sequence on disk
- Sample a full period of read-back signal with high resolution analog-to-digital converter (ADC)
- Process resulting digital signal using either Discrete Fourier Transform or Correlation analysis
- Polynomial x^7+x^3+1: 127 bits sequence $y(i+7)=XOR\{y(i),y(i+3)\}$

10000001 00010011 00010111 01011011 00000110 01101010
01110011 11011010 00010101 01111101 00101000 11011100
01111111 00001110 11110010 1100100

Shift and Add Property

- Product of 2 elements of PRBS is the same sequence with some shift XOR(y(k),y(k+p)) = y(k+M)
- XOR is equivalent to product of NRZ bits

a1	a2	product of a1*a2	compare with	x1	x2	XOR $x1 \oplus x2$
+1	+1	+1		0	0	0
-1	-1	+1		1	1	0
+1	-1	-1		0	1	1
-1	+1	-1		1	0	1

- When NLTS is present, it creates the terms proportional to product of several bits , e.g. a(k-1)a(k)a(k+1).
- Read-Back voltage is approximately $V_0(t)+kV_0\ (t+M)$
- M=25.5 ; k is proportional to NLTS

Theory of the dipulse extraction method

Let us write a readback voltage from the head as the following sum:

$$V(t) = \frac{1}{2}\sum_k [a(k+1) - a(k)]h(t+kT) \qquad (7.31)$$

Here *h(t+kT)* describes the shape of an isolated pulse. Indeed, if pattern is defined in NRZ terms, the transition corresponds to a change from +1 to -1 magnetization (negative read-back pulse) or to a change from -1 to +1 magnetization (positive read-back pulse). If NLTS equal to Δ is present, readback can be written in the following way:

$$V(t) = \frac{1}{2}\sum_k [a(k+1) - a(k)]h(t + kT - \frac{\Delta}{4}[a(k+1) - a(k)][a(k) - a(k-1])) \qquad (7.32)$$

If at least one of the differences *a(k+1)-a(k)* or *a(k)-a(k-1)* is equal to zero, (7.32) becomes equal to linear signal (7.31). However, if the current transition is preceded by the previous one, the term Δ is added to the delay of the *h(t+kT)* and NLTS is present.

Theory of the dipulse extraction method

A similar trick is used to include different non-linearities into Eq.(7.32). For example, Hard/Easy transition shift equal to value ε is described by the term $-\frac{\varepsilon}{2}+\frac{\varepsilon}{4}[a(k+1)-a(k)]$. For a particular polarity of the transition, the difference of *a(k+1)-a(k)* = *2* and the resulting shift is zero. For a different polarity of transition the shift equals to $\boldsymbol{\varepsilon}$.

The next step in analyzing Eq.(7.32) is to expand the function *h(t)* into the Taylor series around *t+kT* . The Taylor Series expansion results in quadratic terms of pseudorandom sequence coefficients. After a sequence of mathematical transformations which could be found in the original paper by Palmer et.al., it appears that the main contribution into the playback signal is introduced by the cross-terms of the pseudorandom sequence. For example, the dominant contribution for NLTS is given by the term *a(k-1)a(k)a(k+1)* . For the polynomial x^7+x^3+1 this term causes the shift of M=-25 bit periods. The resulting waveform is approximately written as:

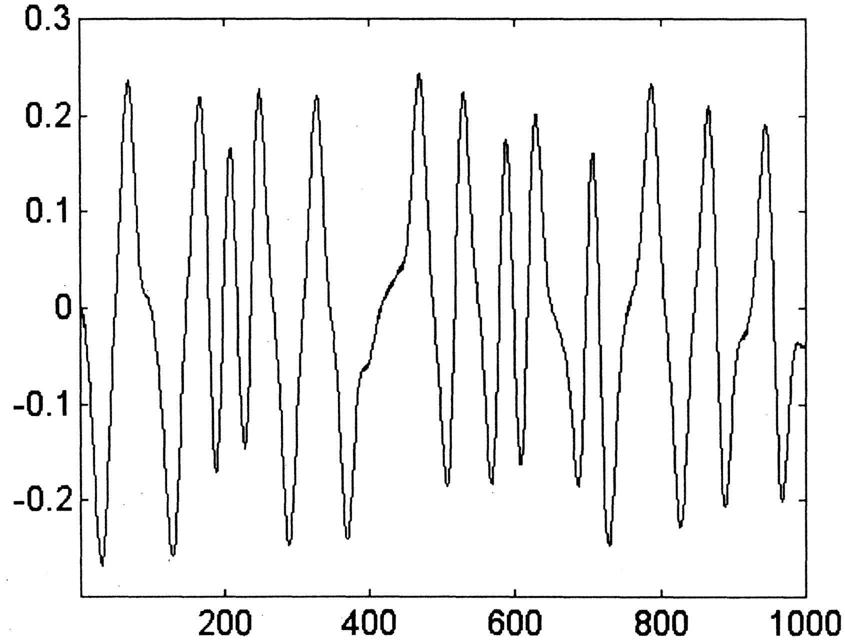
$$V(t) \approx V(t+\frac{\Delta}{2})+\frac{\Delta}{2T}V(t+\frac{\Delta}{2}-\frac{3T}{2})-\frac{\Delta}{2T}V(t+\frac{\Delta}{2}+[M-\frac{1}{2}]T) \qquad (7.33)$$

As seen from Eq.(7.33), the read-back signal consists of its several delayed and shifted versions (echoes). Several echoes are created by NLTS, (main, delayed by 1.5T and 25.5 bit periods).

Dipulse Extraction Method

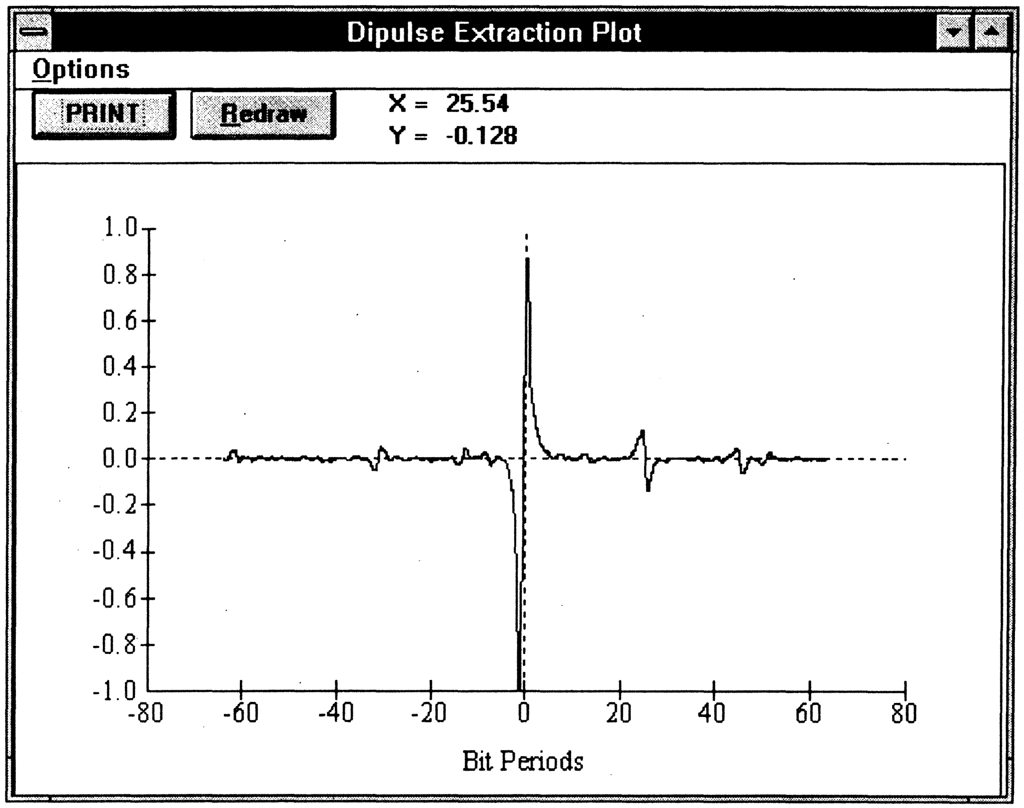
- Write Pseudorandom Sequence on Disk
- Digitize and extract read-back signal from exactly one period of this sequence
- Resample Data to obtain N samples per bit period
- Create oversampled NRZ sequence of the same length
- Calculate Fourier Transform of Read-back data
- Divide it by Fourier Transform of the NRZ sequence
- Obtain Dipulse Plot. If NLTS=0, echo at 25.5 bit periods is absent
- NLTS/T = 2(amplitude of echo)/(amplitude of main dipulse)

Pseudo-random sequence Read-Back



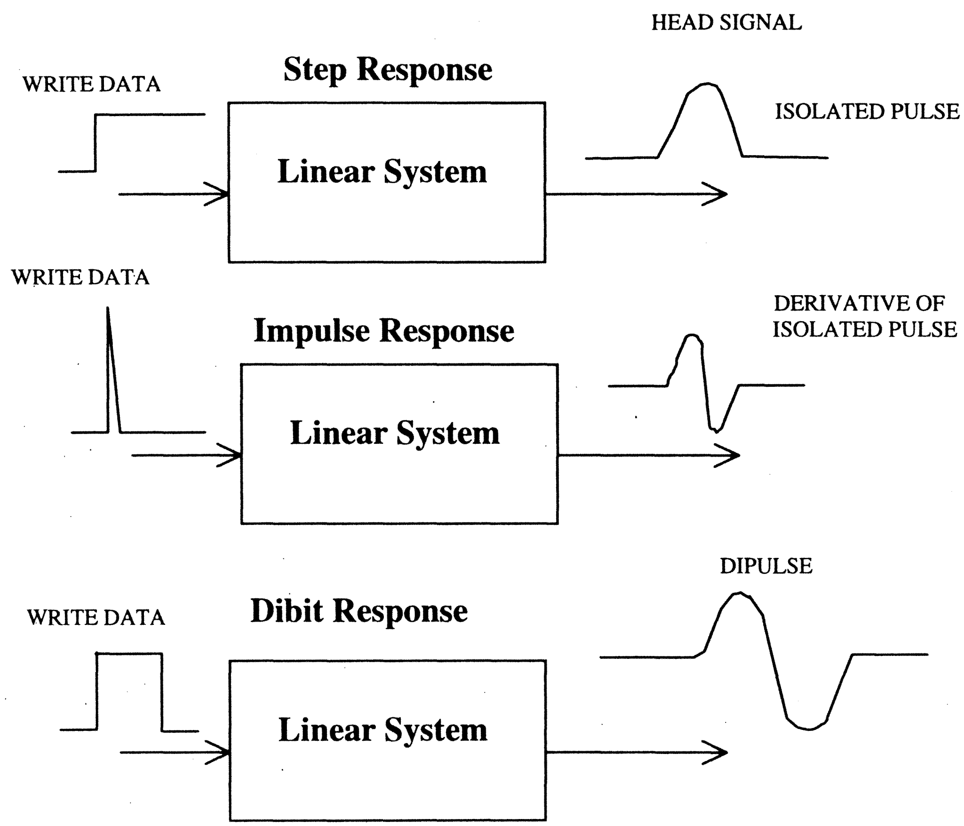
- Exactly one full period of the pseudorandom sequence should be captured

Dipulse Extraction Plot (WITE software)

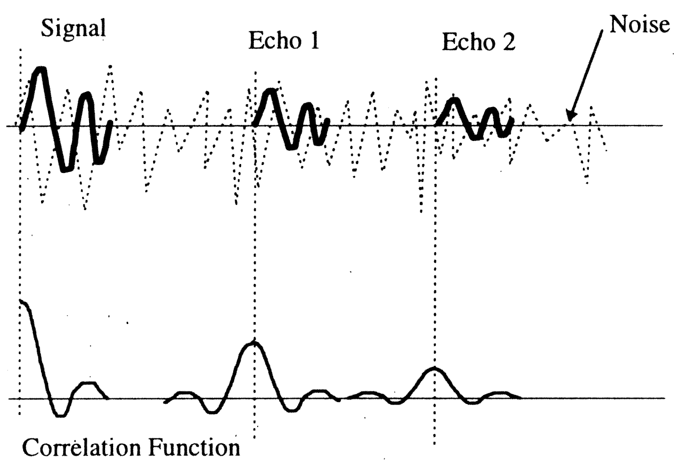


Meaning of Dipulse Plot

Methods for Characterization of Linear Systems



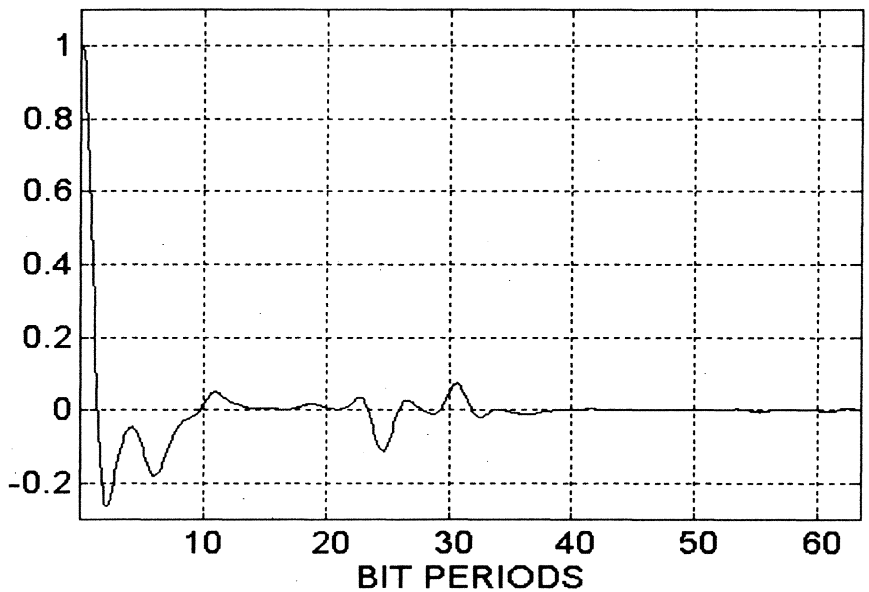
Method of Time Correlation



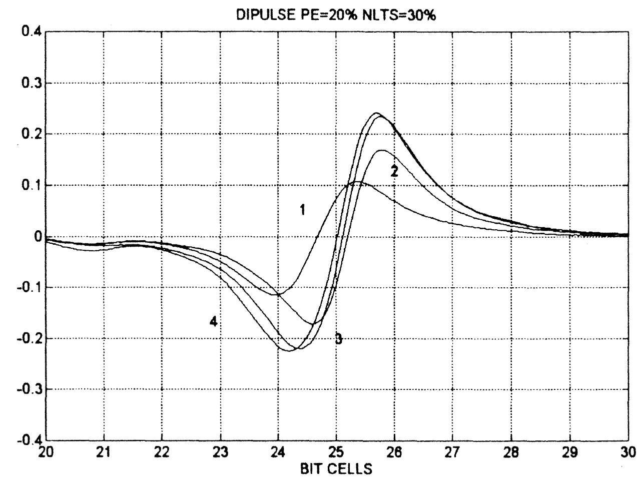
Algorithm of Time Correlation measurement

