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TESTS OF FLAT, THIN-FILM, MAGNETORESISTIVE HEAD ARRAYS FOR VLBI TAPE RECORDERS

as presented by

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at TMRC ’98

ABSTRACT

We have demonstrated the feasibility of greatly improving the bandwidth and capacity of Very Long Baseline Interferometry (VLBI) tape recorders by replacing ferrite headstacks with monolithic flat-topped arrays of thin-film (TF) inductive write and magnetoresistive (MR) read heads. TFMR head upgrade of VLBI recorders is also expected to greatly reduce operational cost and increase reliability, because TFMR arrays will be relatively inexpensive to manufacture, do not wear, and maintain initial performance.

Flat-lapped chips of four 16-channel Advanced Tape System arrays were mounted on carriers and paired in a 128-channel assembly, which physically replaced a 36-channel VLBI headstack. The tape was wrapped with 2.5 degrees with respect to the flat surfaces at each edge. A SSI 1574 preamp interfaced one MR head at a time. An SVHS-equivalent, 900 Oe coercivity, inch-wide Quantegy 741 tape, qualified for VLBI, was used in the tests. This tape was prerecorded at 2.26 fc/micron (56 kfci) with 38 micron-wide standard ferrite VLBI heads.

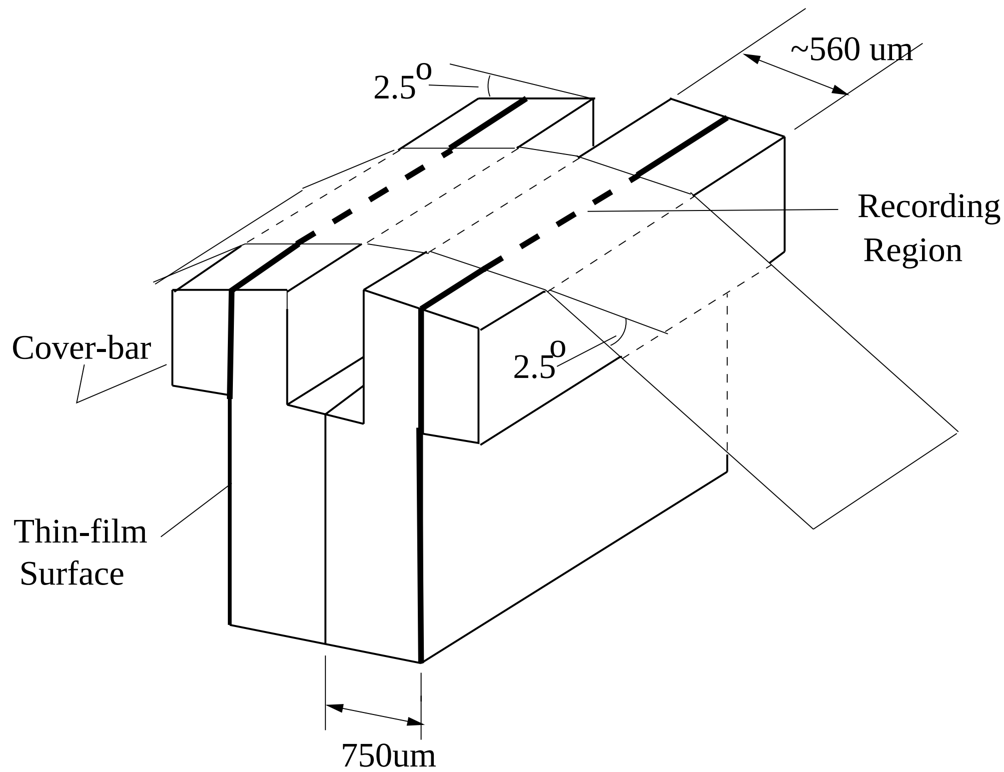
Raw error rate of about 10^{-6} was typical when reading this tape at 2 m/s with an empirically modified fixed equalizer. Tape-noise limited read-performance was achieved with the 12 micron wide MR readers, in spite of excess spacing loss observed. Bandedge SNR at 0.9 micron wavelength was 6 dB higher than with the standard VLBI heads.

The best write performance of the 1 micron gap TF writer was however 6 dB poorer than that of the 0.33 micron gap ferrite head on the same tape and at the same short 'bandedge' wavelength.

Though the tape did not fly, contact at the gap, centered in the 560 micron long flat tape bearing surface, was not achieved. Spacing loss change with speed was calculated with the Wallace formula. Spacing decreased, about 50 nm, as speed was increased from 2 m/s to 8 m/s. This qualitative behavior was predicted with our one-dimensional head-tape interface model, however the model predicted contact where the experiments showed a reducible spacing.

Given the high 35 to 30 dB SNR observed from 3/9 to 7/9 bandedge, respectively, the potential for doubling linear density with a PR4 read-channel, or quadrupling track density by reducing MR sense-width to less than 3 microns, is evident.

