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TAPE RECORDERS FOR VLBI

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ABSTRACT Magnetic tape recorders developed for VLBI have taken advantage of the best available technology to achieve high data rates and large storage capacity. The Mark I,II and III VLBI recording systems have data rates of 0.72, 4 and 224 Mbits/sec respectively. The recorder developed for the VLBA has a data rate of 256 Mbits/sec and can store 5.5 Terabits of data on one tape.

INTRODUCTION

Very Long Baseline Interferometry (VLBI) has almost exclusively used magnetic tape recorders as a means of conveying the signals to the correlator. The first digital VLBI system, known as Mark I and introduced in 1967, used a 7-track computer transport to record a 360 KHz bandwidth baseband signal. The 2400 foot reel of half-inch wide computer tape lasted only three minutes. In Canada, the pioneering VLBI team used analog recording on a studio TV recorder. The "Mark II" system, introduced in 1971, records a 2 MHz bandwidth baseband signal using one bit per sample at the Nyquist rate of 4 Mbits/sec. Initially Mark II used an Ampex VR-660 TV recorder with 2-inch wide tape but later evolved to use the consumer VCR with VHS cassettes. The "Mark III" VLBI recorder, introduced in 1977, returned to the longitudinal transport but with 28 heads, each recording a 2 MHz bandwidth or 4 MHz in "double" speed mode. Initially the Mark III used only fixed heads and, like Mark I, used vast quantities of tape. Now the Mark III has evolved to Mark IIIA which uses moveable "headstacks" to write 336 tracks across 1-inch wide tape in 12 passes. The recorder recently developed for the Very Long Baseline Array (VLBA) carries the technology further by increasing the density of bits along each track on the tape from 33,000 per inch to 56,000 per inch. In addition, the VLBA recorder uses thinner tape and an increase in track density so that an 18,000 foot long 14-inch diameter reel of tape holds 5.5 Terabits of VLBI data. The Japanese VLBI group in collaboration with the Sony Corporation has developed a recorder with similar capabilities to the VLBA recorder but using the professional ID-1 helical scan format. A comparison of the VLBA and ID-1 recorders is shown in Table 1.

TABLE 1 Comparison of ID-1 and VLBA recorders

	ID-1	VLBA
Recorder type	Helical	longitudinal
Head speed at 256 Mb/s (m/s)	40	4
Current max. rec. rate (Mb/s)	256	256
Rate expected with upgrade(Mb/s)		1024
Tape package	D1-L cassette	14" reel
Tape package volume (cm^3)	2500	3000
Weight of packaged tape (kg)	2.7	4.7
Current tape thickness (μm)	16	16
Planned tape thickness (μm)	13	13
Capacity of one 13 μm tape (Tbits)	0.92	5.5
Recording time at 128 Mb/s (hours)	2	12
Error-correction code	yes	no

The Canadian group is developing another system based on multiple S-VHS recorders. Current expectations are that this system will use eight cassette recorders to record 128 Mbits/sec.

At present magnetic media allow the highest volume density. The recorded bit in the present VLBA format is 0.4 μm long by 38 μm wide by 0.3 μm thick, the effective thickness being increased by the thickness of the base film. Other media, like a laser disc, have a high areal density but poor volume density. Figure 1 shows the areal densities for various recording systems.

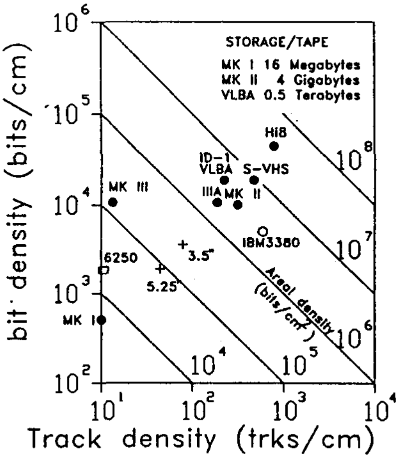

Fig. 1. Densities of magnetic recording systems. The VLBA and ID-1 recorders have almost the same bit and track densities.

