Very Long Baseline Interferometry and the VLBA
ASP Conference Series, Vol. 82, 1995
J. A. Zensus, P. J. Diamond, and P. J. Napier (eds.)

Printed June 13, 1995

CHAPTER 6

VLBA Data Flow: Formatter to Tape

ALAN E. E. ROGERS
HAYSTACK OBSERVATORY

Abstract This chapter presents details of the design and performance of the formatter unit, which prepares digital data samples for recording, and of the tape recorders used to record the data collected at each VLBA site.

Contents

6.1 Introduction **94**
6.1.1 Why Magnetic Tape? 94
6.1.2 VLBI Recording Systems 94
6.2 The VLBA Data Format **97**
6.2.1 Longitudinal Format 97
6.2.2 Transverse Track Format 98
6.2.3 Data and Non-Data Replacement 98
6.2.4 Track Width and Track Structure 98
6.3 The VLBA Formatter **99**
6.3.1 Digital Switch Board 100
6.3.2 Header Control Board 101
6.3.3 Transport Driver Board 101
6.3.4 Timing and Control Board 102
6.3.5 Data Buffer Board 102
6.3.6 Quality Analysis Board 102
6.4 Magnetic Recording Fundamentals **103**
6.4.1 Recording Losses 103
6.4.2 Wavelength Response 104
6.4.3 Head-to-Tape Contact and Tribology 104
6.5 The VLBA Recorder **105**
6.5.1 The Tape Transport 105
6.5.2 The Headstack 105
6.5.3 The Headstack Positioner 106
6.5.4 Control Electronics 106
6.5.5 Signal Electronics and Eye Pattern 107
6.6 Recorder Characteristics and Limitations **108**
6.6.1 Error Rate Versus Bit Density 108

6.6.2 Tape Thickness Interchange 108
6.6.3 Head Flying 109
6.6.4 Overwrite 109
6.6.5 Tracking Errors 109
6.6.6 Headlife and Humidity 110
6.6.7 Thin Tape and Edge Damage by Frictional Heating 111
6.6.8 Tape Reel and Shipping Canister 111
6.7 Future VLBI Recording Systems 112
6.7.1 Expansion Paths for the VLBA Formatter 112
6.7.2 Recorder Improvements 112
6.7.2.1 Thinner Tape 112
6.7.2.2 Higher Data Rates 113
6.7.2.3 Next Generation of Heads 113
6.7.3 Mark IV 113
6.8 Summary and Conclusions 113

6.1 Introduction

6.1.1 Why Magnetic Tape?

Direct data transfer at rates of 100 Mb s^{-1} from many sites via satellite or fiber optic cables is still much more expensive than recording and shipping the recorded media. In the future, fiber-optic cables may be used and VLBI will become more like connected-element interferometry. Magnetic media are very well suited to VLBI for the following reasons:

1. There are few limits to the speed at which a particle can be magnetized so that within the limits of tape use the data rates are virtually unlimited.

2. The magnetic media is inexpensive, easily erased and can be recorded many times.

3. In the length dimension, the size of a recorded bit can be made smaller than the wavelength of light. Many optical recording systems are limited by the wavelength of light and therefore magnetic recording densities are comparable to, or better, than optical recording systems.

6.1.2 VLBI Recording Systems

Mark I: The Mark I was a VLBI recording system (Broten et al. 1967) based upon a computer transport which is now largely obsolete. A 360 kHz bandwidth was Nyquist sampled with 1-bit per sample at 720 kb s^{-1} and formatted into record blocks of 0.2 s duration. Time was not written on the tape but was derived from the record number and bit number following the start of the data which was precisely determined to within one sample. Tapes were 700 m (2300 ft) long, 1/2 in in width, used 7 tracks, and contained 140 Mbits of data. In the original use of Mark I the data were correlated in a general purpose computer. Later a hardware correlation array processor was added as a peripheral to the computer and operated at the Haystack Observatory. Other early recording systems used analog recording (Broten et al. 1967). Digital recording and digital correlation has become the preferred method for VLBI.

Mark II: The Mark II system (Clark 1973) uses a slightly modified television video recorder. A bandwidth of 2 MHz is Nyquist sampled at a 4 MHz rate and formatted along with a frame count into data frames of 66,000 bits. One audio channel is used to encode the day and time of day with enough precision to allow the time of a recorded bit to be calculated from a combination of the position of a bit within a frame, the frame number and the digital data on the audio channel. The Mark II is still in use and has been constantly upgraded to use the most economical TV recorders.