- Write a pseudorandom sequence
- Digitize at least two full periods of this sequence V(t) and V(t+NT)
- Calculate their cross-correlation function R(u)=R(V(t),V(t+NT+u))
- SNR =R(0)/(1-R(0))
- Peak of R(d) at d=25.5T corresponds to NLTS
- NLTS/T= -2R(d)(1+1/SNR)

Time Correlation Plot

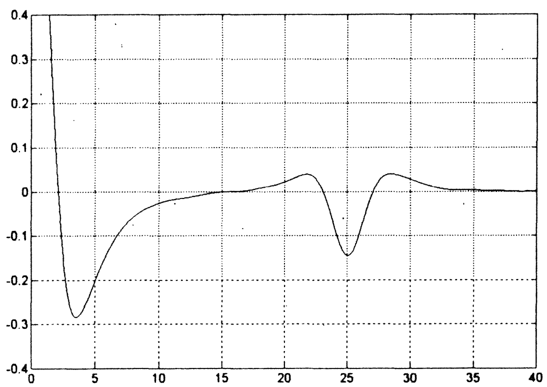


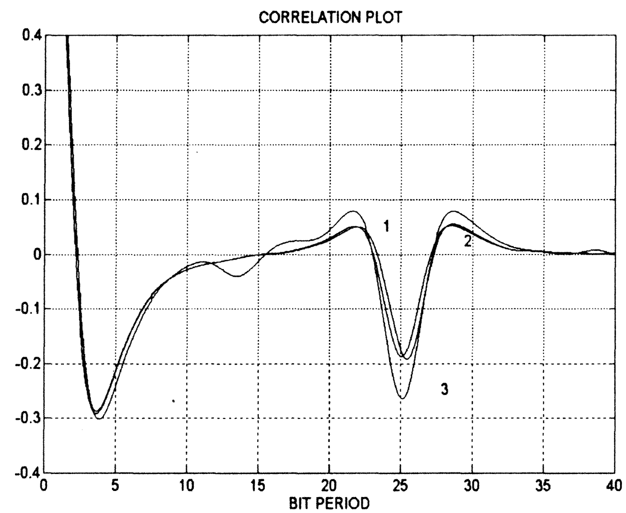
Partial Erasure and Dipulse Extraction



- Echo of PE is 1/2T away from NLTS echo (left figure)
- Superposition of echoes is almost linear:1 - PE=20% NLTS= 0%; 2- PE=0%, NLTS=30%; 3 - PE=20%, NLTS=30%; 4 - sum of echoes 1 and 2 (right figure)

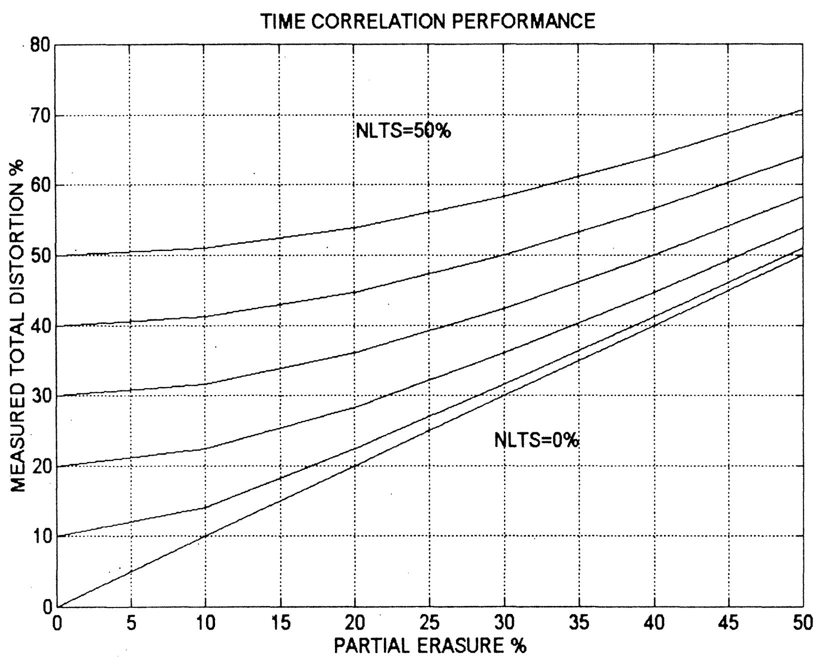
Partial Erasure and Time Correlation



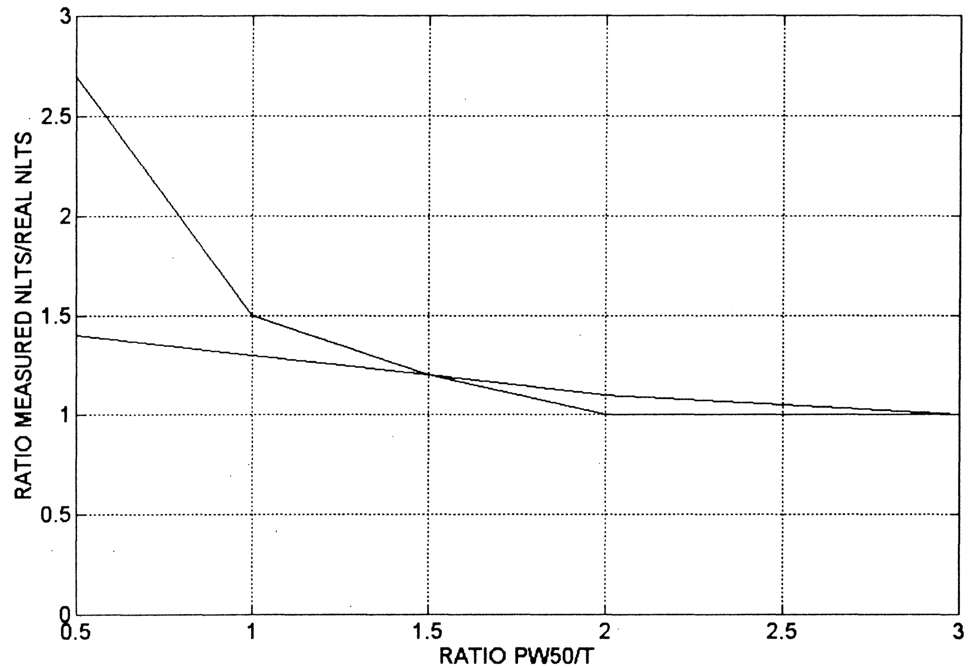


- Partial Erasure Echo is 1/2T away from NLTS echo (left figure)
- Superposition of NLTS and PE echoes is non-linear (right figure): 1- 30% PE and 0% NLTS ; 2- 0% PE and 30% NLTS ; 3- 30% NLTS and 30% PE

Mix of PE and NLTS in Time Correlation method



Influence of PW50 on Pseudorandom methods



Dipulse extraction is more critical to PW50 than Time Correlation

NLTS Measurements: Summary

- Harmonic elimination methods are relatively simple to implement
- Harmonic elimination method measures NLTS for a dibit transition
- Harmonic elimination methods may predict optimal precompensation parameter and dependence of NLTS on bit period
- Pseudorandom methods are complicated
- Pseudorandom method measure NLTS for random pattern
- All NLTS measurement methods are affected by partial erasure
- If Partial Erasure is measured, it can be separated from 5-th harmonic measurement

NLTS Measurements: References

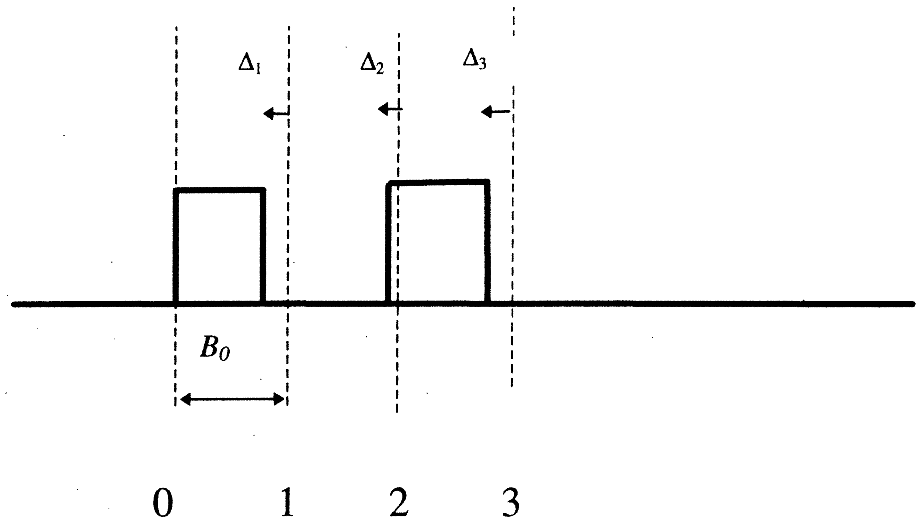
- Harmonic Elimination methods are described by:
- Y. Tang, C. Tsang " A Technique for Measuring Non Linear Bit shift" - *IEEE*
- *Trans. Magn.*, 27, 6, pp. 5316-5318, 1991. First paper describing method of
- harmonic elimination for NLTS measurement.
- X.Che, M.J.Peek and J.Fitzpatric "A Generalized Frequency Domain
- Nonlinearity Measurement Method" - *IEEE Trans. Magn.* Vol.30,6, p.4236,1994
- Description of the second method of harmonic elimination
- X.Che "Nonlinearity Measurements and Write Precompensation Studies for a PRML Recording Channel" - *IEEE Trans. Magnetics*, vol.31, 6, pp.3021-3026, 1995 - a description of the harmonic elimination method and the influence of partial erasure on harmonic elimination.
- Pseudo-random algorithms and dipulse extraction method are discussed in

- D. Palmer, P. Ziperovich et al "Identification of Non Linear Write Effects
- Using Pseudorandom Sequences" - *IEEE Trans. Magn*, 23,5, pp. 2377-
  - 2379, 1987 -Original paper describing Dipulse Extraction method. All mathematics is concentrated in the Appendix and is given almost without explanations. Requires significant effort to read and follow the authors.

NLTS Measurements: References

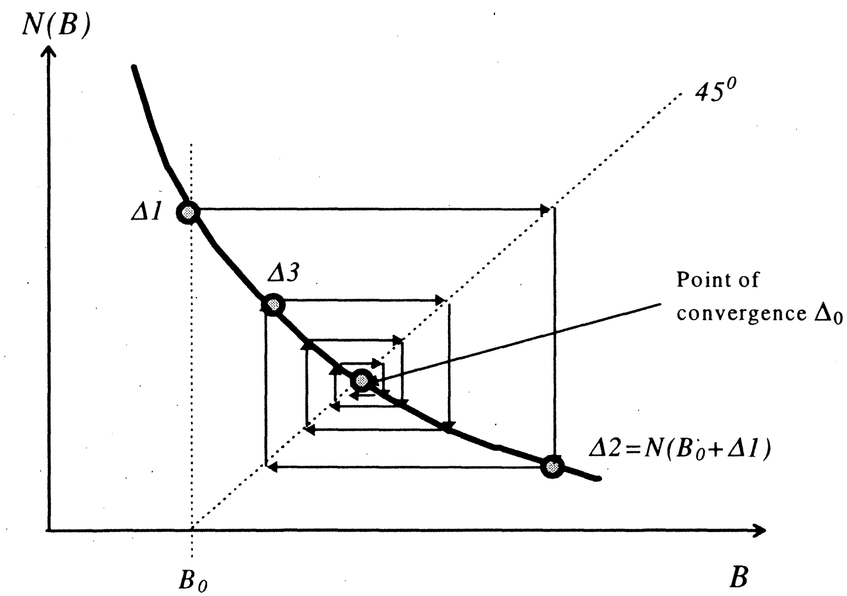
- P. Newby and R. Wood "The effects of Nonlinear Distortion on Class IV
- Partial Response' - *IEEE Trans. Magnetics*, 22,5, pp.1203-1205, 1986 - First
- paper describing application of pseudo-random sequences to study influence of
- NLTS on the quality of PRML signal.
- X.Che and P.Ziperovich "A Time Correlation Method of Calculating Nonlinearities
- Utilizing Pseudorandom sequences" - *IEEE Trans. Magnetics*, vol.30,6, p.4239, 1994
- -This paper presents a description of the time domain correlation method, in particular
- the dependence of results on PW50 of the pulse is studied.
- G. Mian and T. Howell "Determining a Signal to Noise Ratio for an Arbitrary Data
- Sequence by a Time Domain Analysis" - *IEEE Trans. Magn.*, vol. 29,6, p.3999,
- 1993 - Original paper describing the principles of correlation analysis for SNR
- measurement
- G.Mian "An Algorithm for a Real Time Measurement of Nonlinear Transition
- Shift by a Time Domain Correlation Analysis" - *IEEE Trans. Magnetics*, January
- 1995 - Original paper describing the principle of Time domain correlation NLTS
- measurement