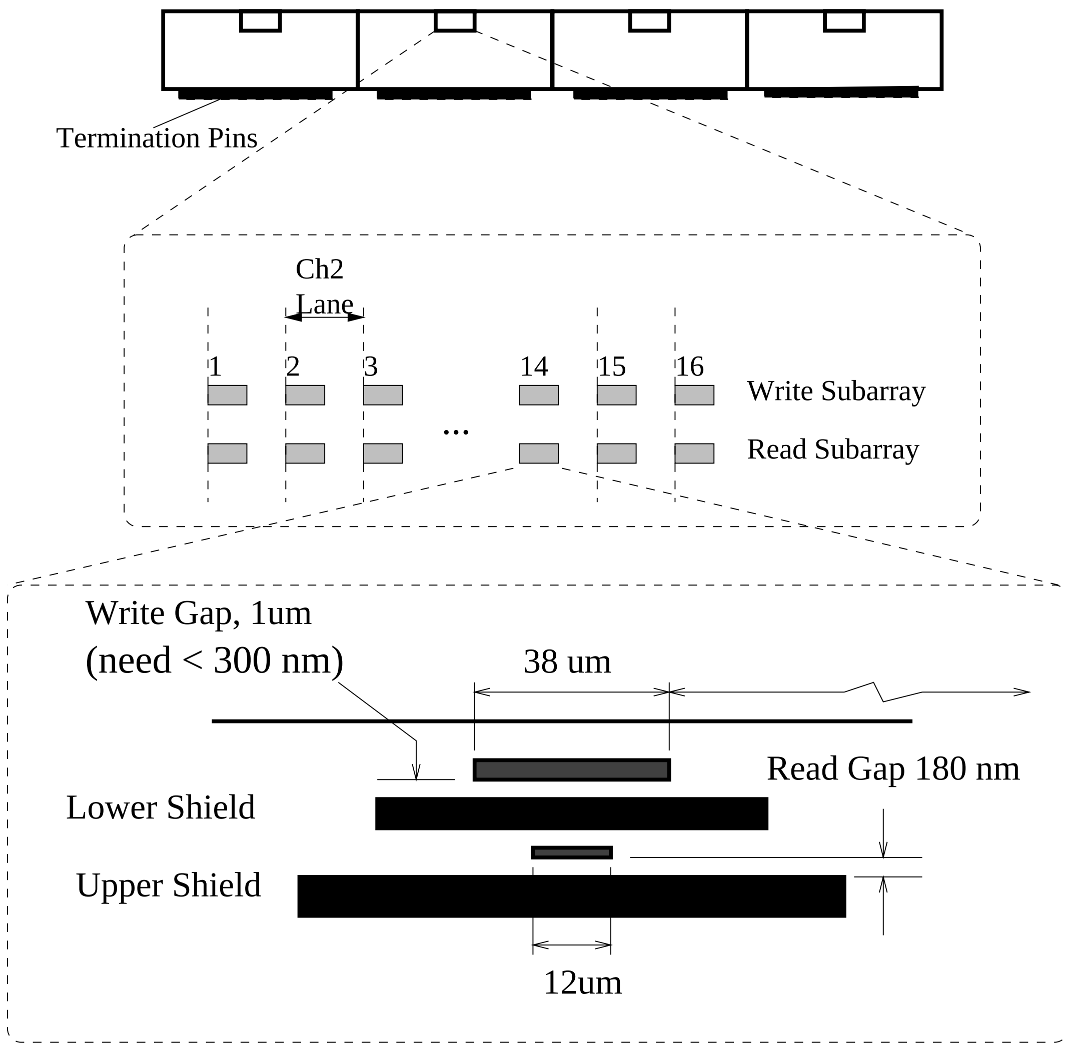
Geometry



Description of the Geometry

- Two head bars with 64 channels/bar were used.
- Head arrays surfaces were lapped flat.
- Head arrays were mounted with 2.5^o relative orientation.
- Half of the 128 channels were electrically connected.
- Only a few of the channels were tested.

Configuration of the ATS Heads on a Bar



Electrical

- A SSI 1574 preamp interfaced one MR head at a time.
- An SVHS-equivalent, 900 Oe coercivity, inch-wide Quantegy 741 tape, qualified for VLBI, was used in the tests.
- This tape was prerecorded at 2.26 fc/μm (56 kfci) with 38μm-wide standard ferrite VLBI heads.

Test Results

Electrical

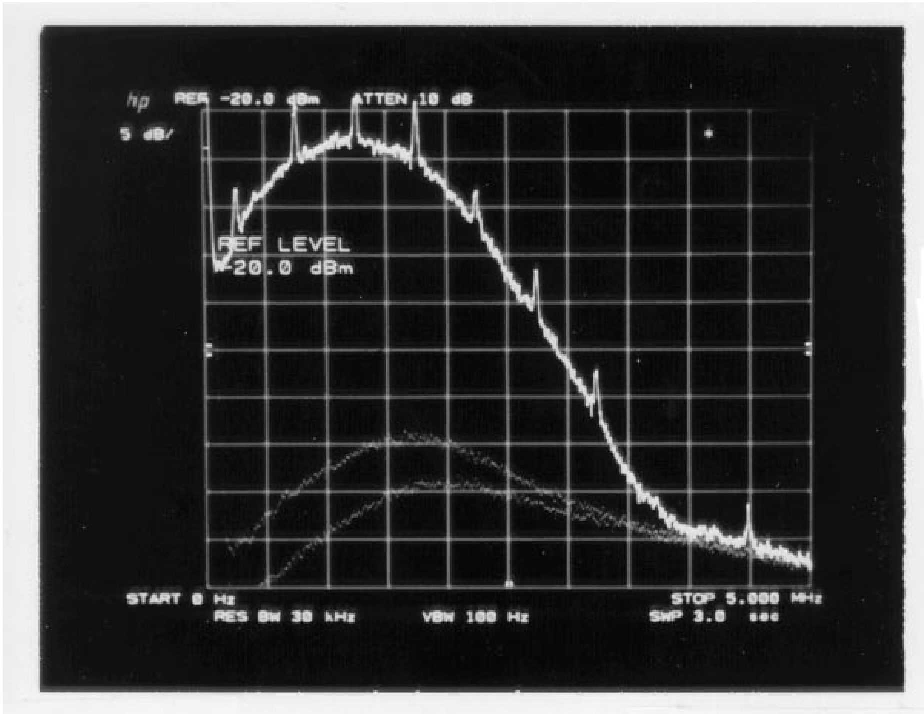
MR Read Performance:

- Raw error rate of about 10^{-6} was typical when reading this tape at 2 m/s with an empirically modified fixed equalizer.
- Tape-noise limited read-performance was achieved with the 12 μm wide MR readers, in spite of excess spacing loss observed.
- Bandedge SNR at 0.9 μm wavelength was 6 dB higher than with the standard inductive ferrite VLBI heads.

TF Write Performance:

- The best write performance of the 1 μm gap TF writer was however 6 dB poorer than that of the 0.33 μm gap ferrite head on the same tape and at the same short "bandedge" wavelength.

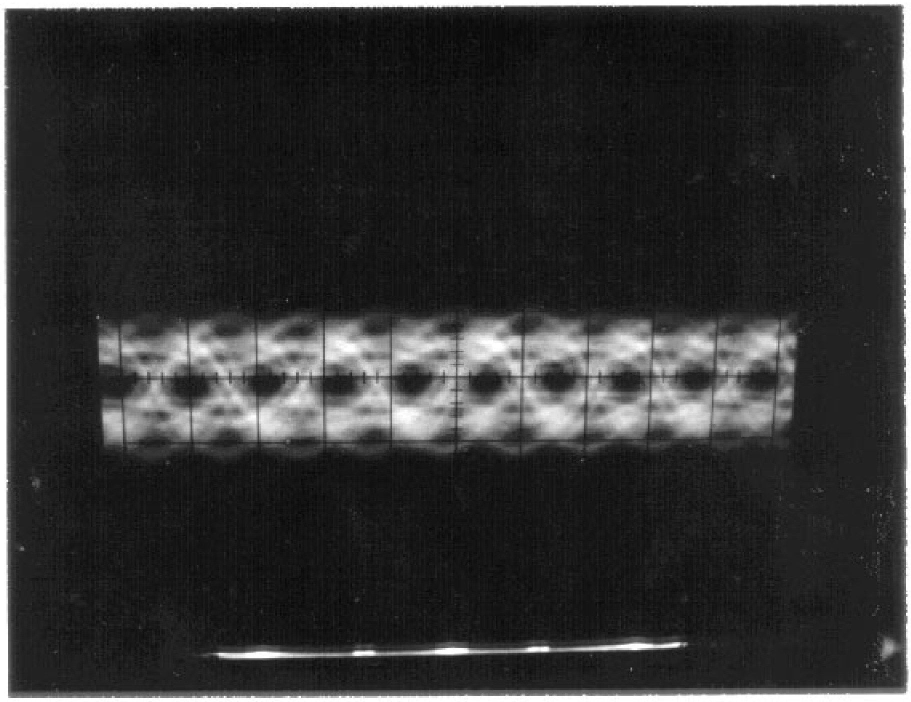
NORMAL DENSITY POWER SPECTRA



Bright (top)	EQUALIZED OUTPUT (S) (80 ips)
Faint (middle)	TAPE NOISE (TN) (80 ips)
Faint (bottom)	ELECTRONIC NOISE (EN) (0 ips)

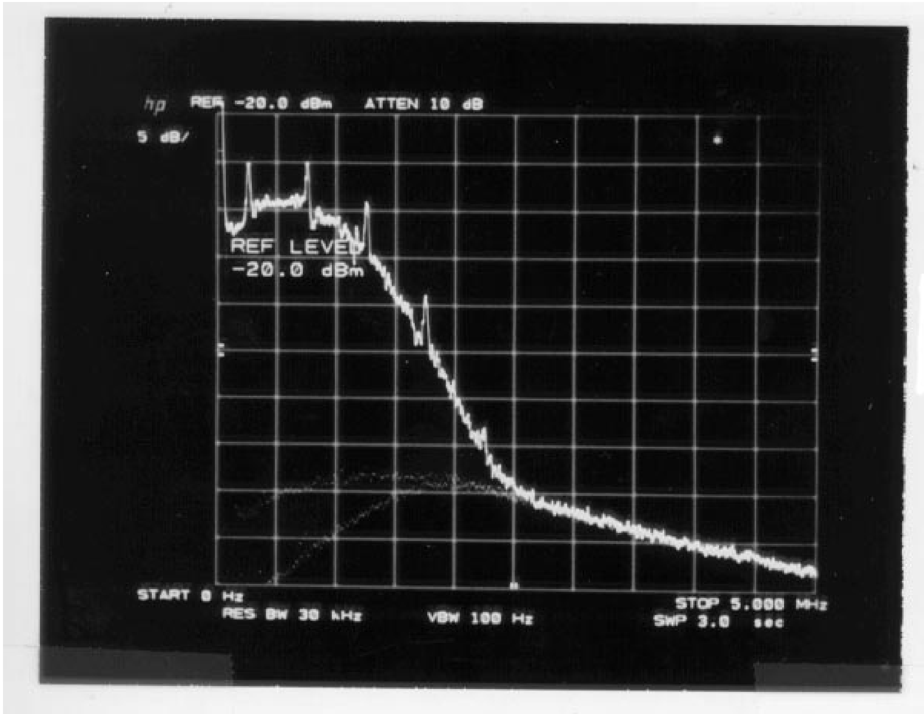
- Parity produces "markers" in output spectrum at odd harmonics of (byte frequency)/2=0.25 MHz.
- The bandedge (all-ones) frequency is 2.25 MHz; bandedge wavelength is 0.9 μm.
- TN is well equalized only from 5/9 to 9/9 bandedge, not for long wavelength.
- TN exceeds EN by only 4 dB at bandedge; spacing can be reduced at least by 90 to 120 nm for a 6 to 8 dB increase in TN/EN.