Before the availability of the VCR, several studio machines were used. The current version of the Mark II uses a VHS recorder with a few minor changes including elimination of the TV modulator and a more direct connection from the formatter to the heads. The VLBI formatting electronics which samples the data, formats, and encodes the audio and video channels, has changed little since its introduction in 1970. Most Mark II data acquisition systems also have a decoder to allow verification of the audio time code data and checks on the video playback. Several Mark II correlators were built and are still in operation. Seven Very Long Baseline Array (VLBA) sites were equipped with Mark II to help support initial operations, while the large correlator for the VLBA recording system was completed. VLBA support of Mark II observations was discontinued in January, 1995. A small number of specially arranged Mark II experiments can be correlated at the California Institute of Technology.

Mark III and IIIA: The Mark III (Rogers et al. 1983) is based on a 1-inch longitudinal instrumentation recorder (originally a Honeywell Model 96, now available as Metrum Model 96; also used is a compatible Penny and Giles Data Systems Model MDR transport). The original implementation used standard 28-track fixed headstacks to record 28 bands, each 2 MHz wide, in a longitudinal format, and provided the same recording capacity as would be obtained by running 28 Mark II terminals simultaneously. Each recorded track is formatted into blocks of 20,000 bits with complete time information at the start of each block replacing a small amount of astronomy data which would have occupied these bits. The recorded data bytes (eight data and one parity bit) could be monitored for quality with another headstack. In practice the read-while-write capability is degraded by cross-talk and only read-after-write is used to check that tapes have been satisfactorily recorded. Unlike the Mark II which has to operate at a fixed data rate the Mark III can record at various sample rates and corresponding tape speeds up to 270 inch s^{-1}(4 MHz bandwidth or 8 Mb s^{-1}per track) and with subsets of tracks enabled. For geodesy a frequently used mode employs 14 tracks to record a total of 56 Mb s^{-1}. In this mode the 14 odd tracks are recorded forwards and the 14 even tracks in reverse making the tape last twice as long and ending with it rewound.

In 1985 a major innovation, known as Mark IIIA (Hinteregger 1982), was made in Mark III to increase the amount of data stored on one tape. A movable headstack assembly was developed to record up to 28 tracks per pass each with 38 μm width so that many passes could be recorded on one tape by moving the headstack between passes to provide adequate guard bands between recorded tracks. For example, the 14 track geodetic mode records 24 passes giving a twelve-fold increase in data storage.

K3: A Mark III compatible system was developed by a group in Japan using the same recorder but with slightly different electronics. The K3 is fully compatible (Kawaguchi 1991) with, and essentially equivalent, to Mark III.

VLBA The Mark IIIA system has been redesigned using modern electronics for the VLBA (Hinteregger et al. 1991). To simplify and reduce operating costs the VLBA recorder uses a single headstack for recording and for playback. The VLBA recorder has VME based electronics with a built-in computer so that more sophisticated commands, self-calibration of pass locations, and diagnostics can be performed. The VLBA formatter is very flexible and provides a variety of programmable formats of which the Mark III is one. A VLBA format is now in use which is similar to Mark III but the time and other ancillary data are encoded as added bits and do not replace astronomy data as in the Mark III. In addition to the 1 bit/sample modes, the VLBA format includes 2 bit/sample modes. As currently implemented, the VLBA recorder has a maximum data rate of 256 Mb/s and VLBA sites are presently equipped with eight baseband converters, one formatter, and two recorders. Two recorders allow operations at 128 Mb/s with only one tape change period in 24 hours. The system is expandable and with added formatter boards can record up to 512 Mb/s. VLBA sites will be equipped with this expansion in 1995. Future upgrades would include Mark IV compatibility.

Mark IV: The Mark IV system (Whitney et al. 1991) is an upgrade of the Mark IIIA recorder to allow operation at data rates up to 16 Mb/s per track on up to 64 heads simultaneously for a maximum total rate of 1 Gb s^{-1}. A new formatter (plug-compatible with the original Mark III formatter) has been developed. In addition, the Mark III video converters are outfitted with 8 MHz filters and the formatter includes 2-bit/sample modes. Both the Mark IV and VLBA recorders have upgraded mechanics to allow the use of 5500 m (18,000 ft) lengths of thin (16 micron) tape on 14 in reels so that one reel can store 4.5 terabits.