Interactions between Transitions

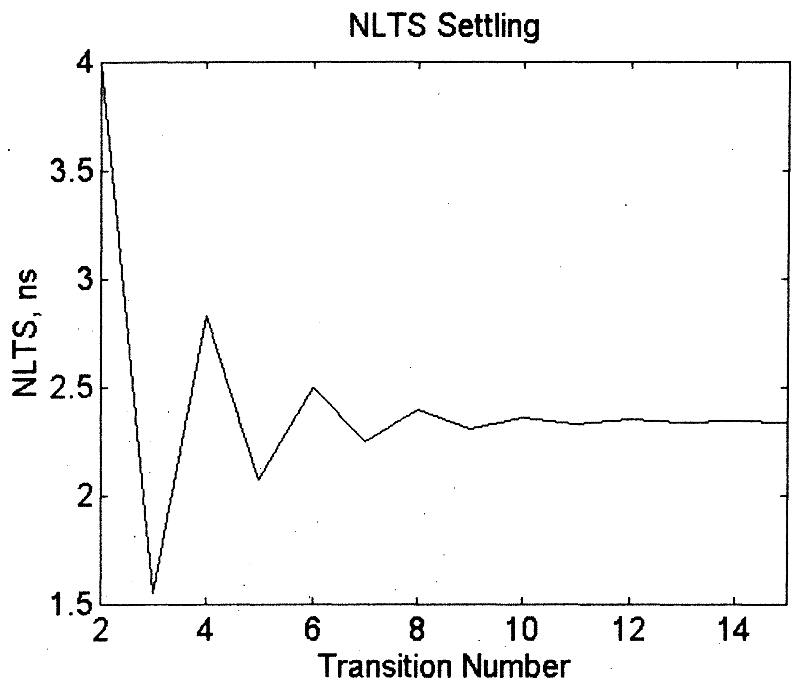


- NLTS(2) is large, NLTS(3) is smaller, NLTS(4) is again larger
- NLTS depends on several previous transitions
- Different NLTS levels for each transition in a series???

Finding NLTS for a Series of Transitions



NLTS settling for a series of transitions



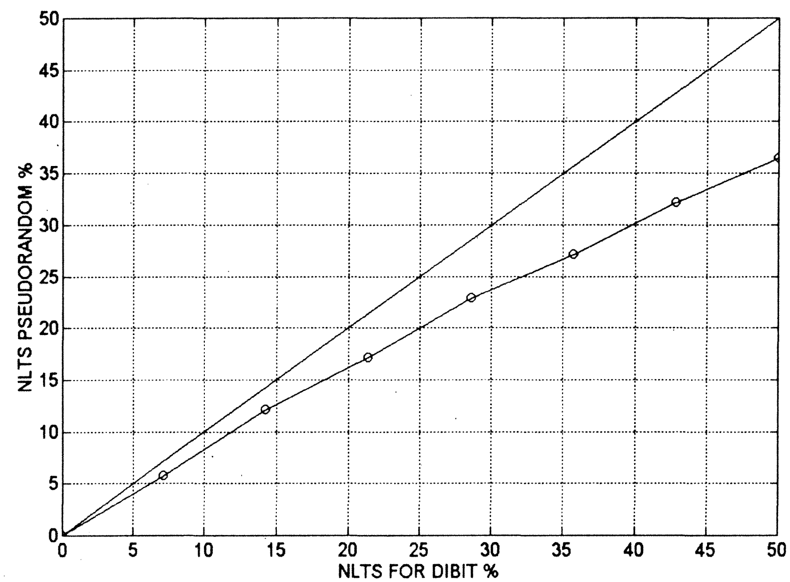
$$\Delta(k) = \sum_{m=1}^{k} (-1)^{m+1} N[mB_0 + \Delta(k-m)]$$

Dibit NLTS vs NLTS for Random Pattern

- $x7+x3+1$ polynomial contains total of:
- 8 dibit transitions
- 4 tribit transitions (3 adjacent transitions)
- 2 series of 4 adjacent transitions
- 1 sequence of 5 adjacent transitions
- 1 sequence of 7 adjacent transitions.
- Total we have:
- 16 transitions with value of (2)
- 8 transitions with value of (3)
- 4 transitions with value of (4)
- 2 transitions with value of (5)
- 1 transitions with value of (6)
- 1 transitions with value of (7)
- When echo is measured

$$\Delta = \frac{16\Delta(2)+8\Delta(3)+4\Delta(4)+2\Delta(5)+\Delta(6)+\Delta(7)}{32}$$

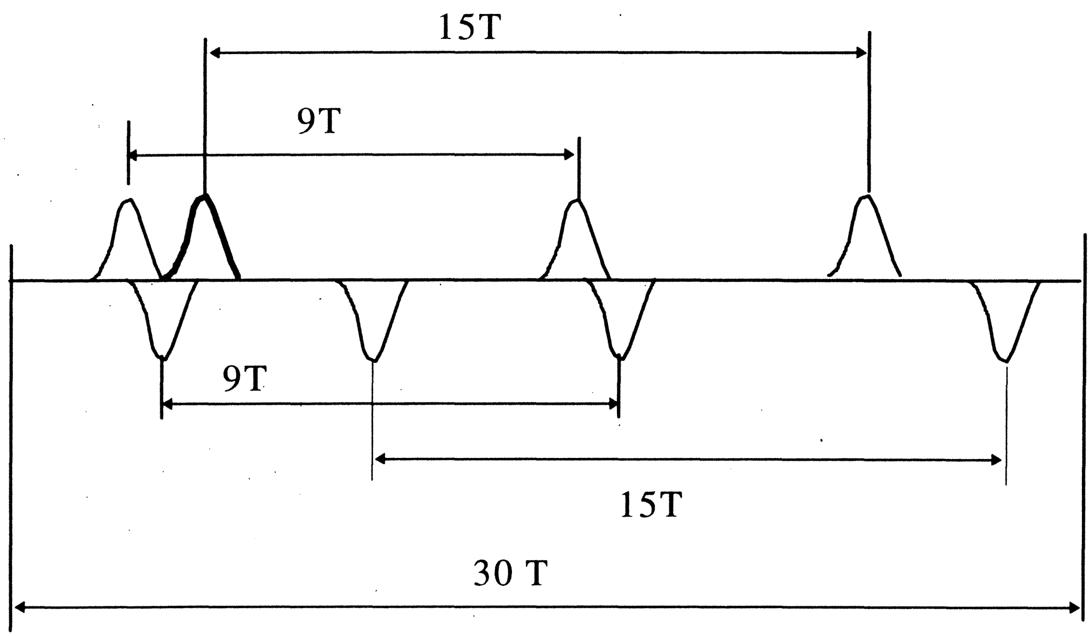
5-th harmonic NLTS vs Pseudorandom NLTS



Interactions with Hard Transition Shift

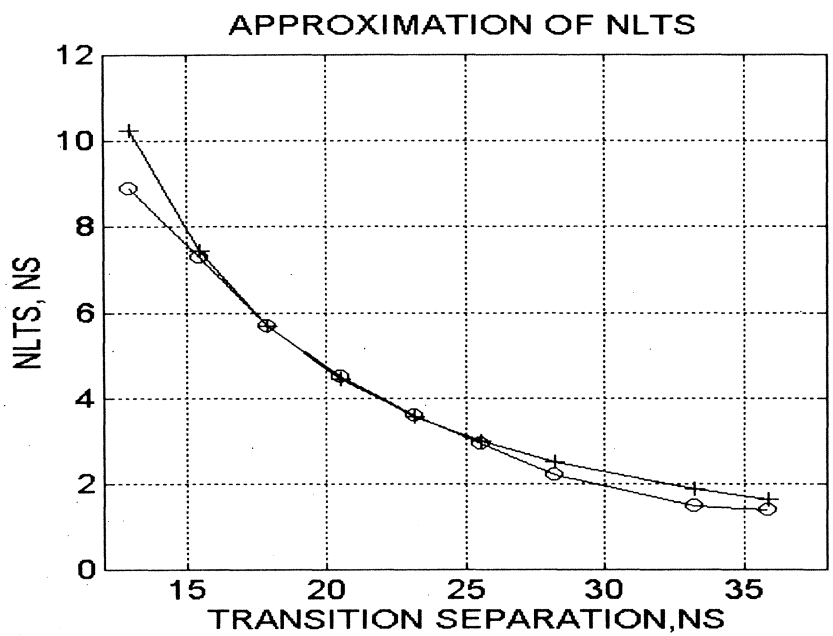
- Easy Transition is affected by previous Transitions
- Hard Transition is affected by previous transitions and by hard transition shift
- NLTS for a series of transitions will never settle
- Transition shift oscillations are larger than the values of hard transition shift (T=16ns, Hard shift= 1ns, NLTS=4ns, oscillations are 2.5 ns)
- Oscillations are different depending on whether the first transition in a train of transitions is hard or easy
- Serious problem: precompensation is not effective

Spectral Measurement of Individual Transition Shift



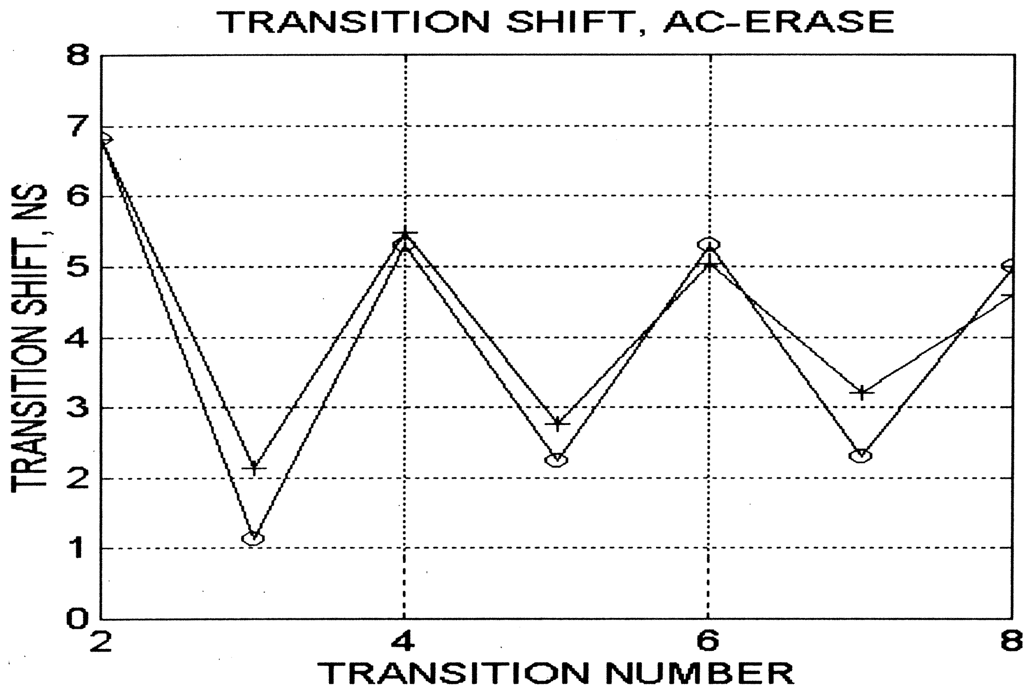
Only NLTS of the 3-d Transition will be measured

Model and Experiment:NLTS versus Transition Number



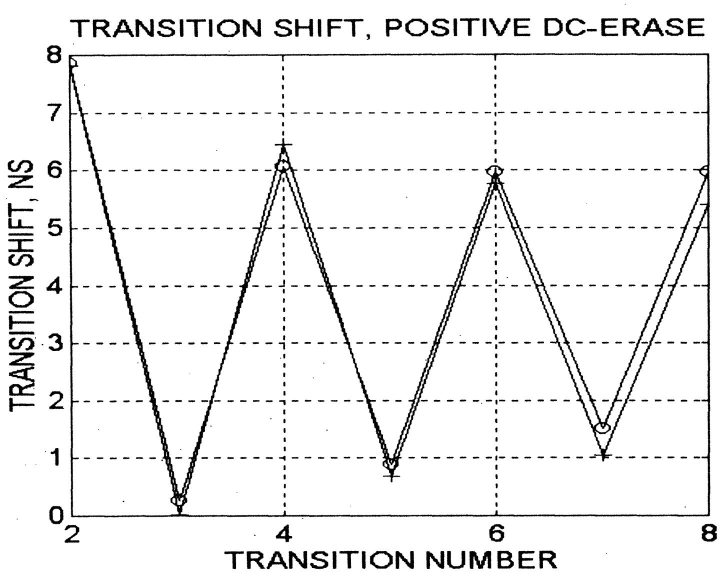
- Approximation of N(B) dependence used for model calculation
- o - measured x-model