Data format for VLBI

VLBI data is now always recorded digitally, as analog recording yields results which depend on the quality of playback. For continuum sources one bit (the sign bit) per sample is simple to implement and almost optimum (D'Addario 1984) in the sense that the SNR is maximized for a fixed number of bits recorded. 2 bits/per sample is almost as efficient (6% less) for continuum, conserves bandwidth, and improves the SNR for spectral line by 37%.

Data is divided into blocks variously known as records, frames or packets. The beginning of frame is marked by a header with "sync" bits containing a pattern that cannot occur in the data with any significant probability. The header also contains auxiliary information and enough time information to uniquely time tag the data bits. Random errors in the data are not serious as they only decrease the SNR. Errors in synchronization or incorrect time tagging of the data such as occurs when the clock recovery "slips sync" are more serious as they bias the correlation. Most VLBI formats, like the Mark III and VLBA, contain CRC and parity for monitoring errors or discarding data blocks but do not presently incorporate codes for error correction. Table 2 gives the specifications for the VLBA recorder.

TABLE 2 VLBA recorder specifications

Average recording rate:	100 Mb/s for 24 hours unattended
High data rate:	200 Mb/s or greater
Fraction of bits out of sync but flagged valid:	$< 10^{-5}$
Fraction of bits which are incorrect and flagged valid (excluding bits out of sync):	$< 3 \times 10^{-4}$
Fraction of bits flagged invalid:	< 0.01
Weight of tape/day/station	< 25 lbs at 100 Mb/s

Magnetic recording fundamentals

The reproduce process consists of detection of the magnetic fields set up by the previously recorded pattern of magnetization of fine particles in the tape. The ring heads, schematically illustrated in Figure 2 and used in most recorders, develop a voltage in response to the changing flux linkage through the head coil.

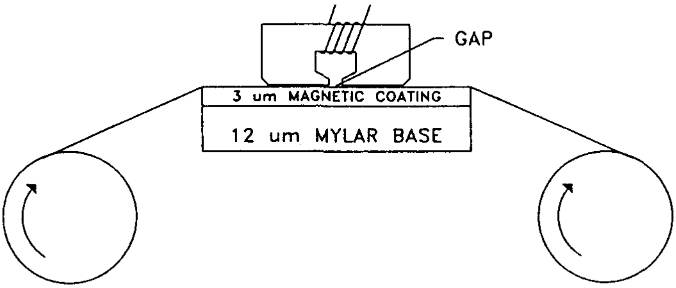

Fig. 2. Ring head

The response to an idealized longitudinal recording of wavelength λ is given by Bertram (1986) as the product of several terms:

a) Gap loss

$$\frac{sin(1.11kg/2)}{1.11kg/2}$$

where k=wavenumber = $\frac{2\pi}{\lambda}$, and g= gap length

b) Spacing loss

$$e^{-kd}$$

where d= spacing between head and media

c) Record depth

$$\frac{(1-e^{-k\delta})}{k\delta}$$

where δ= depth of recording

which show the extreme importance of having a very short gap and very close spacing between the gap and the magnetic particles. There is a null in the head response when the wavelength equals the effective gap length and the head output decreases by 55 dB per wavelength separation.

The record process is very complex in comparison with the reproduce because of interaction between magnetic particles. Without interaction the head field encountered by an individual particle will determine its state if the field exceeds the coercivity. The resulting magnetization is given by the magnetic remanence of the particle. On S-VHS tape, the particles are about 0.2 x 0.1 μm and are oriented in the plane of the tape with long dimension in the direction of tape motion. When the particle interactions are considered, it is difficult to record an abrupt magnetic transition in which particles are all magnetized in one direction, followed by others all magnetized in the opposite direction. The interactions produce a demagnetization which limit the transition to some finite length. Current magnetic theories and models place this transition length at about 0.1 μm for S-VHS or D1 tape. The transition length is influenced by the head field gradient and a separation between the gap and the magnetic particles. Since the transition width has the same functional form as the spacing loss, an increase in transition length produces an equivalent increase in "record spacing loss". This is not as severe as the reproduce spacing loss as head-media separation during record produces a loss of about 20 dB per wavelength for the VLBA heads on D1 tape. Figure 3 shows "headcurves" made with the VLBA recorder using both D1 and metal evaporated tape (MET). These curves were made by recording and reproducing square waves of varying wavelength. The record depth and spacing loss can be estimated by fitting these curves to the theoretical expression for reproduce signal. The "gap null" can be clearly seen.