K4: The Sony ID-1 19 mm cassette recorder (Kawaguchi 1991) has been adapted for VLBI and is known as K4. The system is Mark III compatible via the use of special interface electronics. Since ID-1 is already a digital recording standard there was no need for VLBI-specific recorder electronics. Like other VLBI systems the IF conversion and VLBI sampler/formatter are contained in a separate electronics rack. The K4 has a maximum record and playback rate of 256 Mb s^{-1}. K4 also supports a "burst" mode in which data can be stored in

Table 6.1: VLBA playback specification

Fractions of bits out of sync but flagged valid	$< 10^{-5}$
Fraction of bits which are incorrect and flagged valid (excl. bits out of sync)	$< 3 \times 10^{-4}$
Fraction of bits flagged invalid	< 0.01

bursts at a much higher rate.

S2: A recording system based on the VHS recorder (Wietfeldt et al. 1991; Wietfeldt and D'Addario 1991) has been developed in Canada. With eight transports this system, known as S2, can record and play back 128 Mb s^{-1}. Data sampling rates are compatible with the VLBA. S2 tapes have been copied to Mark III format for compatibility tests and future VLBI processors are expected to support the S2 format either by transcription or direct interface to the correlator.

Figure 6.1 shows the relative capabilities of the various VLBI recording systems.

6.2 The VLBA Data Format

VLBI data is 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%.

6.2.1 Longitudinal Format

Data along a single track 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 possibility. 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 very serious as they bias the correlation. VLBI formats, like the Mark III and VLBA, contain CRC (cyclic redundancy check) and parity for monitoring errors or discarding data blocks but do not presently incorporate codes for error correction. For the VLBA, the specification for playback quality is given in table 6.1.

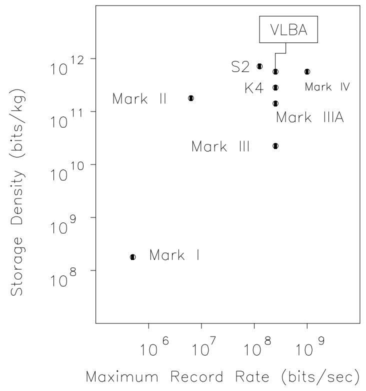

Figure 6.1: VLBI recording systems

6.2.2 Transverse Track Format

In the simplest modes, a single track contains the "sign" bits (1 bit per sample) from the upper or lower sideband output from two single baseband converters. In the 2-bit per sample modes, the "magnitude" bits are put on another track. At high sample rates the data from a single sampler can be "fanned-out" to several tracks. Conversely at low sample rates the data from many basebands can be "fanned-in" to a single track.

In order to equally distribute the effects of unreadable tracks among all the baseband channels the track assignments can be permuted each frame in a "barrel-roll". In this way, with barrel-rolling turned on, each track will contain the data from a different baseband for each frame in a manner which repeats every n frames (where $n = 1, 2$, or 4).

6.2.3 Data and Non-Data Replacement

The VLBA formatter has the ability to insert the sync words and auxiliary data without replacing any of the astronomy data from the samplers. The simpler Mark III and Mark IV formatters replace the astronomy data with sync words and auxiliary data during the time that the header is inserted. Another feature available in the VLBA formatter is the ability to multiply the sampled data with a pseudo-random code to "whiten" the spectrum and avoid higher error rates which can occur when the baseband contains a strong maser line.

6.2.4 Track Width and Track Structure

The VLBA headstacks (which have 36 heads) record a track width of 38μm with a separation between heads (known as the head pitch) of 698.5μm. The recorded tracks fill up the available area across the tape in several passes. Each pass is written with a different head position in such a manner that small guard