Model and Experiment: NLTS versus Transition Number

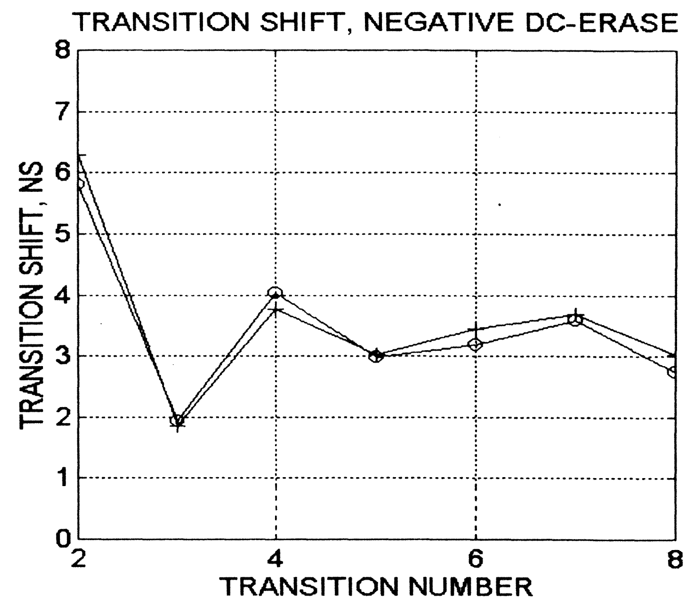


Dependence of NLTS on transition number.
Medium is AC-erased. o-measured data,
x- experimental data

Model and Experiment: NLTS versus Transition Number

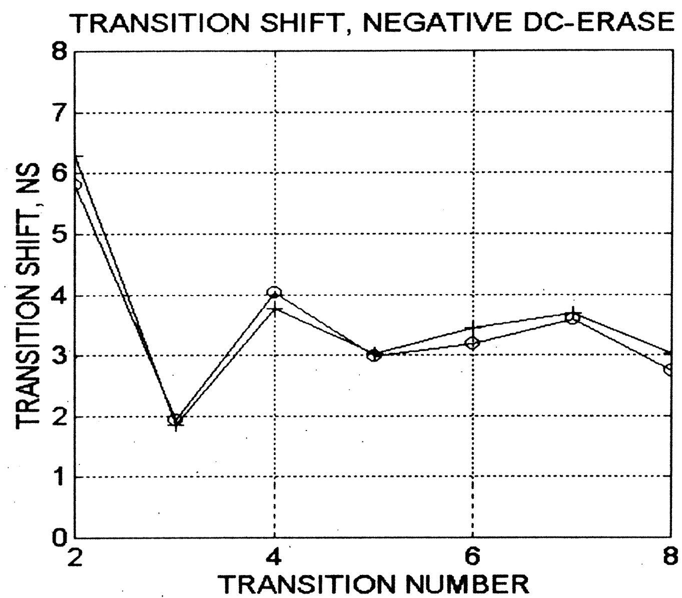


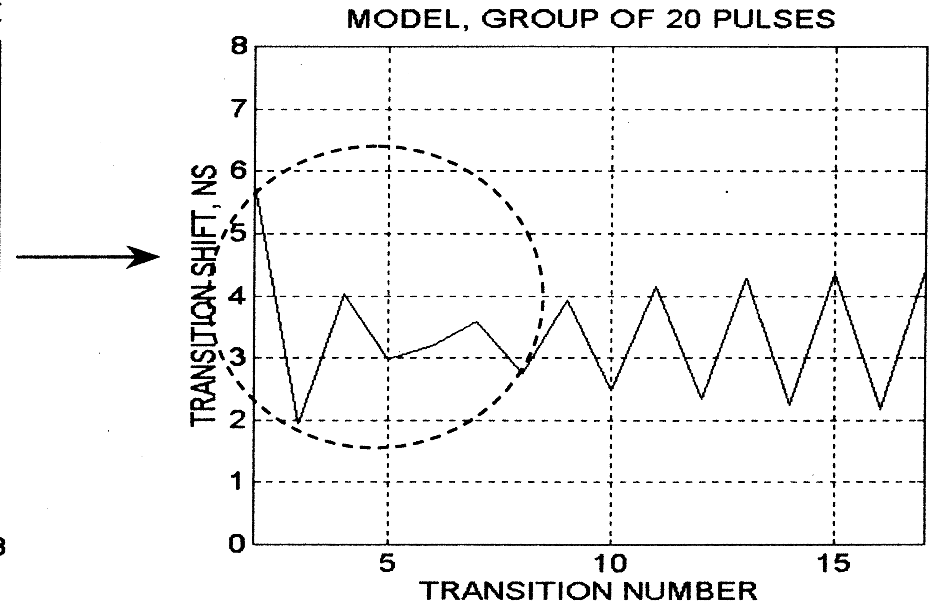
Dependence of NLTS on transition number. Medium is positive DC-erased.
o- measured data, x- experimental data



Dependence of NLTS on transition number. Medium is negative DC-erased.
o- measured data, x- experimental data

Model and Experiment: NLTS versus Transition Number





Dependence of NLTS on transition number.
Medium is negative DC-erased.
o- measured data, x- experimental data

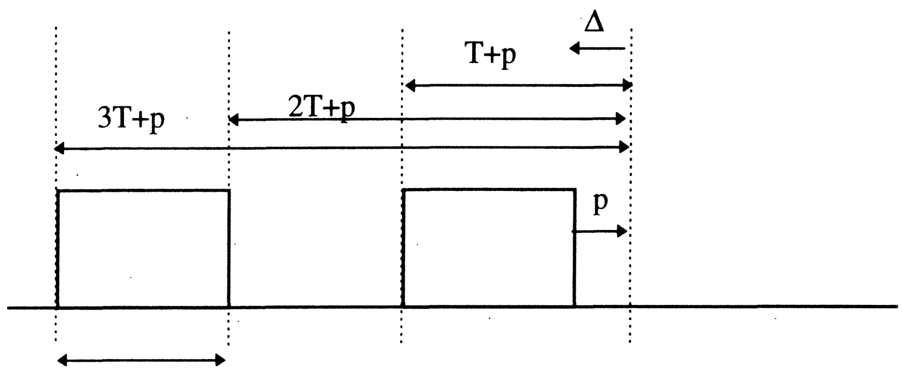
What happens if HTS interacts with NLTS?

- *HTS modulates transition shift in a square wave pattern.*
- *Transition shift oscillates between largerand smaller values.*
- *Resulting oscillations exceed the value of HTS*

A.Taratorin, J.Fitzpatrick, S. Wang and B.Wilson, Non-Linear Interactions in a Series of Transitions, IEEE Trans. Mag, January 1997

- Excessive oscillations of transition shift
- Precompensation is not effective: we don't know the old information pattern
- Old story: Overwrite
- **Non-linearities limit performance of magnetic recording channels**

Precompensation of Adjacent Transitions

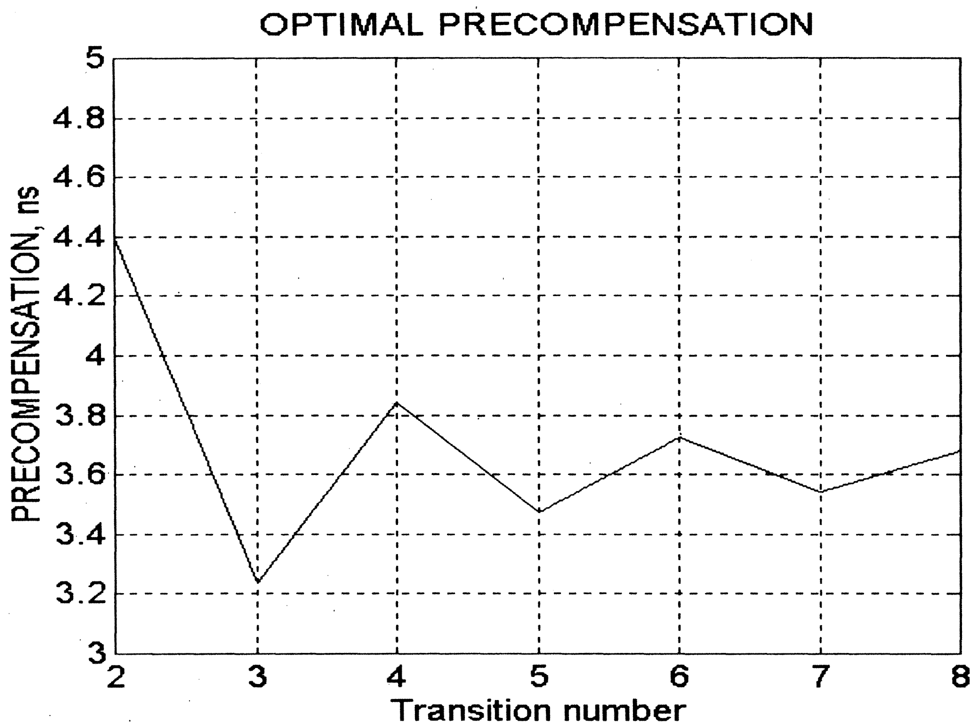


$$T + p_k - \Delta = T$$

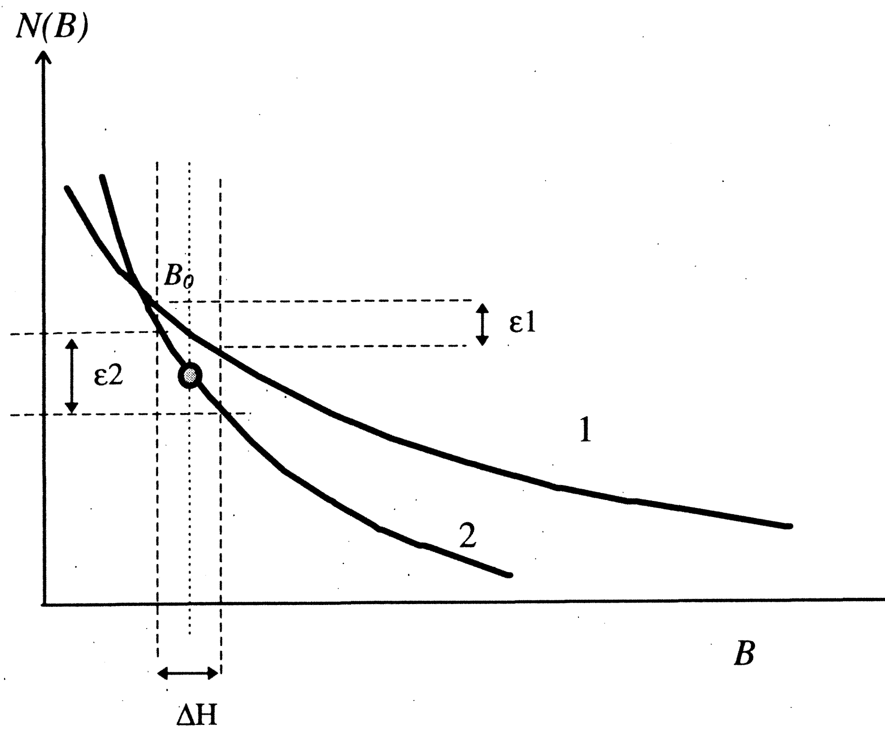
$$p_k = \sum_{m=1}^{k} (-1)^{m+1} N(mT + p_k)$$

- Individual Precompensation levels are required for each transition in series

Optimal Precompensation vs Transition Number

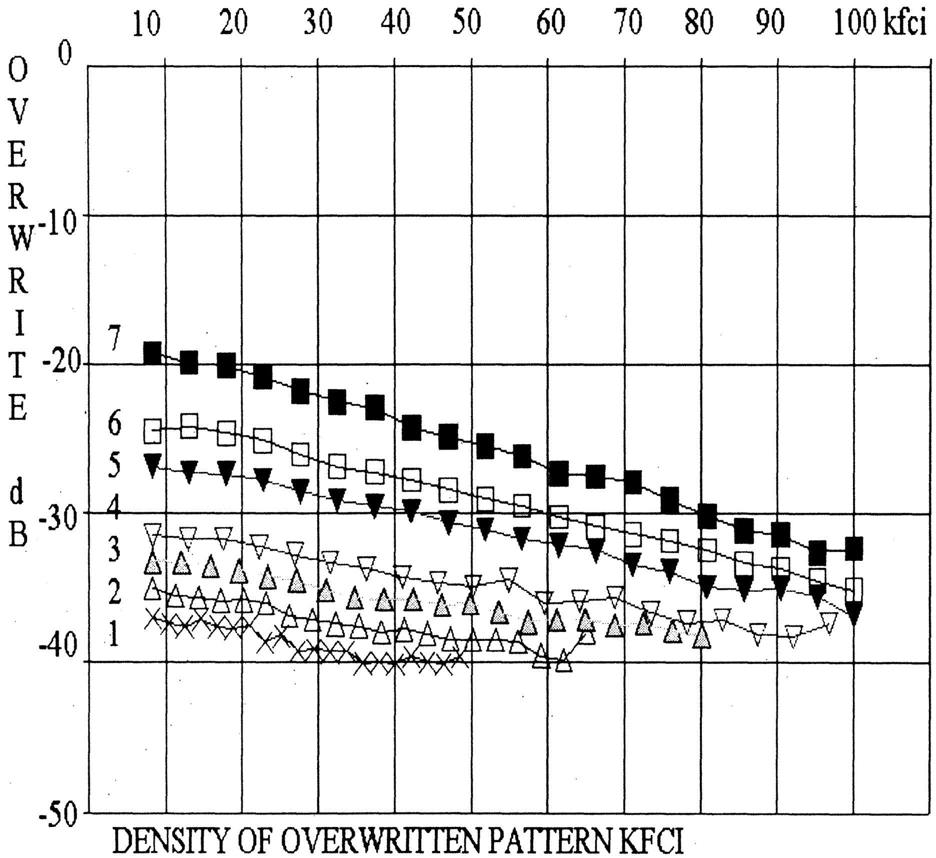


Transition Modulation and Head/Media Parameters



- N(B) is steep (curve 2): influence of previous transitions is smaller, but influence of hard transition shift is larger
- N(B) is flat (curve 1): influence of previous transitions is larger, individual precompensation is required but influence of hard transition shift is smaller