NORMAL DENSITY EYE PATTERN



- 50 Kbpi (56.25 Kfci, odd-parity 8/9 mod. code).
- BER $\sim 10^{-6}$, typical, is very good in VLBI application. (12 μm MR better than 38 μm ferrite read head).
- Prerecorded S-VHS-like, 900 Oe, Quantegy 741 tape.
- Recorded with std. 0.33 μm gap, ferrite VLBI head.
- Partial penetration recording method: Write current only high enough to maximize bandedge (all ones) response.
- Used VLBI zero-crossing bit detector without new DC restore and old standard bit sync, with non-optimized bit and clock recovery.
- VLBI "write-waveform-restore" equalizer was modified empirically for MR head, but has not yet been optimized.

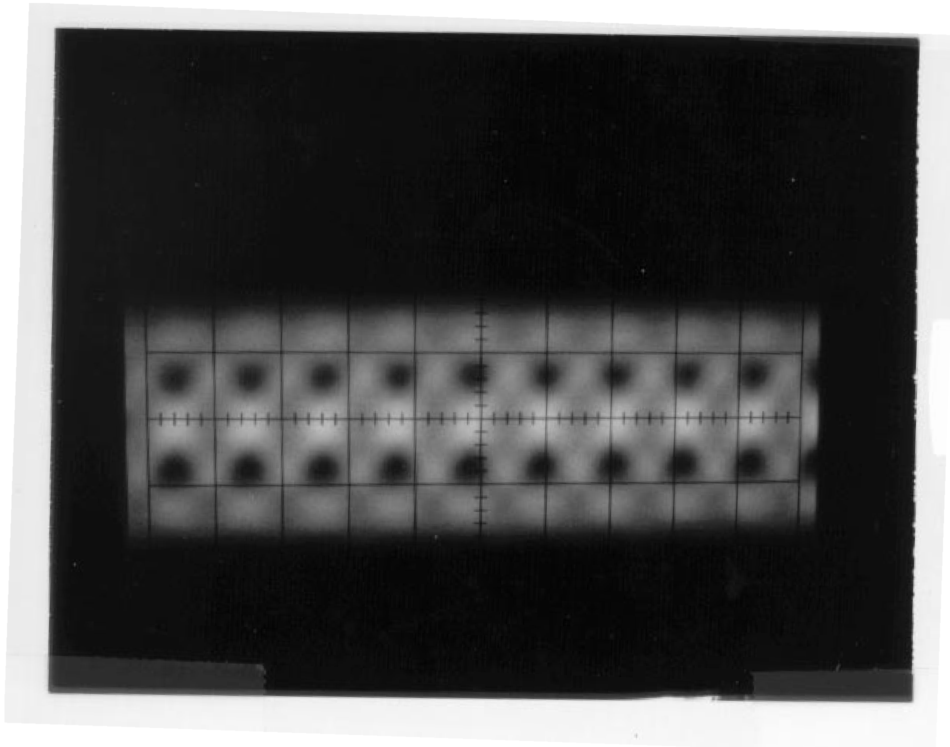
DOUBLE DENSITY POWER SPECTRA



Bright (top)	EQUALIZED OUTPUT (S) (40 ips)
Faint (middle)	TAPE NOISE (TN) (40 ips)
Faint (bottom)	ELECTRONIC NOISE (EN) (0 ips)

- Write 100 Kbpi (112.5 Kfci recording at 40 ips), Otherwise identical to Normal Density write with ferrite head at 80 ips.
- Read using same equalizer as for normal density.
- TN is well equalized at long and short wavelengths. This is good for optimal partial response detector which is not yet tried.