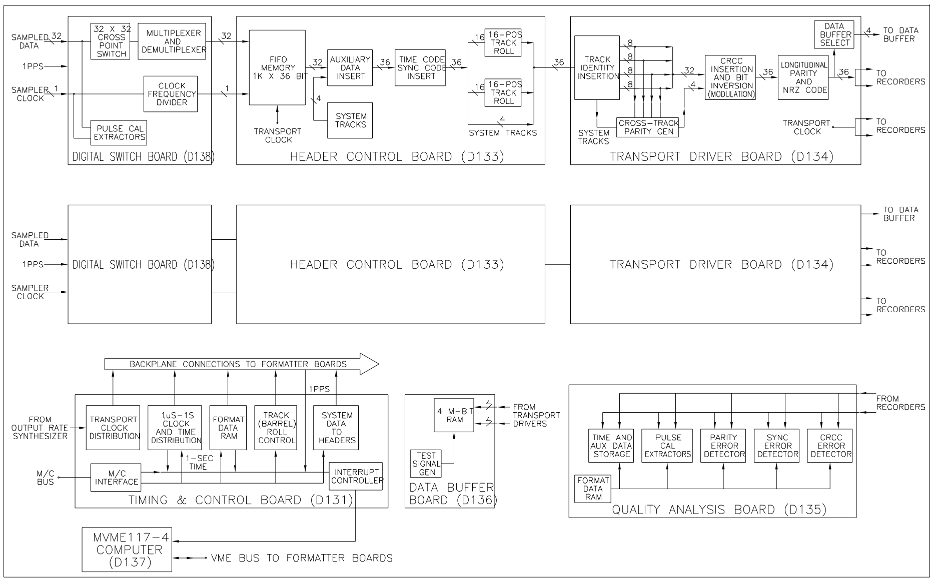

Figure 6.2: Simplified block diagram of VLBA Formatter (Thompson 1993)

bands exist between the recorded tracks. The standard format records a total of 576 tracks in 14 passes (7 forward and 7 reverse).

6.3 The VLBA Formatter

This description of the VLBA Formatter is taken primarily from Thompson (1993). The formatter takes the digital data streams from the two sampler modules described by Thompson (this volume, section 5.7 on page 82) and rearranges them into the data streams required for input to the tape recorders. In the process the header information, parity bits, etc., described in section 6.2 above are added. The two sampler modules can process a total of 16 basebands, each sampled at 32 Mb/s, with a maximum of two bits per sample. The corresponding maximum data rate is 1024 Mb/s. A VLBA tape recorder has 36 heads recording in parallel, of which 32 are for data and four for other system requirements. The maximum recording rate is 8 Mb/s per track, or 256 Mb/s for 32 tracks. Two tape recorders will handle a total data rate of 512 Mb/s, just half the maximum output of the baseband converters. The formatter therefore selects the data as required and produces up to 64 data streams and eight system streams for the 72 tracks of the two recorders. An important feature of the VLBA formatter is that it allows a wide selection of format parameters, chosen values for which are loaded into the formatter from the site control computer during initialization. These include the length of a frame, the length and definition of the header, whether or not data are lost when the header is written, multiplexing or demultiplexing of data streams onto recording tracks, the implementation of longitudinal parity, cross-track parity, a CRCC correcting code, a track (or "barrel") roll of the data streams relative to the recording tracks, and other features. The standard format chosen for VLBA observations is defined in detail in VLBA Specification A56000N003. The Mark III VLBI format is also commonly implemented with the VLBA formatter. A simplified block diagram of a formatter is shown in figure 6.2. It is built in a VME chassis and contains six types of modules in the form of VME boards as well as a MVME117-4 computer. The board types are referred to by the following names:

1. Digital switch (DS)
2. Header control (HC)
3. Transport driver (TD)
4. Timing and control (TC)
5. Data buffer (DB)
6. Quality analysis (QA)

6.3.1 Digital Switch Board

The input data from the samplers first go to a 32×32 crosspoint switch in the digital switch board. This switch connects the 32 input bit streams into the 32 data tracks for one recorder. One input stream can be reproduced on more than one output track if required, but any track can be connected to only one input stream at this point. The 32-track streams then go to a multiplexer and demultiplexer. The maximum output bit rate for the recorder tracks is 8 Mb/s, so for baseband bandwidths of 8 or 16 MHz the bit stream must be demultiplexed into two or four streams, or more if the tape recorder is running at less than the maximum rate. Similarly, if the baseband bandwidths are small, as in certain spectral line observations, data from several input streams can be multiplexed onto one output stream. For narrow bandwidths, the 32 Mb/s sampling rate results in redundant samples which can be discarded at this point. The 32 Mb/s clock is also divided down to the appropriate frequency for the output bit stream. Some special formats for testing can also be implemented. Each digital switch board also contains circuitry for extracting eight pulse calibration signals from the bit streams. These can be assigned one to each data stream or two or four at a time to the same stream. An early version of the digital switch board used an analog switch and was known as the A/D buffer board. It did not have the extraction circuitry for the calibration lines. A/D buffer boards have been replaced in the VLBA, but some may remain in use in other VLBA-type systems.