Frequency Dependence of Overwrite after Edge Trimming



HF pattern density (kfci):
1-50
2-66
3 -83
4-100
5-133
6-150
7-180

- **Overwrite is a function of old pattern density**

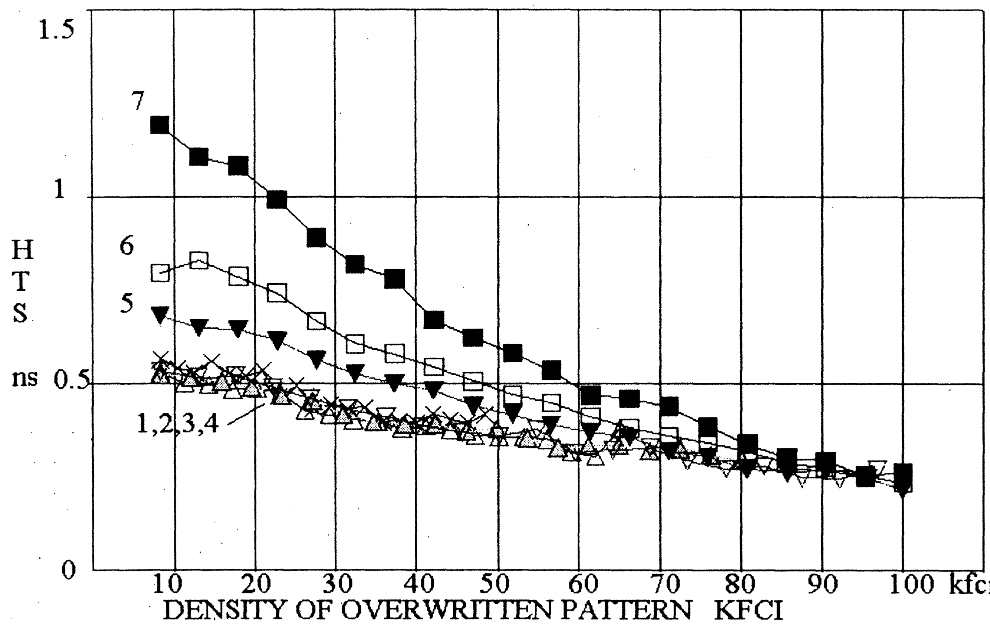
Overwrite including Proximity Effect

$$OW = 20\log_{10}\left(\frac{\Delta}{T}\Psi(\omega)\right)$$

Where Δ is the value of HTS, T - period of the HF pattern, Ψ(ω) - a function, describing attenuation of HTS caused by transitions of old pattern (decreasing the effective value of HTS at high densities of the LF pattern)

- Ψ(ω) depends on the density of the LF pattern. This function should not depend on the density of the overwriting (HF) pattern.

Equivalent HTS - product $\Delta\Psi(\omega)$



HF pattern density (kfci):

1-50

2-66

3-83

4-100

5-133

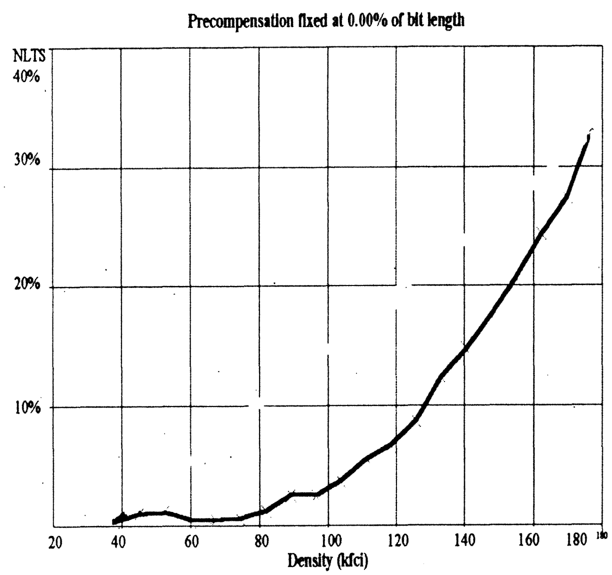
6-150

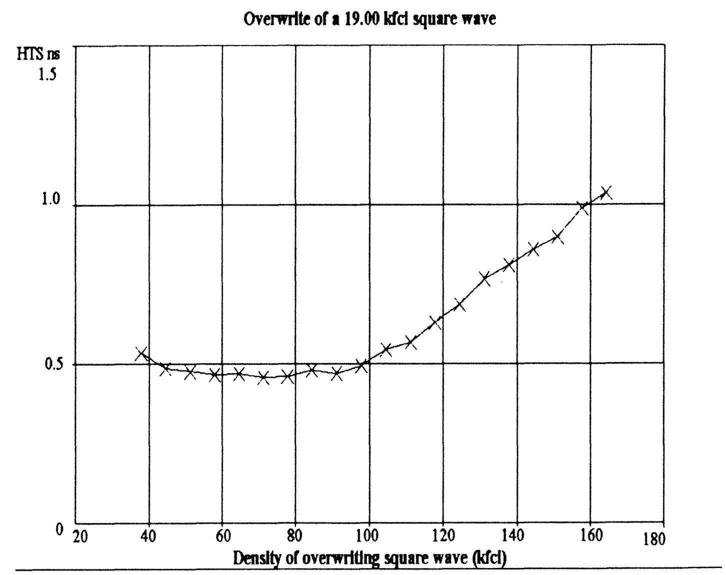
7-180

Curves 1,2,3,4 (up to 100 kfci) - same trend - good agreement with theory

Starting from 100 kfci - amplification of HTS, deviation from the theoretical model

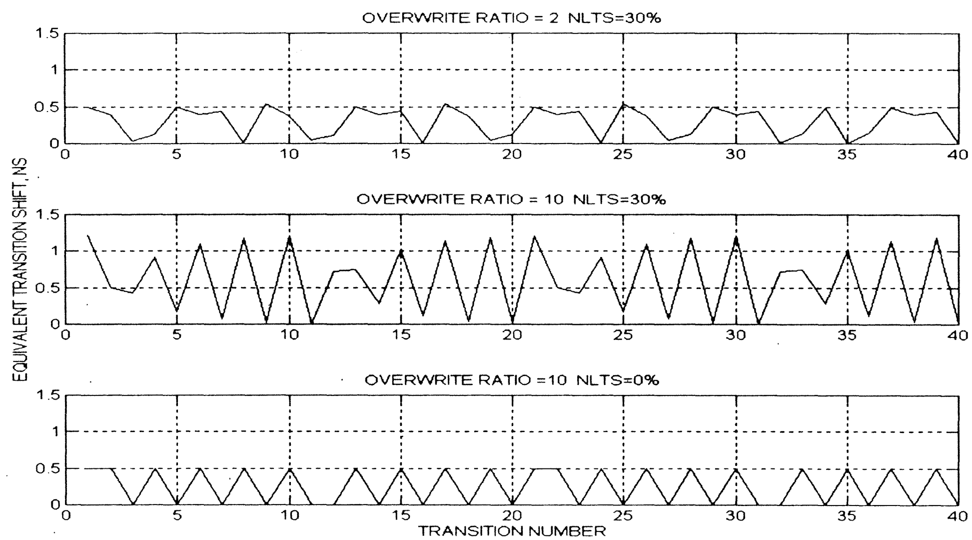
NLTS and amplification of HTS





- Left: NLTS dependence on density; Right - Equivalent HTS dependence on density, LF pattern is fixed at 19 kfci, overwritten by HF square waves at density 38-160 kfci. **These curves demonstrate that the onset of the amplification of HTS is similar to the onset of the NLTS in the HF pattern**

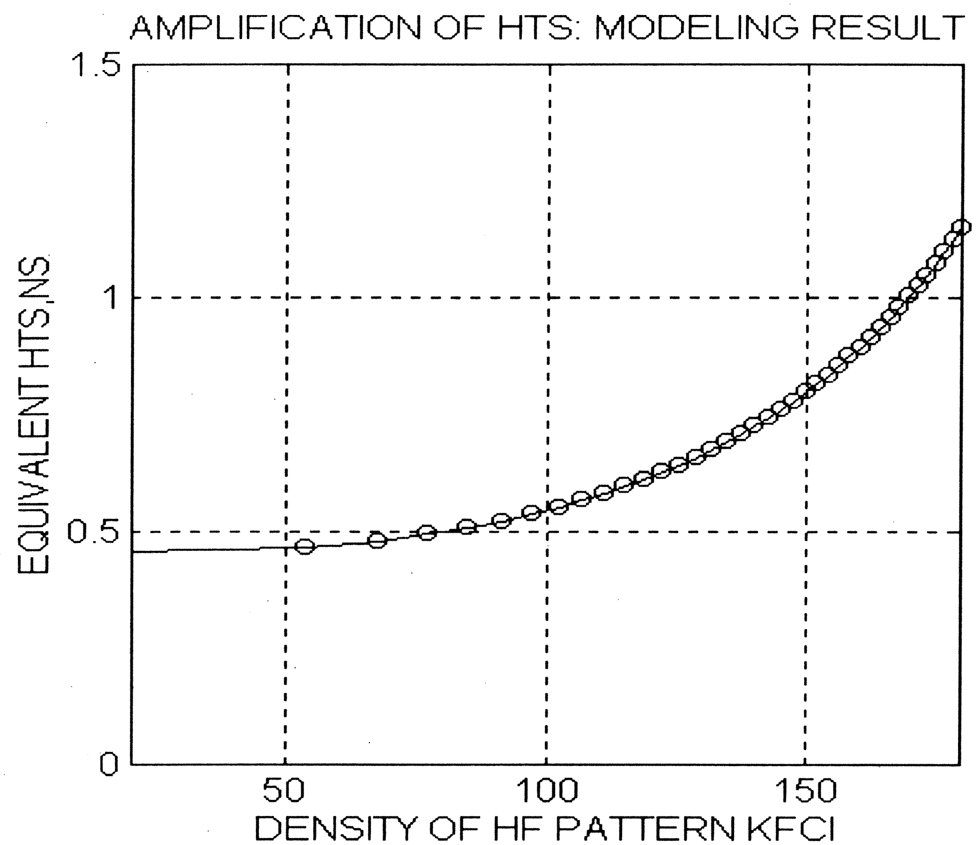
Overwrite: Model of Transition Shifts



Transition Shifts in a HF square wave

- Upper: OW at ratio 2, NLTS=30%
- Middle: OW at ratio 10, NLTS =30%
- Bottom: OW at ratio 10, NLTS = 0%

Amplification of HTS: Model



- Modeling result: Amplification of equivalent HTS with density

Overwrite and NLTS: summary

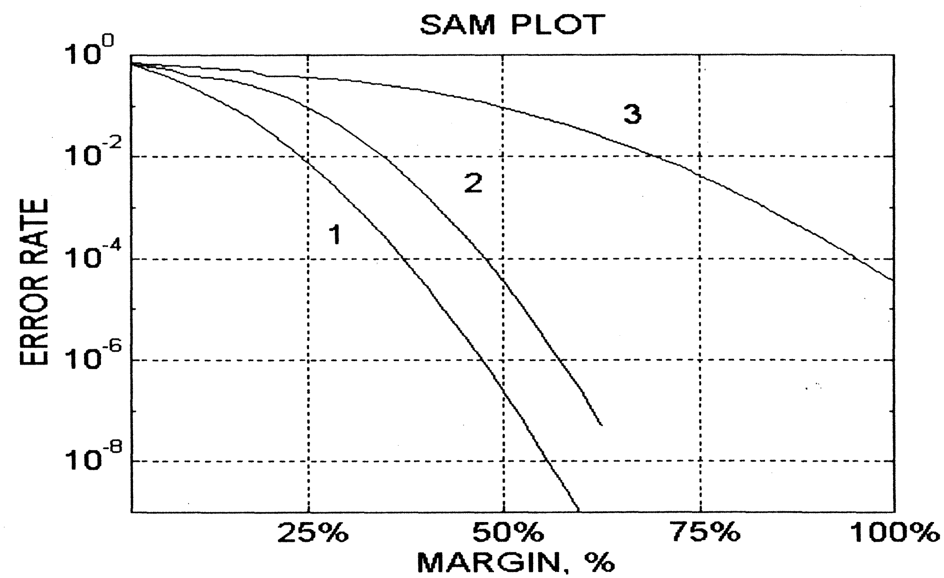
- Overwrite depends both on the LF pattern density (proximity effect) and the HF pattern density (NLTS in the overwriting pattern)
- NLTS in the overwriting pattern cause degradation of overwrite
- Overwrite degradation can be explained by oscillations of transition shift in the HF pattern. These oscillations are caused by interactions between HTS and NLTS
- Degradation of overwrite is stronger at high overwrite frequency ratios (up to 6-8 dB)

Shape Distortions and Random Noise

- **PRML Assumptions:**
- Shape of Isolated Transition is Pre-Determined
- Magnetic Recording Channel is Linear
  - If these assumptions are met, performance of PRML channel is determined only by random noise (medium and electronics)
  - If these assumptions are not met, performance of PRML channel is determined also by:
    - Shape Distortions (Equalization)
    - Channel Non-Linearity (NLTS, Partial Erasure)