DOUBLE DENSITY EYE PATTERN

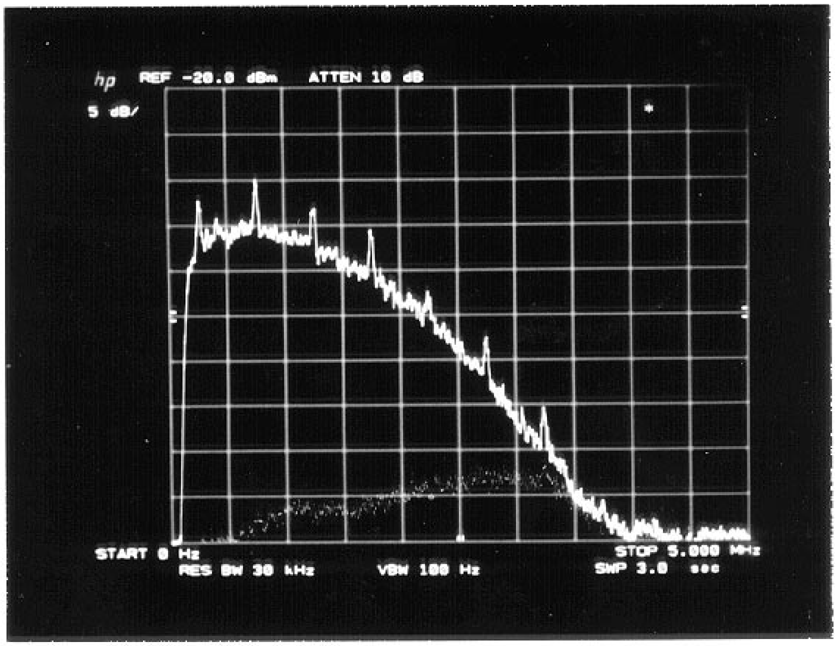


- 100 Kbpi (112.5 Kfci) 3-level, ternary eye pattern at 40 ips.
- Same equalizer produces 2-level, binary eye pattern for normal density at 80 ips.
- Should yield low error rate with partial response detector, which is not yet tried:
  Since S/TN $\sim$ 21 dB $\Rightarrow$ 6dB margin.