6.3.2 Header Control Board

The data streams next go to the header control board, and are clocked into a FIFO (first-in, first-out) array of dimensions 36×1000. The bits are clocked out with a higher speed clock to allow extra bits for parity or headers to be added. This second clock is known as the transport clock because it governs the bit rate of the data recording. The transport clock is generated in the output rate synthesizer board in the data acquisition rack. For the Mark III format, the transport clock rate is 9/8 times the input clock to allow for one longitudinal parity bit per 8 data bits. With this format, data are lost when the headers are added. The standard VLBA format is a non-data-replacement type and the transport clock is faster by a further small factor to allow for headers that do not overwrite data. The output rate synthesizer can generate the transport clock frequency for the Mark III format or for the VLBA format. The four system tracks are inserted just after the FIFO. They can be used to carry data streams for test purposes, or cross track parity bits which are added in the next board. Some, but not all, of the header bits are inserted at this point. The first 36 bits of the header are the sync word, and time and auxiliary data are also included in the header. In the VLBA format, some header-type data go at the end of the frame. Next, the track (barrel) roll operation is performed. In this operation, the assignment of data streams to recording tracks is rotated periodically within a group of tracks. The purpose of this rotation is to distribute any loss of data resulting from a bad write or read track equally over a number of data streams. Each data stream within a selected group steps periodically through each of the tracks assigned to that group. There are eight possible roll modes to choose from, some based on groups of eight tracks and some on sixteen. A step of the roll occurs at the end of each frame or at the end of a group of frames.

6.3.3 Transport Driver Board

The bit streams then go to the transport driver board where track identity data are inserted into the headers. Cross track parity is generated and can be recorded on one of the system tracks. Note that if one parity bit is generated for each eight tracks, the four system tracks are completely filled. Next, cyclic redundancy check characters (CRCC) are generated. In the VLBA format, this is done only for the time information in the headers. Longitudinal parity is then added, and the bit coding is changed to a non-return-to-zero (NRZ) form in which a one is represented by a transition and a zero by the absence of a transition. To facilitate clock recovery during a string of zeros, a periodic inversion of the data is inserted at the same point as the CRCC code. These inversions and the track roll transitions are removed on playback of the tapes at the correlator. The outputs of the board consist of the 36 data streams for the recording heads and the transport clock waveform. These go to the two recorders in parallel.

There are two of each of the three boards (DS, HC and TD) described above in each formatter. Each transport driver output is connected to the inputs of both tape recorders. Switches in the recorders select the inputs to be recorded. In some cases, both recorders are run simultaneously for maximum bandwidth recording, and, in other cases, the recorders are used alternately so that no observing time need be lost in changing tapes. Each formatter contains one each of three other kinds of boards, which are described below.

6.3.4 Timing and Control Board

The timing and control board performs a number of functions involving time-keeping and storing the format definition information. A clock in the board keeps time in the range microseconds to seconds, the coarser time information being provided by the control computer. The board also distributes the transport clock generated by the output rate synthesizer. It generates control waveforms for the track (barrel) roll functions and converts system status information into serial data that are included in the headers. The timing and control board contains the format data RAM which holds up to 65,535 16-bit words. Each word specifies one bit of the output data frame: the maximum frame length is thus 65,535 bits. However, the standard VLBA format uses only 22,680 bits per frame. The format data control the frequency of the transport clock, the size and content of the headers, the use of parity and CRCC codes, etc.. The board also contains the interrupt controller that processes interrupts, including the 1 pps station sync pulse and passes them on to the computer.

6.3.5 Data Buffer Board

The data buffer board allows extraction of sample quantities of data that can be transmitted to the AOC by the monitor and control data network. At the AOC data obtained in this way from two or more antennas can be correlated in a computer to obtain almost-real-time fringes. This provides a useful check on the correct functioning of a site. The board contains a 4 Mb RAM buffer which can be filled from one, two, or four tracks, the tracks being returned from the output of the transport driver board. The data buffer board also contains a test generator that can be used to fill the RAM for certain tests.