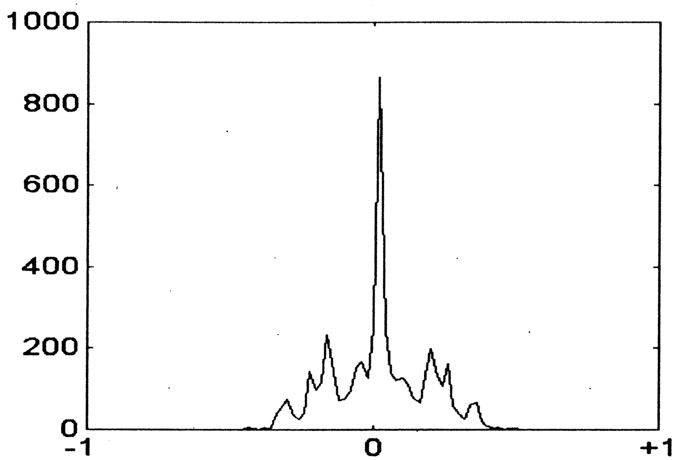
Error Rate and Noise

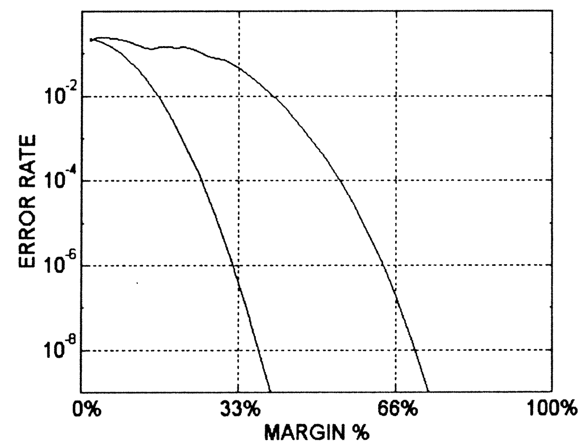
- 1 - On-track
- 2- misequalized
- 3 - off track



- Noise decreases the slope of the SAM plot
- Shape distortions: shift of SAM plot

Shape vs Random Noise: Distances in the Trellis



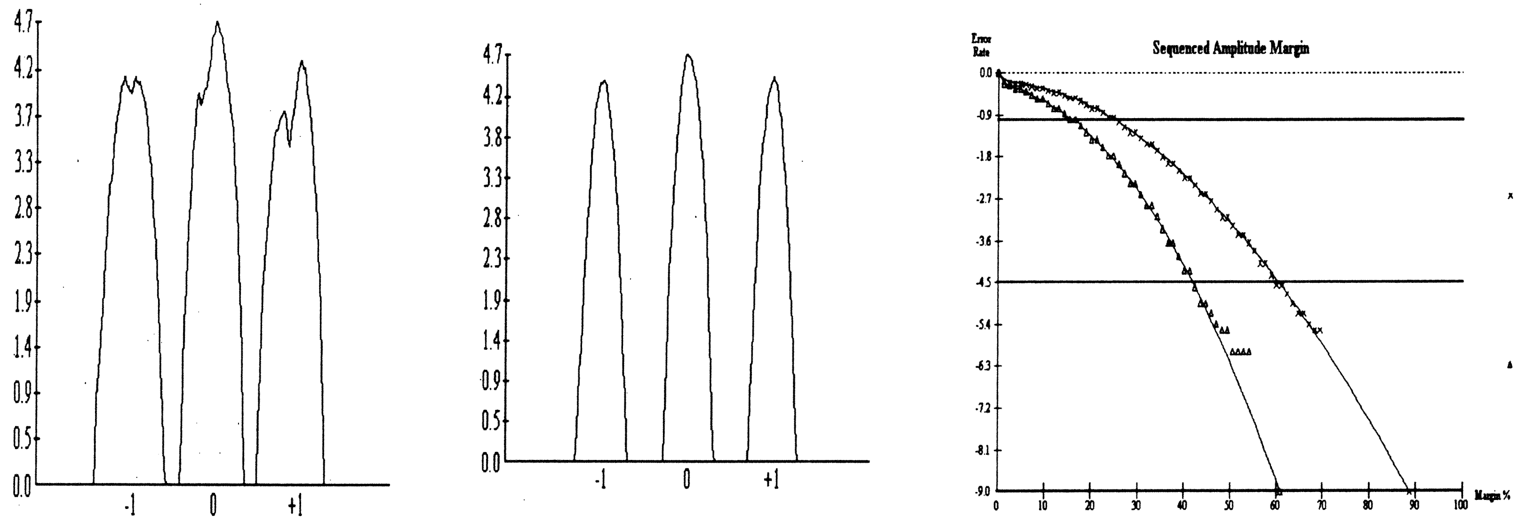


- Only noise distortions: peak at "0"; convolve noise distribution with this peak
- Shape Distortions: Extra peaks are generated. Each Extra peak is convolved with the noise distribution. SAM shifts to the right

NLTS and Partial Erasure

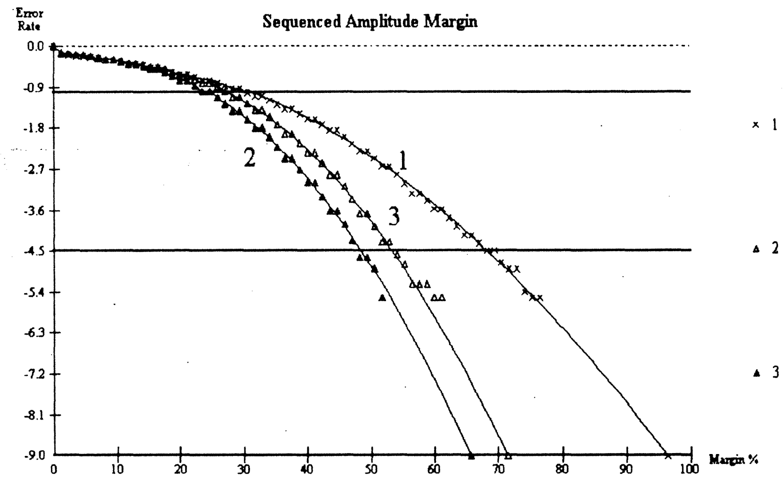
- NLTS and PE decreases amplitude of dipulse
- These distortion match the most dangerous error pattern for the ML detector. E.g. typical PR4 error sequence is {1,0,-1}
- NLTS is "worst case" distortion

NLTS Precompensation



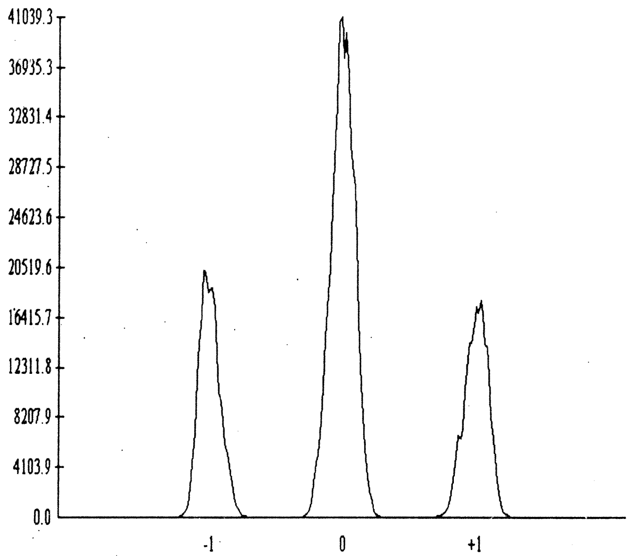
- Left - histograms before precompensation, center - histograms after precompensation, right - SAM plot before and after precompensation
- NLTS is small (about 15% of the bit period)

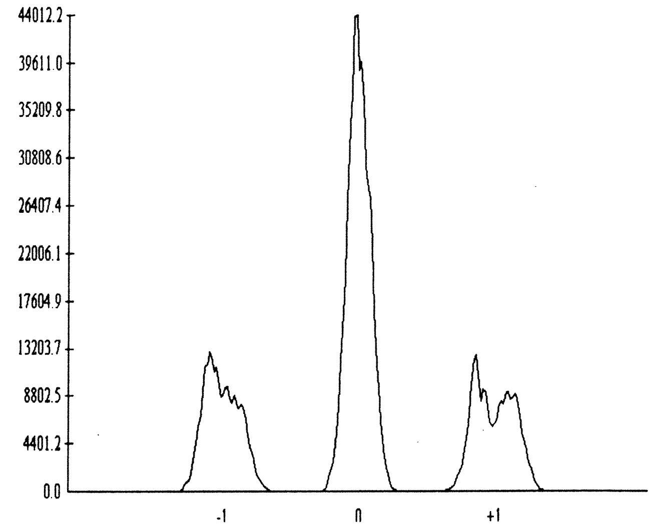
NLTS Precompensation



- 1 - Random pattern, all adjacent transitions are precompensated the same way
- 2 - dibit pattern, same precompensation as (1)
- 3 - Random pattern, 2-nd,3-d and 4-th adjacent transitions have different values of precompensation

NLTS and Hard Transition Shift

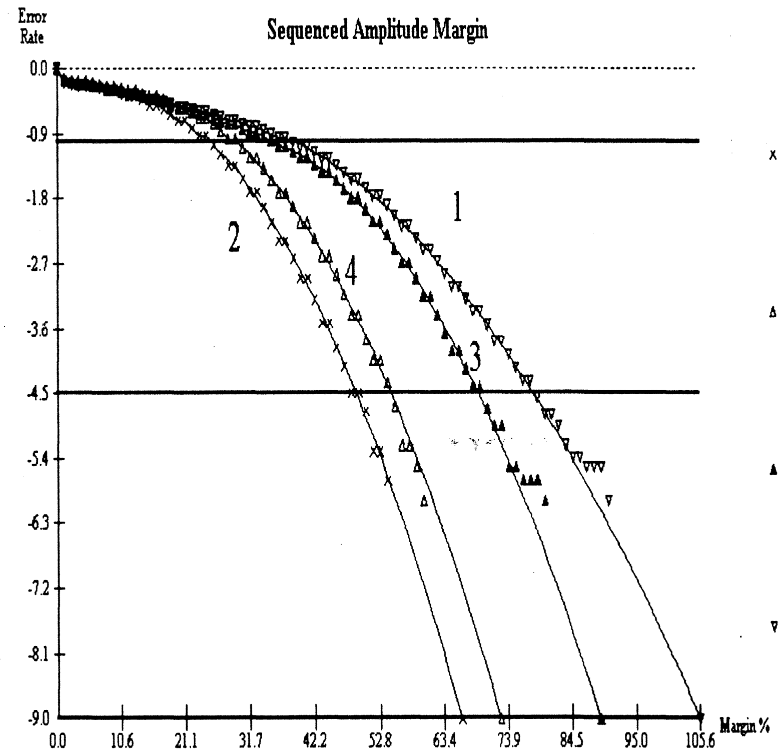




- Left: Pattern is Precompensated, AC-erased medium
- Right - same precompensation, after medium is DC-erased. NLTS interacts with hard transition shift and samples are distorted

NLTS and Hard Transition Shift

- 1 - Random Pattern, no precompensation
- 2 - random pattern, AC-erased medium and precompensation
- 3 - Same as (2) after medium is DC-erased
- 4 - Medium is DC-erased, each transition is precompensated depending on its polarity. Hard and Easy Transitions are precompensated separately

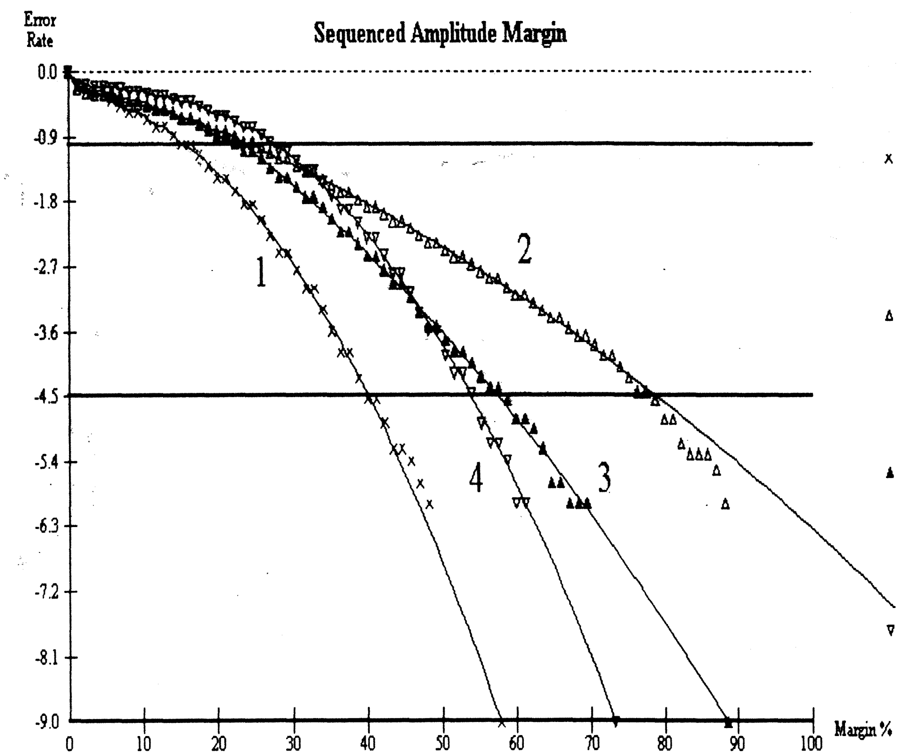


PRML and Non-Linear Distortions

- Error Rate is degraded
- Precompensation may not work at all
- At high recording density interactions between NLTS and Hard Transition shift are significant
- Partial Erasure can not be precompensated

Pattern Dependent Equalization

- 1 - Isolated pulses, optimal equalization
- 2 - equalization is same as (1), random pattern
- 3 - Equalizer is adjusted for random pattern
- 4 - same equalization as (3), isolated pulses
- **Which Equalization is optimal?**



A Generalized Method for Measuring Read-Back Non-linearity Using a Spin-Stand

Bruce A. Wilson, Shan X. Wang
Solid State Laboratory, Stanford University, Stanford CA 94305-4055

Alex M. Taratorin
Guzik Technical Enterprises, 4620 Fortran Dr., San Jose, CA 95134

A new method for measuring the read-back transfer function of a magnetic recording system is proposed. For this method square wave patterns are recorded over a range of linear densities. The resulting read signals should exhibit certain superposition properties if the read process were linear. The transfer function of a MR head distorts read-back signals and makes the read process non-linear. The inverse transfer function is modeled using an arbitrary function such as a polynomial or cubic spline. This model is then used to linearize the distorted read-back signals. Superposition properties are used to evaluate the accuracy of this correction and optimize the parameters of the model. The transfer function is then obtained directly from the optimum inverse transfer function. The effectiveness of the proposed method is confirmed by comparing the read-back transfer function obtained experimentally using this method and a MR read head with a direct measurement of the transfer function of the same read head.