NORMAL DENSITY S/TN SPECTRUM

0.33 μm GAP FERRITE WRITE/MR READ

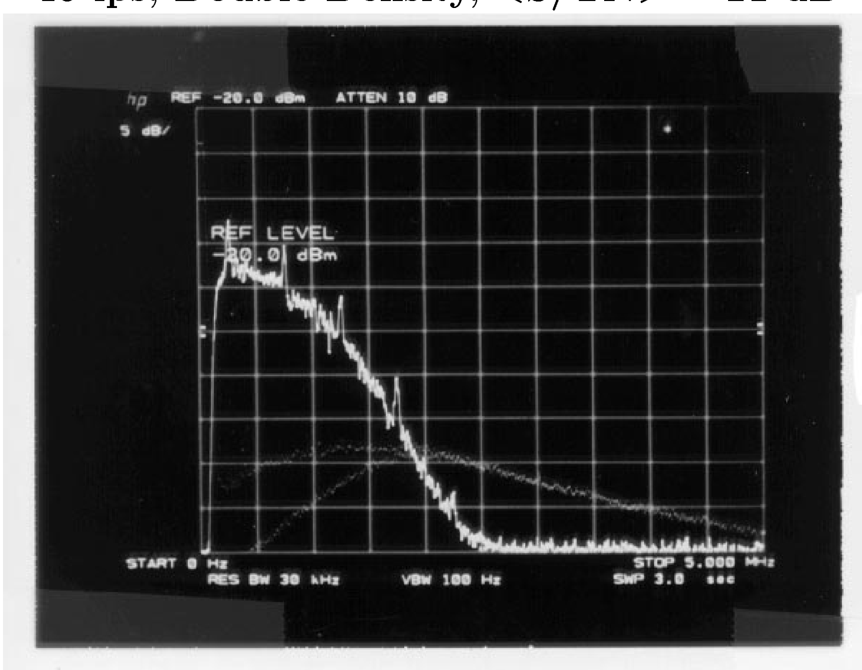
80 ips, Normal Density, <S/TN> ~ 31 dB



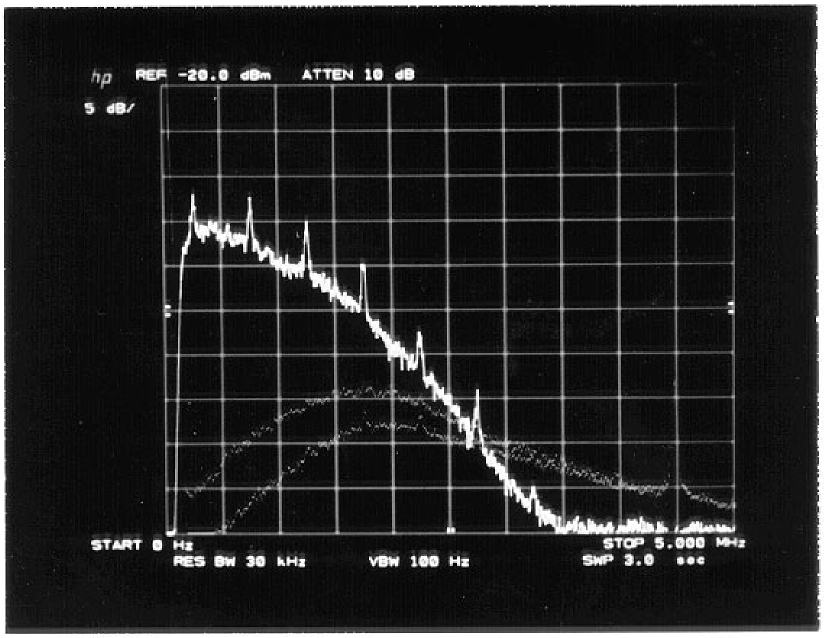
DOUBLE DENSITY S/TN SPECTRUM

0.33 μm GAP FERRITE WRITE/MR READ

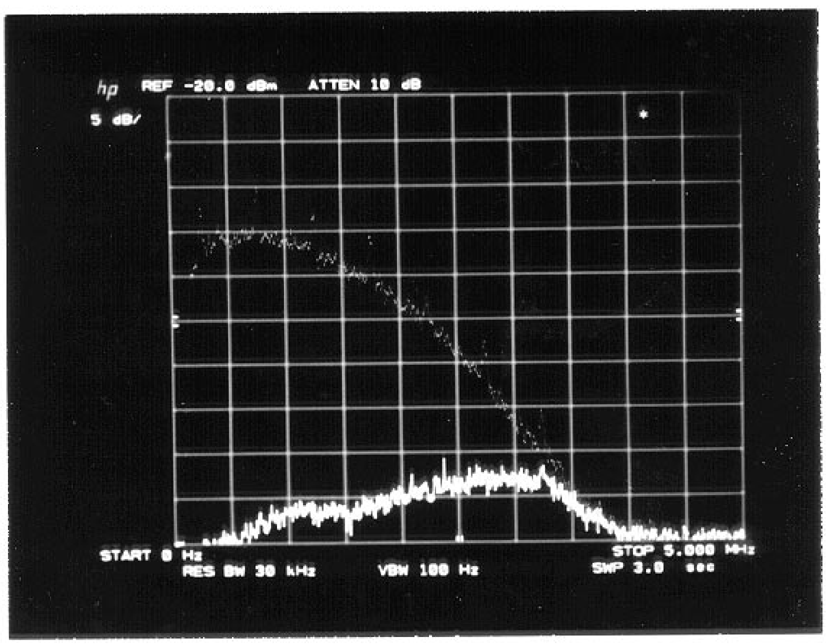
40 ips, Double Density, <S/TN> ~ 21 dB



NORMAL DENSITY S/TN SPECTRUM
1 μm GAP TF WRITE/MR READ



(0.33 μm GAP FERRITE) - (1 μm GAP THIN FILM) WRITE



SHORT GAP WRITE ADVANTAGE
6dB at $\lambda = 0.9$ μm
7dB at $\lambda = 0.6$ μm

Test Results

Mechanical (Head Tape Spacing)

- Spacing loss change, ΔL, was calculated with the Wallace formula:
$$\Delta L = 55\frac{\Delta h}{\lambda} dB \tag{1}$$
where, Δh is the change in head tape spacing and λ is the wavelength of the recorded signal.

- Though the tape did not fly, contact at the gap, centered in the 560 micron long flat tape bearing surface, was not achieved.

- Spacing **decreased**, about 50 nm, as speed was increased from 2 m/s to 8 m/s.

- This qualitative behavior was predicted with our one-dimensional head-tape interface model, however the model predicted contact where the experiments showed a reducible spacing.

Projections-I

- **<u>Cost Reduction:</u>**

  (A Major VLBI Concern)

  - **<u>Ferrite VLBI Headstack:</u>**
    - Current VLBI headstack has 36 channels.
    - Replacement cost is $9,000.
    - Wear Life is too short except in very dry environment: less than 5,000 hours at over 35%RH in tape path.
  - **<u>Thin Film MR Heads on Altic:</u>**
    - Expect $\sim$ $1,000 per “standard” bar in “custom” assembly.
    - 64$^+$ channels per assembly required for VLBI implementation, anticipate a 3-bar assembly in TFMR-gen1.
    - Expect a very long wear life,
      (Müftü, and Hinteregger, 1998).

Projections-II

Ferrite to Thin Film MR Conversion of VLBI Heads

- <u>**Data Rate Increase**</u>

  - <u>**From VLBA Configuration**</u>
    - 1 Headstack, 32 channels, 8 MBits/sec per ch., 4 m/s.
    - Total Recording Rate: $32 \times 8 =$ $\boxed{\textbf{256 MBits/sec}}$.

  - <u>**or Mark IV Configuration**</u>
    - 2 Headstacks, 64 Channels, 16 MBits/sec per ch., 8 m/s.
    - Total Recording Rate: $64 \times 16 =$ $\boxed{\textbf{1024 MBits/sec}}$.

  - <u>**To Thin Film MR Configuration**</u>

    ATS-like, 2-bar assembly, 128 channels

    $\Rightarrow$ Total Recording Rate: $128 \times 8 =$ $\boxed{\textbf{1.024 GBits/sec}}$.

    at 4 m/s and Normal Density = 50 Kbpi,

    or up to

    $\Rightarrow$ Max Recording Rate: $128 \times 32 =$ $\boxed{\textbf{4.096 GBits/sec}}$.

    at 8 m/s and Double Density = 100 Kbpi,which requires a new partial response read electronics.

Projections-III

- **Storage Capacity Increase:**
  - On inch wide 18,000 feet-long, S-VHS-like, 900 Oe tape.
  - **From**
    - $\boxed{0.7 \text{ TB}} = 1/8 \times 512$ tpi $\times$ 50 Kbpi $\times$ 2.16×10^5 in^2
      (512 tpi = 16 passes $\times$ 32 channels)
      or,
    - 0.7 TB = 128 Mb/s $\times$ 12 hours.
      Track-pitch $\sim$ 48 μm for 512 tpi.
  - **To $\times$ 4 in TFMR-gen1 (Target 1999)**
    - $\boxed{2.8 \text{ TB}}$
      for Track-Pitch = 24 μm, at Double Density = 100 Kbpi.
  - **To $\times$ 16 in TFMR-gen2 (Target 2001)**
    - $\boxed{11.2 \text{ TB}}$
      for Track-Pitch = 6 μm, at Double Density = 100 Kbpi.
  - **To $\times$ 32 in TFMR-gen3 (Target 2003)**
    - $\boxed{22.4 \text{ TB}}$
      for Track-Pitch = 1.5 μm, at Normal Density = 50 Kbpi.
  - **To $\times$ 128 in TFMR-gen3 with Advanced Tape**
    - $\boxed{89.6 \text{ TB}}$
      for Track-Pitch = 1.5 μm, at Quad. Density = 200 Kbpi