6.3.6 Quality Analysis Board

The quality analysis board performs an error analysis on two data tracks which are selected in the recorder and fed back to the formatter. The inputs are converted from the NRZ code to TTL, and as the data are scanned, 32 bits of time code or auxiliary data can be captured from each header. Synchronization errors, parity errors, and CRCC code errors are counted. The quality analysis board also contains circuitry for extraction of a pulse calibration signal. The extraction capacity is limited to one signal line per baseband channel and the frequency is limited to the sample frequency divided by 8N for 2-level quantization or by 16N for 4-level, where $1 < N < 32,768$ (Rogers and Nesman 1988). Note that

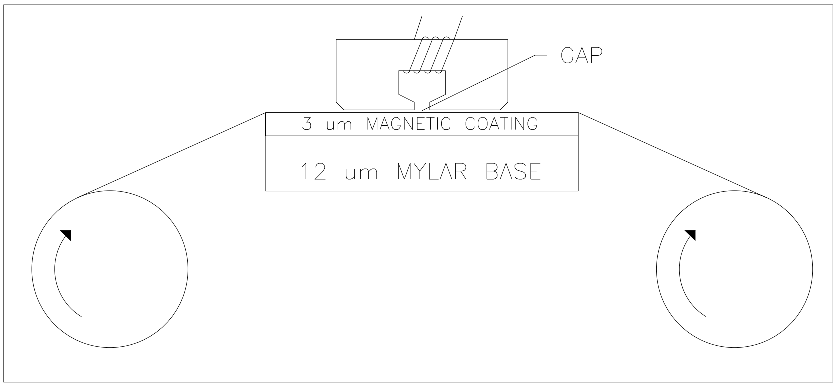

Figure 6.3: Ring read/write head

the extraction capability in this board was included to provide a basic testing capability before the larger and more flexible extraction capability in the Digital Switch Board was designed.

6.4 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 6.3, used in most recorders, develop a voltage in response to the changing flux linkage through the head coil.

6.4.1 Recording Losses

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

1. Gap loss $\frac{\sin(1.11kg/2)}{1.11kg/2}$, where $k = \frac{2\pi}{\lambda}$ is the wave number and g is the gap length.

2. Spacing loss e^{-kd}, where d is the spacing between head and media.

3. Record depth $\frac{1-e^{-k\delta}}{k\delta}$, where δ is the depth of recording.

These terms 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.

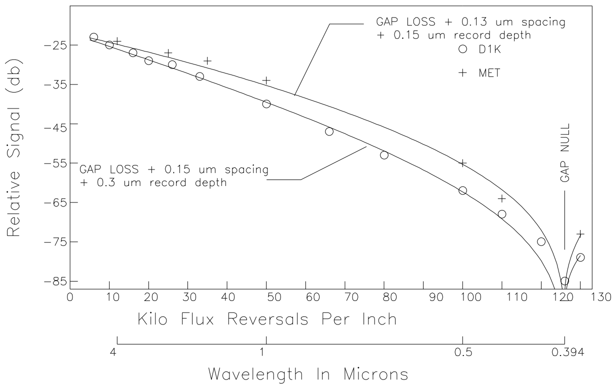

Figure 6.4: Headcurves for VLBA recorder

6.4.2 Wavelength Response

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 (Super-VHS) tape, the particles are about $0.2 \times 0.1\mu$m and are oriented in the plane of the tape with their 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 0.2μm 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 produces an increase in transition length or an equivalent "record spacing loss". This is not as severe as the reproduce spacing loss and we have measured a value of about 20 dB per wavelength for the VLBA heads on D1 tape. Figure 6.4 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.

6.4.3 Head-to-Tape Contact and Tribology

As can be seen from the exponential dependence of the spacing it is critical to maintain a very small head-to-tape spacing. On the other hand, too much friction and wear can severely limit the head life. The wear process, which is

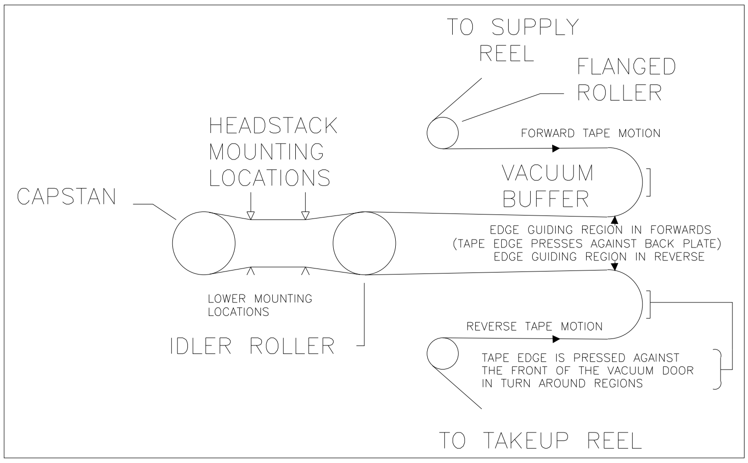

Figure 6.5: Tape path for Model 96

known as tribology (from the Greek $\tau\rho\iota\beta\omega\sigma$ tribos, meaning rubbing) is complex and depends on humidity. Heads much be kept clean and the tape must be slightly abrasive in order to maintain a clean contact without the deposition of "friction" polymers.