I. INTRODUCTION

The response of an MR head is intrinsically nonlinear. By careful biasing and the use of media with a reduced $Mr\delta$ product, the severity of this non-linearity can be reduced. In practice, significant non-linearity often remains. Partial response maximum likelihood (PRML) detection schemes are able to tolerate a large degree of inter-symbol interference by assuming linear superposition of signals. Non-linearities in the write process such as non-linear transition shift (NLTS) and hard transition shift (HTS) seriously degrade the performance of PRML channels and these effects have been studied by several authors [1,2]. Recent studies have shown that the non-linear transfer function of the MR read element can also degrade PRML performance [3,4].

In this paper a new method for measuring the MR transfer function is presented. This method can be implemented *in-situ* in a drive or using a spin-stand. This method is a generalization of an existing method [5] which measures departures from linear superposition of square-wave patterns in the frequency domain.

II. METHOD

In order to study the behavior of the read process, non-linearities in the write process must first be controlled. When a square-wave pattern is recorded, NLTS affects each transition equally and thus is not observed [6]. In this work, hard transition shift is minimized by erasing the medium with a very high frequency pattern prior to writing. Partial erasure and transition broadening are minimized by writing only at moderate densities. For linear read-back the signal is then given by the convolution sum (after [7]):

$$v(t) = \sum_i a[i] v_{is}(t - iT) \qquad (1)$$

where $v(t)$ is the ideal, linear read-back signal, $v_{is}(t)$ is the read-back pulse from an isolated transition, $a[i]$ is the sequence of written data taking values of $+1, 0, or -1$, and T is the bit period. Consider the following square-wave data sequences

$$a_1[i] = \{... + 1,\ 0,\ 0, -1,\ 0,\ 0, +1,\ 0...\}, \qquad (2)$$

$$a_3[i] = \{... + 1, -1, +1, -1, +1, -1, +1...\} \qquad (3)$$

$$= a_1 + a_1[i+2] + a_1[i-2]. \qquad (4)$$

Thus a high frequency pattern of alternating transitions can be expressed as the sum of three lower frequency patterns of alternating transitions. From eqs. 1 and 4

$$v_3(t) = v_1(t) + v_1(t + 2T) + v_1(t - 2T) \qquad (5)$$

When an inductive read head is used, playback is linear and eq. 5 holds as shown in figure 1. However, when a MR head is used, this superposition property no longer holds as shown in figure 2.

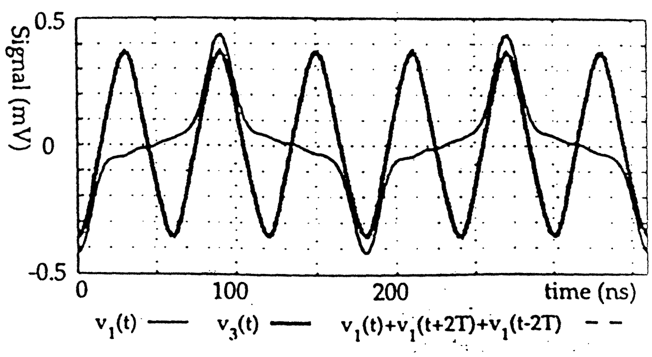


FIG. 1. Read signals obtained experimentally using an inductive head (averaged over 1000 sweeps). Read-back with an inductive head is a linear process and superposition applies Note that the high frequency signal is equal to the sum of three low frequency signals.

brucew@leland.stanford.edu

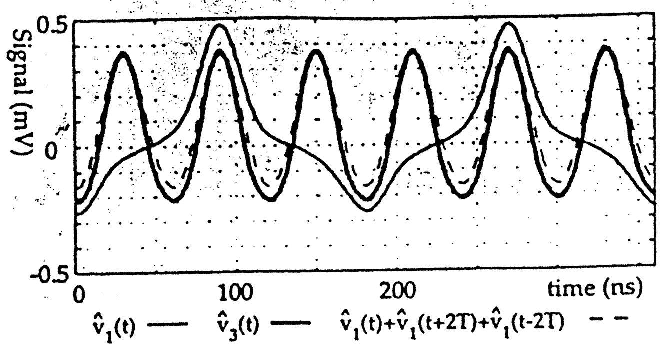


FIG. 2. Read signals obtained using the test MR head (averaged over 1000 sweeps).

If we assume the transfer function of a MR head is a memoryless function $f(x)$ we can write

$$\hat{v}(t) = f(v(t)) \tag{6}$$

where $\hat{v}(t)$ is the distorted read-back signal. If we assume further that $f(x)$ is invertible then equation 5 can be expressed in terms of the distorted signals

$$f^{-1}(\hat{v}_3(t)) = f^{-1}(\hat{v}_1(t)) + f^{-1}(\hat{v}_1(t+2T)) + f^{-1}(\hat{v}_1(t-2T)) \tag{7}$$

this relationship is the key property we use to find the MR transfer function. We can model the inverse transfer function using some general function such as a polynomial or cubic spline. The problem then reduces to one of model fitting where the model parameters are optimized so that eq. 7 is most nearly satisfied. For this method we add additional constraints by assuming that there is no output from the head for zero applied field and the head has unity gain for small signals thus $f(0) = 0, df/dx|_{x=0} = 1$. For example a very simple model, with zero value and unity slope at the origin is

$$f^{-1}(x) \approx x + \alpha x^2 + \beta x^3 \tag{8}$$

Now substituring this into eq. 7 yields

$$\begin{aligned}\hat{v}_3(t) &+ \alpha\hat{v}_3^2(t) + \beta\hat{v}_3^3(t)\\ &= \hat{v}_1(t) + \alpha\hat{v}_1^2(t) + \beta\hat{v}_1^3(t)\\ &\quad + \hat{v}_1(t+2T) + \alpha\hat{v}_1^2(t+2T) + \beta\hat{v}_1^3(t+2T)\\ &\quad + \hat{v}_1(t-2T) + \alpha\hat{v}_1^2(t-2T) + \beta\hat{v}_1^3(t-2T) + \epsilon\end{aligned} \tag{9}$$

where ϵ represents the model fitting error. Applying eq. 9 repeatedly for different values of t yields an overdetermined system of linear equations. This system is then posed in matrix form and solved by pseudo-inverse to find the values of α and β which minimize the mean squared error $< \epsilon^2 >$.

This method is very sensitive to errors in DC levels. For ideal linear read-back the signals are symmetric and thus the median value of the signal is zero. An invertible, memoryless function does not change the rank order of samples and thus the median value of the distorted signal is simply $f(0) = 0$. This property allows the DC levels of signals to be set accurately.

III. EXPERIMENT

A 3.5", 1 $memu/cm^2$ disk was used with a highly asymmetric MR head to test this method. All measurements were made using a Guzik 1701MP spin-stand and 1601+PRML read-write analyzer with optional high-speed analog to digital converter.

High frequency square wave patterns were recorded near the inner diameter (I.D.) with densities of 50, 57.5, 60, 62.5 and 65 kfci. Corresponding low frequency square wave patterns were written with densities between 16.6 and 21.6 kfci. Recording near the I.D. ensures that the preamp bandwidth is much greater than the bandwidth of the read signals. Gathering data across a range of densities makes this method more robust, reducing sensitivity to noise and residual write non-linearities. Readback signals were digitized at 2Gsamples/sec and averaged over 100 sweeps. Each erase-write-read cycle was repeated 10 times, to minimize the effects of instantaneous flying-height variation, and the resulting signals were aligned and averaged. The test process is automated and all measurements can be made in approximately 2 minutes. A polynomial with four degrees of freedom was used to model the inverse transfer function. A system of equations was constructed from the data and solved to yield the four parameters of this model. Figure 3 shows the signals of figure 2 after applying the inverse transfer function.

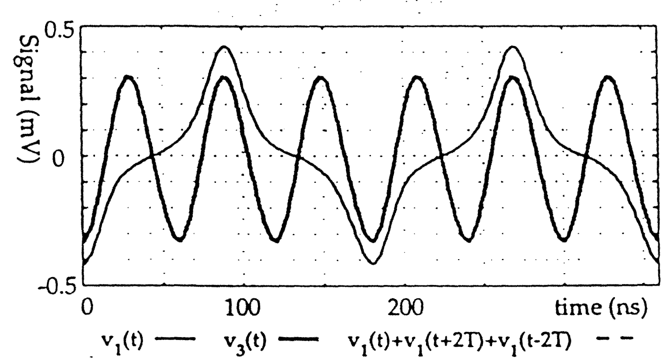


FIG. 3. MR read signals after applying the inverse MR transfer function. Note that the high frequency linearized signal is equal to the sum of three low frequency linearized signals and that peak amplitudes are symmetrical.

The MR transfer function can be obtained by plotting the inverse transfer function and exchanging axes as shown in figure 4. MR head output as a function of applied field can be measured directly by applying a known field to the head in a solenoid. There is reasonable agreement between the transfer curve obtained using this method and the transfer curve measured directly. Discrepancies between the two methods are greatest at around 50 Oe where there appears to be significant hysteresis and an abrupt change in slope. Hysteresis violates our assumption of a memoryless non-linearity and a smooth function such as a polynomial can not faithfully reproduce an abrupt change in slope.

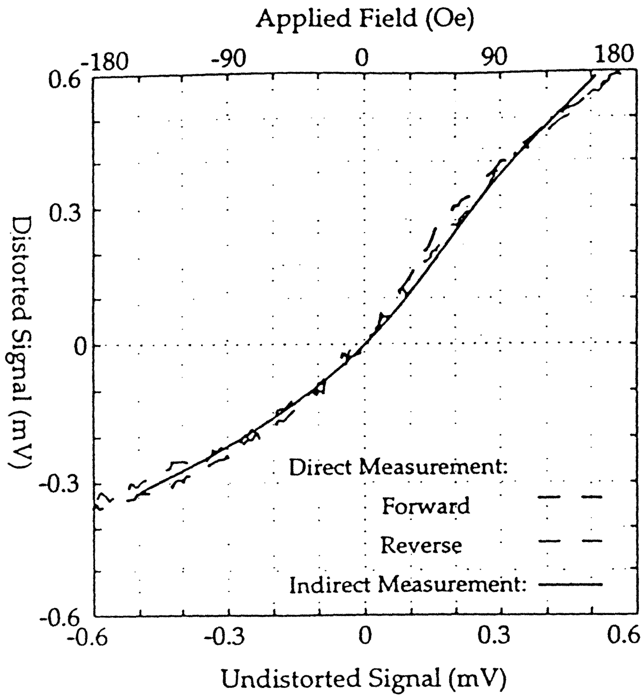


FIG. 4. The MR transfer function. The dashed lines were obtained directly by applying a known field to the head with a MR head tester. The solid line was obtained using the method described here using a 4th order polynomial to model the inverse transfer function. The field strength above the medium was inferred by comparing peak signal amplitude with the direct measurements of the MR transfer curve.

The choice of function used to model the inverse transfer function should have only a small effect on MR transfer curve obtained by this method. Figure 5 shows MR transfer curve obtained for the same system using different functions to model the inverse transfer function. For this combination of head and medium it appears that choice of polynomial order has relatively little effect. A cubic spline, being continuous only up to the first derivative, seems to follow the abrupt change in slope more faithfully than polynomial models.

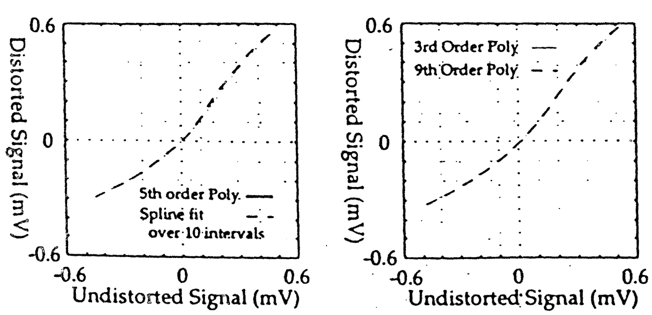


FIG. 5. MR transfer curves obtained using different functions to model the inverse transfer function.

Our experience with this method suggests that models with more degrees of freedom, such as this cubic spline, may perform better than simple polynomials for good data but that where there is significant measurement noise or residual write non-linearity a simple model is more reliable.

IV. CONCLUSION

In this work we present a new method for measuring the read-back transfer function of a magnetic recording system. In particular this method can be used to find the shape of the MR transfer function. Trials with a test head have demonstrated results consistent with the MR transfer curve obtained by directly applying a known field to the head.

This method may provide a useful tool for in-drive linearization of read-back signals for improved channel performance. This method can also be used to eliminate the effect of read-back non-linearity in standard tests for write non-linearities such as NLTS and partial erasure.