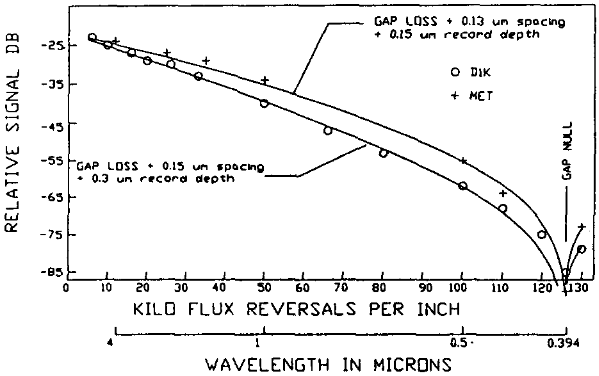

Fig. 3. "Headcurves from VLBA recorder"

VLBA recorder

1] Tape transport

The VLBA recorder uses the Honeywell Model 96 tape transport with tape whose path is shown in Figure 4.

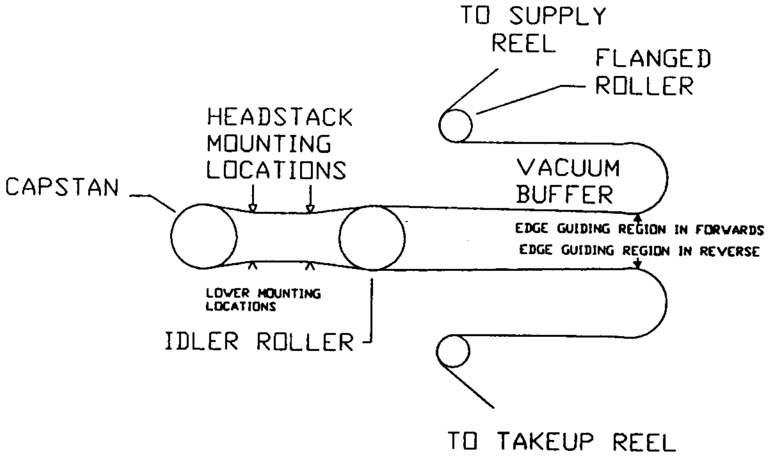

Fig. 4. Tape path in Honeywell model 96 transport

The vacuum buffers serve to provide a uniform tape tension and edge guiding of the tape path for tracking that is repeatable at the μm level. The walls of the vacuum compartments are slightly tilted to provide a force which pushes the far edge of the tape into a precision plate at the regions of edge guidance shown in Figure 4. A vacuum of 10" of water produces a tape tension of 2.2 N (0.5 lbs). This tension with a 10 degree wrap around the heads with 300 μm contact arc length produces a contact pressure of 48 KPa which is adequate to maintain head to tape contact without flying for speeds up to 8 m/s.

2] Headstack positioner

High track densities are achieved by utilizing a stack of 36 heads separated with a pitch of 698.5 μm, where each head has a trackwidth of 38 μm. The headstack is moved between recording passes by an amount sufficient to provide a small guardband from the adjacent pass in the same direction. A larger guardband is provided between passes in opposite directions to accommodate the forward-reverse tracking signature which results from a change in the edge guiding point from upper to lower vacuum buffers (see Figure 4) and anisotropy in the elastic properties of the tape.