6.5 The VLBA Recorder

6.5.1 The Tape Transport

The VLBA recorder uses the Metrum (formerly Honeywell) Model 96 tape transport with tape whose path is shown in figure 6.5.

The vacuum buffers serve to provide a uniform tape tension and edge guiding of the tape path for tracking that is repeatable at the micron 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. These regions of edge guidance are as shown in figure 6.5. A vacuum of 10 in of water produces a tape tension of 2.2 N (0.5 lbs). This tension with a 10° wrap around the heads with 300μm 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^{-1}.

6.5.2 The Headstack

The headstack is fabricated from a single crystal manganese zinc ferrite "VHS-equivalent" gapped bar (Hitachi) with 0.33μm gap length, in which the individual headtips are defined by slotting of the gapped bar with a "super-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

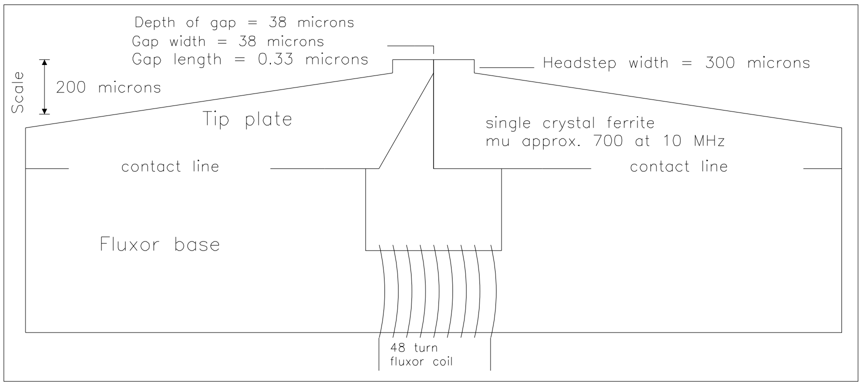

Figure 6.6: Head cross section

the "tip" plate formed from the gapped bar. A cross-section through one head is shown in figure 6.6.

6.5.3 The Headstack Positioner

High track densities are achieved by utilizing a stack of 36 heads separated with a pitch of 698.5μm. Each head has a trackwidth of 38μm. 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 mostly results from a change in the edge guiding point from upper to lower vacuum buffers (see figure 6.5) and anisotropy in the elastic properties of the tape.

The headstack is moved by a piezoelectric "inchworm" motor and its position is measured using an LVDT (linear variable differential transducer). 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.

6.5.4 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

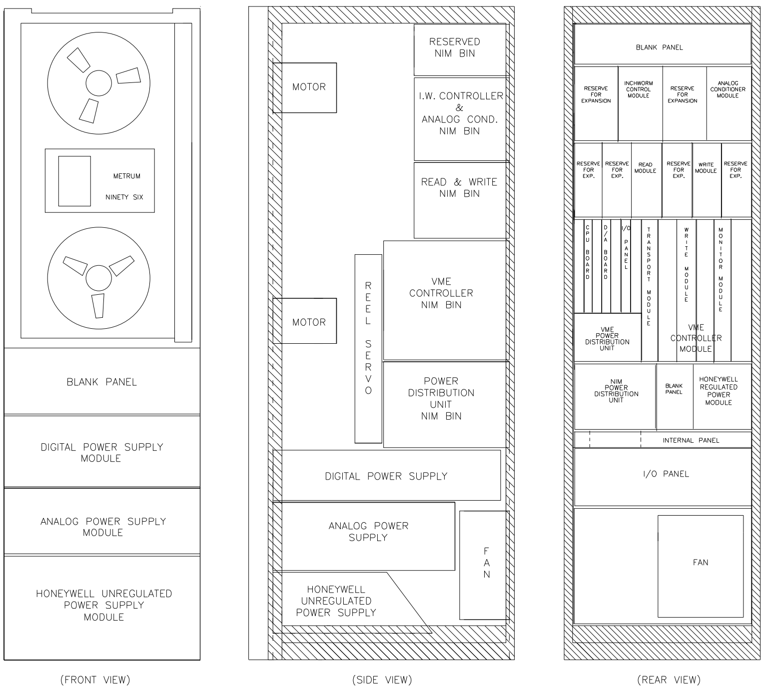

Figure 6.7: Recorder rack layout (dimensions 22 ft ×29 ft ×77 ft)

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 6.7.