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Linearizing the Read Process for Write Nonlinearity Measurements

Bruce A. Wilson and Shan X. Wang
Department of Electrical Engineering, Stanford University, Stanford, CA 94305-4045

Alex M. Taratorin
Guzik Technical Enterprises, 4620 Fortran Drive, San Jose, CA 95134

***Abstract*—Many standard tests for write nonlinearities such as nonlinear transition shift and partial erasure assume a linear read process. Nonlinear effects from readback with a magnetoresistive head can make the results of these tests difficult to interpret. We show how a polynomial can be used to approximate the inverse transfer function and thus linearize the read channel. Write nonlinearities can be measured more easily by performing tests on the linearized channel. We also show how linearizing the channel for PRML detection is limited by amplification of noise over parts of the inverse transfer curve with high differential gain.**

I. Introduction

Magnetoresistive (MR) read heads are rapidly replacing inductive heads in high-density digital magnetic recording applications. The response of MR heads to applied field is intrinsically nonlinear. By careful design, good fabrication and through the use of media with a reduced $Mr\delta$ product these nonlinear effects can be minimized. In practice significant nonlinearities often remain.

Many standard tests for write nonlinearities assume a linear read process. These tests attribute all observed nonlinearity to effects such as nonlinear transition shift (NLTS) and partial erasure. Because of this these tests often produce unexpected results when used with MR heads [1], [2]. In this paper we show how the response of a MR head can be linearized and how this procedure greatly simplifies the interpretation of some standard tests for NLTS and partial erasure. We briefly examine PRML detection with a linearized channel.

II. Method

We assume that the transfer function of the MR head is memoryless, continuous and invertible. Under these conditions the inverse transfer function can be approximated by a polynomial. In this paper a polynomial of the form

$$f^{-1}(x) = x + \alpha x^2 + \beta x^3 + \gamma x^4 + \delta x^5 \qquad (1)$$

was used. The parameters α, β, γ and δ of this polynomial model were chosen to most nearly linearize the read channel. The method for finding these polynomial coefficients is described elsewhere [3]. Fig. 1 shows the approximate inverse transfer function obtained and the corresponding approximate forward transfer function.

Read signals were linearized by digitizing the waveforms at 2 Gs/s and applying the polynomial of eq. 1. The resulting linearized waveforms were analyzed numerically. Time domain methods such as dipulse extraction [4] and correlation [5] were performed directly on the sampled waveforms. Frequency domain methods such as harmonic elimination tests for NLTS [6] and third harmonic ratio tests for partial erasure [1] were implemented using a discrete Fourier transform to extract the desired frequency components from the signal.

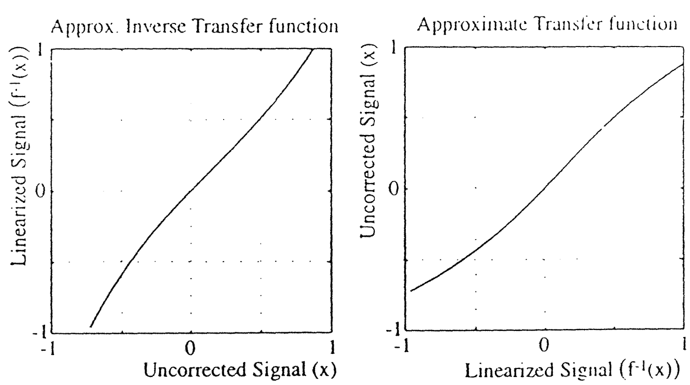

Fig. 1. Polynomial approximation for the inverse transfer function. Axes are scaled so that the height of a positive isolated peak is one unit.

III. Experiment

A 3.5″, 1 $memu/cm^2$ disk was used with a soft-adjacent-layer (SAL) biased MR read head. Read current was set at the maximum recommended value of 12mA to yield maximum signal amplitude. At this bias current peak asymmetry of approximately 30% was observed. Measurements were made using a Guzik 1701MP spin stand and 1601+PRML read-write analyzer with optional high speed analog-to-digital converter.

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B. Wilson email brucew@stanford.edu
A. Taratorin is now with IBM Almaden Research Center, San Jose CA 9512, email: amt@almaden.ibm.com
S. Wang is also with the Department of Material Science and Engineering, Stanford University, Stanford CA 94305-2205, email: sxwang@ee.stanford.edu

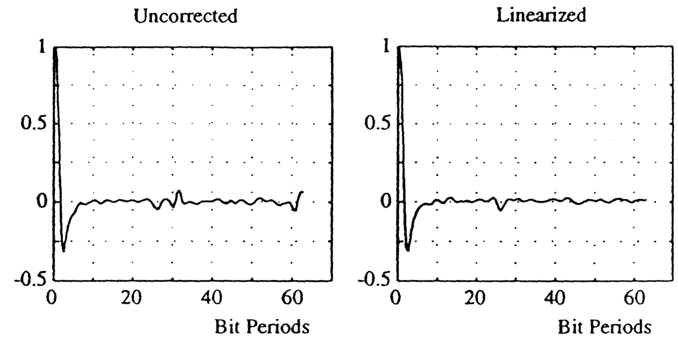

Fig. 5. Read signal autocorrelation function for a pseudorandom pattern. Nonlinear readback produces a strong "echo" which overlaps the echo due to NLTS. Linearizing the channel eliminates this "echo". Density is 110 kfci.

recorded, with precompensation, at a density of 100 kfci. The read signal was digitized at 2 Gs/s, linearized, and the data clock was recovered by correlating the received signal against the known data sequence. The waveform was decimated using the recovered clock and the resulting waveform was equalized to a PR4 target using a minimum-mean-squared-error 24 tap filter. For comparison the same proceedure was repeated without linearization.

Optimal equalization for the linearized signals achieved a smaller r.m.s. error and narrower distributions as seen in Fig. 6. Fig. 7 shows the sequence amplitude margin plot obtained using the method of error filters [9]. The SAM error rate for the linearized signal is significantly better than for the uncorrected signal for margin up to 40%, reflecting improved equalization after linearization. At higher margin, detection using the uncorrected signal performs better than detection using the linearized signal. Some parts of the inverse transfer function have a steep slope to compensate for the flat response of the MR head as it begins to saturate. By a first order approximation

$$\begin{aligned} \hat{x} &= f(x) + n \\ g(\hat{x}) &\approx x + ng'(\hat{x}) \end{aligned}$$

where x is the ideal undistorted read signal, $\hat{x}$ is the noisy and distorted read signal, $f(\cdot)$ is the MR transfer function, $g(\cdot) = f^{-1}(\cdot)$ is the inverse transfer function and n is additive noise. Thus steep regions of the inverse transfer curve have high differential gain which significantly amplifies noise. This amplified noise degrades error performance at high margin. While MR distortion degrades the performance of PRML channels it is not possible to fully recover this loss by linearizing the read channel.

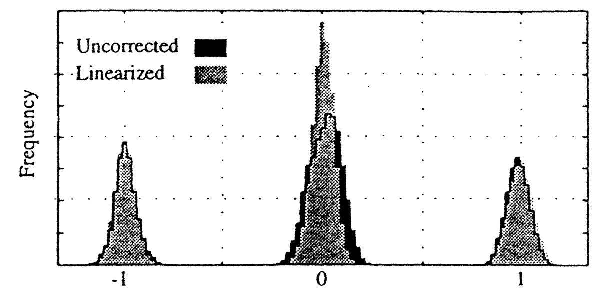

Fig. 6. Histogram of sample values for recording at 100kfci. Linearization before equalization produces a slimmer distribution.

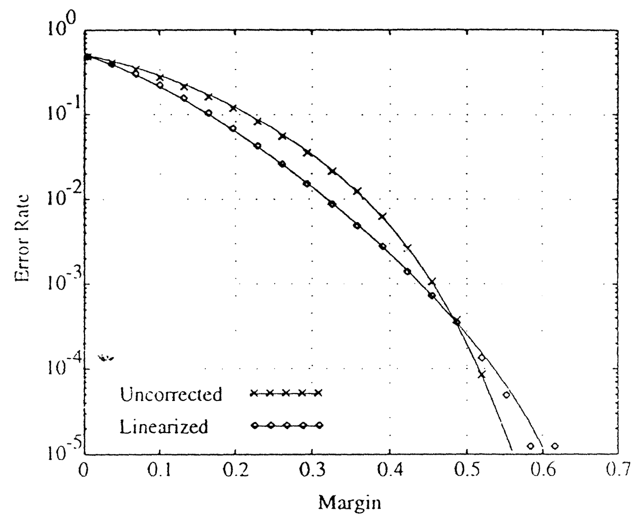

Fig. 7. Sequence amplitude margin at 100kfci with and without linearization. Linearization before equalization shows improved performance for small margins.

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A. Measuring Partial Erasure

Partial erasure can be measured by recording a square wave pattern at density f and again at 3f [1]. Partial erasure reduces the amplitude of the high density pattern and for linear readback the amplitude loss factor α due to partial erasure is given by

$$\alpha(3f) = 1 - \frac{V_{3f}(3f)}{3V_f(3f)}$$

At low densities, high fields above the medium begin to saturate the MR element and thus reduce the amplitude of the low density pattern[2]. This effect causes the value of α to become negative, incorrectly suggesting a negative partial erasure. At very low density both low and high density patterns are attenuated by read nonlinearity and α remains at unity. By linearizing the read channel the true partial erasure can be measured as shown in Fig. 2.

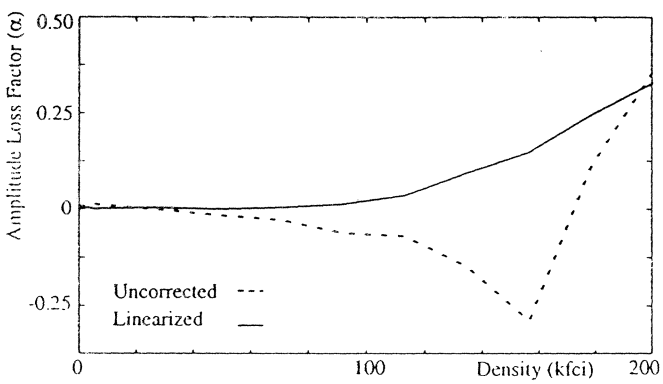

Fig. 2. Partial erasure amplitude loss factor measured using the third harmonic ratio method. Negative values of amplitude loss factor at moderate density are an artifact of nonlinear readback. Linearizing the channel eliminates this effect.

B. Measuring NLTS by harmonic elimination

NLTS can be estimated by writing a pattern which has no energy at some harmonic frequency kf_0. For a linear channel the read signal will also contain no signal at kf_0. NLTS can be inferred from signal amplitude at kf_0 under the assumption that NLTS is the only nonlinearity present [1], [6]. Nonlinear readback will also contribute to the signal at kf_0, making it difficult to estimate NLTS in this way. Fig. 3 shows net NLTS as a function of write precompensation. Ideally net NLTS should approach zero for optimal precompensation. When a MR head is used, NLTS measured in this way remains high regardless of precompensation. Once the read channel is linearized the net NLTS drops close to zero for optimal precompensation.

C. Measuring NLTS by Dipulse Extraction

By calculating the dipulse response of the channel using a pseudorandom test pattern it is possible to measure

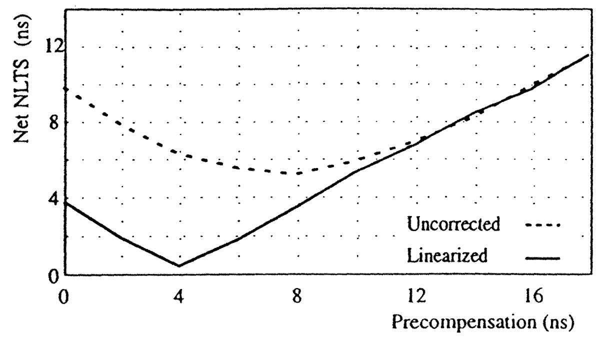

Fig. 3. NLTS estimated by 5th harmonic elimination. For the uncorrected channel net NLTS appears to remain high regardless of precompensation. Bit period is 36 ns. Density is 90 kfci

many nonlinear effects in the channel [4]. Nonlinearities in the read process produce several additional "echos" in the dipulse response. Some of these additional "echos" overlap "echos" for NLTS and hard transition shift and make it difficult to interpret the dipulse plot as shown in Fig. 4. Linearizing the read channel eliminates these additional "echos".

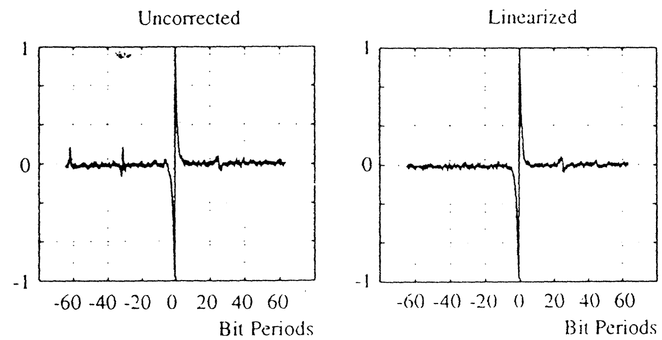

Fig. 4. Dipulse response of the uncorrected channel shows many additional "echos" due to nonlinear readback. Density is 110 kfci.

D. Measuring NLTS by Correlation

The channel autocorrelation function for a pseudorandom input is the autocorrelation of the dipulse response calculated from the same pseudorandom input. It is thus possible to identify many of the same "echos" seen in the dipulse response. These "echos" in the autocorrelation function can also be used to measure write nonlinearities [5]. The presence of read nonlinearities produces additional "echos" which overlap "echos" produced by write nonlinearities as seen in Fig. 5. Again linearizing the read channel eliminates these additional "echos".

E. Linearizing the channel for PRML detection

Nonlinear readback has been shown to degrade the performance of partial-response maximum-likelihood (PRML) channels [7], [8]. In this section we examine the performance of PRML detection on the linearized channel. A pseudorandom data pattern of length 127 was