The headstack is moved by an Inchworm motor and its position is measured using an LVDT. The scale of the readout can be calibrated by moving the headstack by one pitch as determined by reproducing a signal previously recorded by an adjacent head. The readout zero offset can be accurately established by recording a single track at a location nominally in the center of the tape and then reproducing this track with the tape flipped over end for end (by exchanging supply and take-up reels). With zero offset, this center track will appear at the same headstack position with the tape flipped.

Headstack

The headstack is fabricated from a VHS gapped bar made of single crystal manganese zinc with .33 μm gap length, in which the individual headtips are defined by slotting of the gapped bar with a precision dicing saw. The material between headtips is filled with calcium titanate spacers and the magnetic circuits are completed by bonding a base with 48 turn fluxors to the "tip" plate formed from the gapped bar. A cross-section through one head is shown in Figure 5.

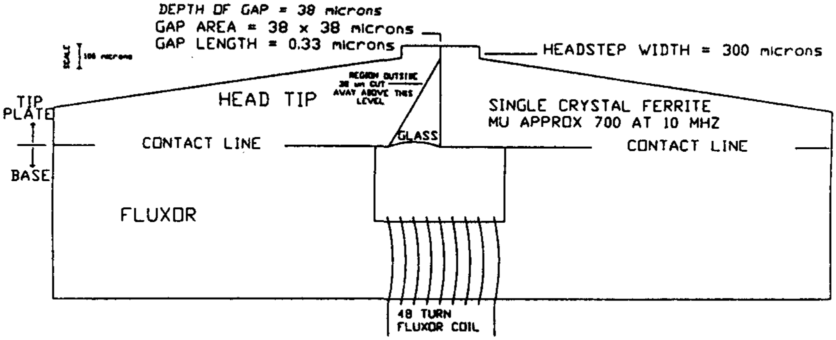

Fig. 5. Cross section of head

Transport and headstack control electronics

The transport and headstack are controlled using a combination of commercial and custom VME-based digital electronics. The control intelligence resides in a Motorola 68010 microprocessor. The transport analog control electronics, part of the standard Honeywell model 96, is interfaced directly to the VME digital electronics. All transport and headstack motion functions are available via serial communication with the VME computer on board. Accurate speed control is provided for synchronization of tapes at the processor. The overall VLBA recorder layout is shown in Figure 6.

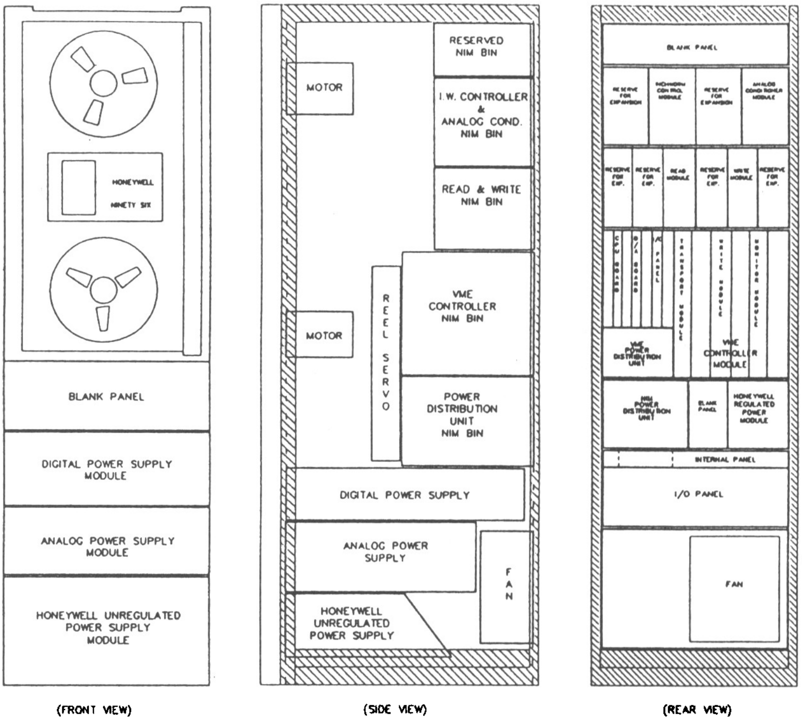

Fig. 6. Recorder rack layout - dimensions 22”x29”x77”