Projections-IV

Notes on TFMR-gen1,2,3

- **TFMR-gen1:**
  - Minimum ($\times$ 4) capacity increase expected for VLBI implementation; compatible with industry roadmap in near future.
- **TFMR-gen2:**
  - Track-pitch below about 9 μm will be paced by industry.
  - New head-proximate edge-guide should be developed to support track pitch much less than 9μm.
  - Excess SNR still allows 100 Kbpi without switching to MP or BaF tape.
- **TFMR-gen3:**
  - At track-pitch = 1.5 μm (MR width = 0.8-1.0 μm), with less than 0.1 μm tape wander, S-VHS like tape could still be used but linear density should be reduced to 50 Kbpi to conserve SNR.
  - If advanced MP or BaF tape is introduced, linear density can be increased to at least 200 Kbpi.

Acknowledgments

The thin-film magnetoresistive heads were manufactured and processed by **Seagate Technology Inc.**, Springtown, Ireland. The authors would like to gratefully acknowledge the help of Mr. Mark Troutman, Dr. David Hutson of STI, Springtown and Dr. Peter Brew of STI, Minneapolis for their help in this project.

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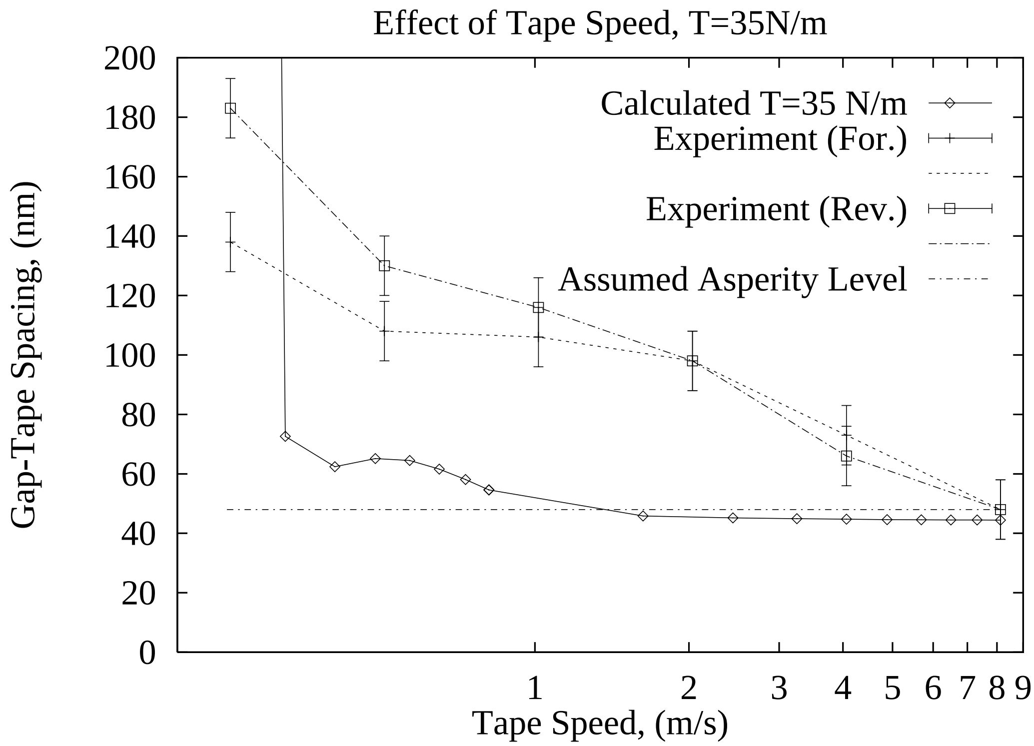
References

[1] Hans F. Hinteregger and Sinan Muftu. Contact tape recording with a flat head contour. *IEEE Transactions on Magnetics*, 32(5):3476–3478, September 1996.

[2] Sinan Muftu. *Computer software to analyze the mechanics of the head-tape interface: p4 ver. 2.24.* June 1998.

[3] Sinan Muftu and Hans F. Hinteregger. The self-acting, subambient foil bearing in high speed, contact tape recording with a flat head. *STLE Tribology Transactions*, pages 19–26, January 1998.

Measured and Calculated Head Tape Spacing Values



Discussion

- 1D head/tape interface model predicts [2] lower spacing than experiments.
- Experiments and the theory agree well qualitatively on the "self-acting negative foil bearing" effect over a flat head, i.e. **suction effect** [1, 3].
- Quantitative discrepency is attributed to the side air flow.