Signal electronics

The signal electronics is deliberately kept as simple as possible. Write electronics consists of line receivers, signal reclocking and head current drivers. The digital signals for recording are generated in a separate data acquisition rack which contains VLBI specific A/D conversion and formatting electronics. Each head is driven by an NRZ-M data stream made up of blocks with a synchronization word, time of day, auxiliary data, and A/D output data. CRC check characters and parity bits are recorded along with the data bits from the radio source.

Reproduce electronics consists of pre-amplifiers, which are close to the heads, post-amplifiers, equalizers, D.C. restoration, comparators and bit synchronizers. The “flat equalization” detection method is very simple and produces the binary “eye pattern” shown in Figure 7.

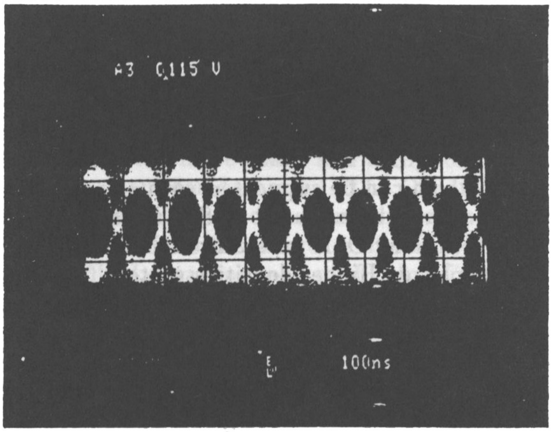

Fig. 7. "Eye" pattern from VLBA recorder

This type of detection is used in many commercial systems. Recently, Wood (1990) has compared this method with other more sophisticated methods usually involving "Viterbi" algorithm. Wood's comparison of detector types for the RDAT shows little gain (less than 1 dB) for the sophisticated methods over the simple flat equalization. Because the VLBA code is not completely D.C. free, a "D.C. restoration" circuit (Huber 1981) is added and the signal and noise path is shown schematically in Figure 8.

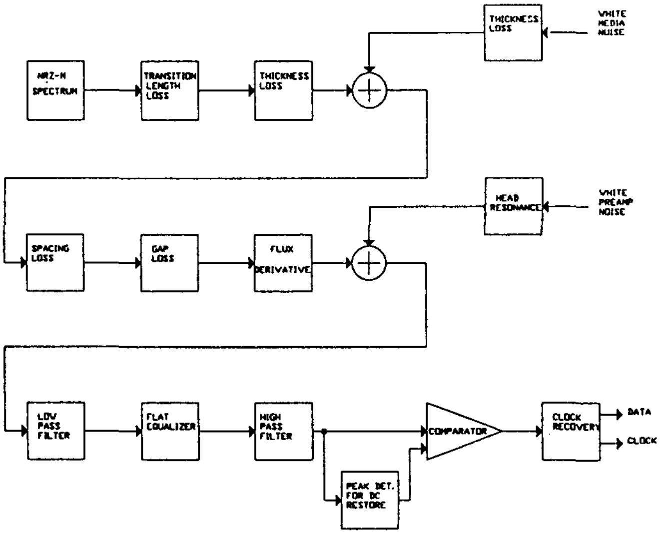

Fig. 8. Reproduce signal and noise path

The data acquisition recorders also contain some limited capabilities for decoding the VLBI format so that checks can be made of the playback quality of each head. The same heads are used for both record and reproduce as accommodated by read/write circuitry attached to the head coils.

Recording characteristics and limitations

The density of flux reversals which can be supported with a tape whose magnetic and surface characteristics are similar to D1 or S-VHS is 2.25 flux reversals (fr)/μm (57.15 Kfrpi). With Sony D1K tape a broadband SNR of 18 dB is obtained at 9 Mbit/sec per head. Higher densities up to 3 fr/μm (75 Kfrpi) can be achieved but the BER drops from 10^{-5} to 10^{-3}. The better short wavelength response and output of metal evaporated tape (MET), (shown in Figure 3) would allow reliable operation with densities in the 3 fr/μm range with the present head. In the future, new heads using a shorter gap and higher saturation materials will be needed to take full advantage of MET.

There is a trend towards thinner tapes to increase the area of tape on a reel. Small quantities of 16 μm thick tape are presently undergoing operational tests on the VLBA recorders. This tape is packaged in 18,000 foot lengths on 14-inch reels. Laboratory tests have been made with even thinner tapes down to 4 μm. At present, however, these very thin tapes are not available in quantity. A tape inventory with various thickness poses some special problems as the head profile worn by the tape depends on its thickness. The profiles can be computed from the mechanics of a bending beam under tension. There is often a problem in using a thin tape on a head whose profile was worn by a thicker tape. A transition between 25 and 16 μm thick tape can be made by operating the thick tape at higher tension. Figure 9 shows the initial head-to-tape separation for running a 16 μm tape on a head worn by 25 μm tape. If the 25 μm tape is run at 16 inches vacuum then the separation is less than 0.05 μm for 16 μm tape run at a vacuum of less than 7 inches. Even if there is an initial separation it will be worn away as all tapes are made to be slightly abrasive as a means of maintaining good performance. The typical wear rate is about 0.005 μm per hour at humidities less than 60% but can increase by a factor of ten or more at high humidity.

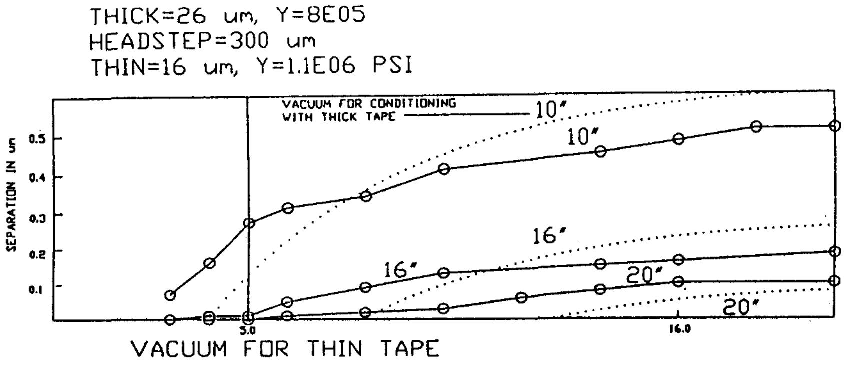

Fig. 9. Spacing between tape and gap for replay of a thin tape after running a long time with thick tape. Dotted lines are theory and small circles are measured points.

Conclusions

VLBI recorders are close to the state-of-the-art and will benefit from continued development aimed at taking advantage of new tapes as they become available at reasonable cost. The VLBA recorder can be upgraded for higher data rates by using more heads and a Gigabit/sec record rate (Hinteregger et al. 1990) has been demonstrated. The Canadian and Japanese VLBI recorders take greater advantage of commercially available systems. In the event that VLBI is carried out with a mixture of recorders there is a need to be able to transcribe VLBI data from one media and format to another. Alternately the processors will be required to have multiple playback systems.

Acknowledgements

The high density longitudinal recorder is the brainchild of Hans F. Hinteregger of Haystack Observatory. He developed the narrow track headstack and has successfully transferred this technology to industry. Others who have made major contributions to the VLBA recorders are John C. Webber (now at Interferometrics, Inc.), William T. Petrachenko (now at the Canadian Geological Survey), Roger Cappallo (Haystack Observatory), Daniel L. Smythe (Haystack Observatory), George Peck (NRAO), and the Honeywell Test Instruments Division (now Metrum Information Storage) under the leadership of Harry Allen.

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