Calculated Head Tape Spacing Values

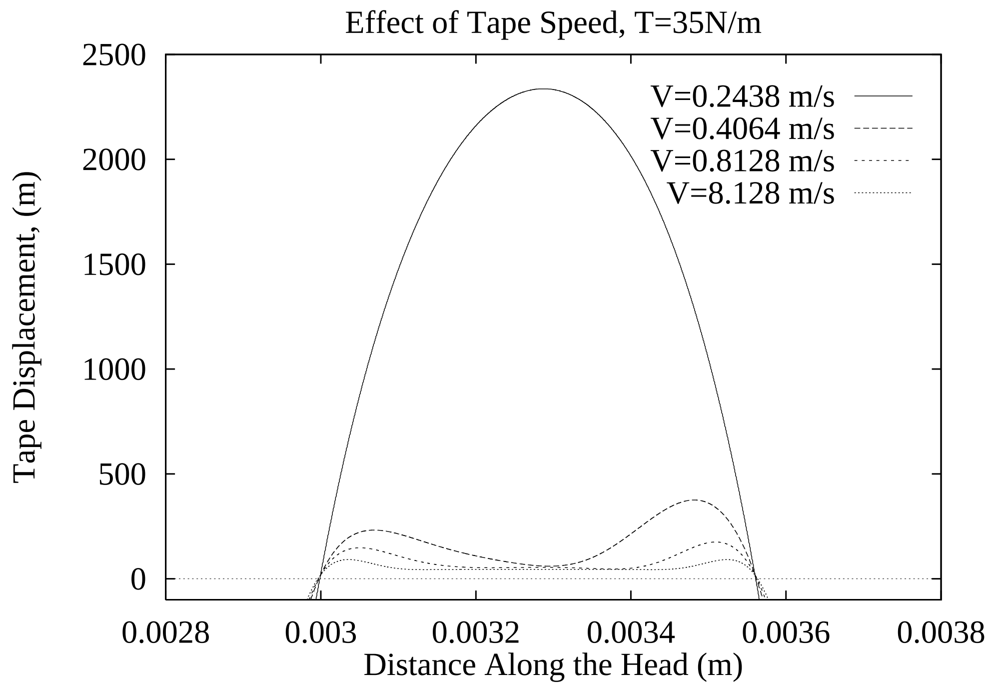


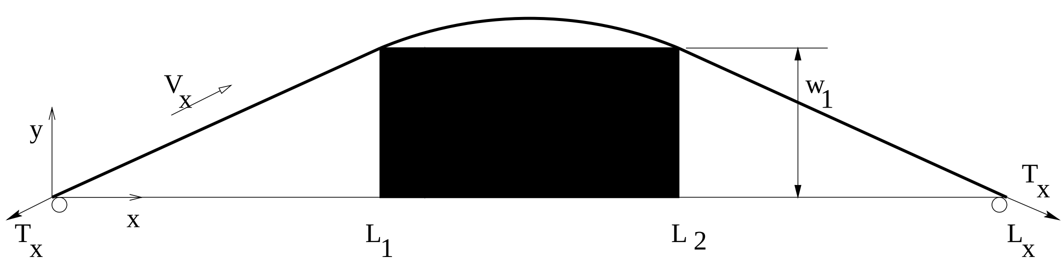
Figure 1: At the lower tension of 35 N/m it takes a considerably higher tape speed to "snap" the tape into contact. Shown are the tape speed of 0.24, 0.41, 0.81 and 8.1 m/s.

- The tape tends to take a "cupped" shape over the head at low speeds ($V < 0.23$ m/s.)
- As the tape speed is increased the "suction" generated under the tape causes the tape to deform toward the surface.

Model of the Head-Tape Interface

$$
\begin{array}{llcll}
\underline{\textbf{Tape Eqn.:}} & r_t & = & D\frac{d^4w}{dx^4} + (\rho_a V_x^2 - T_x)\frac{d^2w}{dx^2} - (p - P_a) - P_c = 0 & (a) \\
\underline{\textbf{Reyn. Eqn.:}} & r_p & = & \frac{d}{dx}[ph^3\frac{dp}{dx}(1 + 6\frac{\lambda_a}{h})] - 6\mu V_x\frac{d(ph)}{dx} = 0 & (b) \\
\underline{\textbf{Contact P.:}} & P_c & = & \frac{P_{max}}{\sigma_t^2}(h - \sigma_t)^2[1 - H(h - \sigma_t)] & (c) \\
\underline{\textbf{Spacing:}} & h & = & w + \delta & (d) \\
\underline{\textbf{Disp. BC:}} & w & = & -w_1, \frac{d^2w}{dx^2} = 0 \text{ at } x = 0,\ L_x & (e) \\
\underline{\textbf{Pressure BC:}} & P & = & P_a \text{ at } x = L_1, L_2 & (g)
\end{array}
\quad (2)
$$

Coordinates for Head-Tape Interface Model



Nomenclature

x	Coordinate axis	P_c	Contact pressure
w	Tape displacement	$P_{max} = 10MPa$	Contact pressure at $h = 0$
h	Head-tape spacing is	$\sigma_t = 48nm$	Asperity engagement height
$D(= \frac{Ec^3}{12(1-\nu^2)})$	Bending stiffness	H	Heaviside step function
T_x	Tape tension	$E(= 4GPa)$	Modulus of elasticity
V_x	Tape speed	$\nu(= 0.3)$	Poisson's ratio
p	Air pressure	$c(= 15\mu m)$	Tape thickness
$P_a(= 101.3kPa)$	Ambient pressure	w_1	Tape disp., $x = 0, L_x$
$\lambda_a(= 63.5nm)$	Molecular mean-free path	r_t, r_p	Residuals
$\mu(= 18.5\mu Nsm^{-2})$	Air viscosity		