6.5.5 Signal Electronics and Eye Pattern

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 (non-return-to-zero mark) data stream made up of blocks with a synchronization word, time of day, auxiliary data, and A/D output data. CRC (cyclic redundancy 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, DC. restoration, comparators and bit synchronizers. The "flat equalization" detection method is very simple and produces the binary "eye pattern" shown in figure 6.8. This type of detection is used in many com-

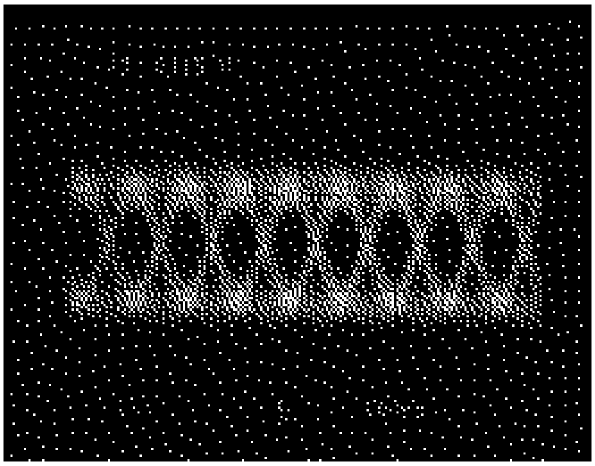

Figure 6.8: Eye pattern reproducing data written with 56,000 bpi at 160 in s^{-1}

mercial systems. Recently, Wood (1990) has compared this method with other more sophisticated methods usually involving the "Viterbi" algorithm. Wood's comparison of detector types for the RDAT (rotary head digital audio tape recorder) shows little gain (less than 1 dB) for the sophisticated methods over the simple flat equalization. Because the VLBA code is not completely DC free, a "DC restoration" circuit (Huber 1981) is added.

6.6 Recorder Characteristics and Limitations

6.6.1 Error Rate Versus Bit Density

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 per μm (57.15 kfrpi). With Sony D1K tape a broadband SNR of 18 dB is obtained at 9 Mbit s^{-1}per head. Higher densities up to 3 fr μm^{-1} (75 kfrpi) can be achieved but the bit-error rate drops from 10^{-5} to 10^{-3}. The better short wavelength response and output of metal evaporated tape (MET, shown in figure 6.4) would allow reliable operation with densities in the 3 fr μm^{-1} 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.

6.6.2 Tape Thickness Interchange

There is a trend towards thinner tapes to increase the area of tape on a reel. 16μm thick tape has been purchased for the VLBA and is currently in operation. This tape is packaged in 18,000 foot lengths on 14-inch reels. Laboratory tests have been made with even thinner tapes down to 4μm. 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 16μm thick tape can be made by operating the thick tape at higher tension.

6.6.3 Head Flying

At high tape speeds an air bearing can form between the tape and the head which substantially increases the spacing loss and results in high error rates. At the standard VLBA playback speed of 160 ips (4 m s^{-1}) head flying starts at a vacuum setting of about six inches of water. Figure 6.9 shows the playback strength of a signal of 1-μm wavelength as a function of tape tension for the current VLBA headstack design. These are results only after some improvements were made in the design of the head profile needed to reduce the pressure build-up at the leading edge which initiates head flying. At present, the VLBA transport operates at 10$''$ of water in order to provide some margin against head flying. However, consideration is now being given to using a somewhat lower tension in order to increase the headlife.

6.6.4 Overwrite

The current VLBA headstack design has no shields between the heads in the stack and it is possible to overwrite a previously recorded track via the cross-talk. An extreme case is when one pass is written with the odd heads in a head position already used to write tracks at locations corresponding to the even heads. The problem does not occur unless the record current is high enough for the cross-talk field to exceed the tape coercivity. In practice there is not an overwrite problem provided the write current is correctly maintained and is not allowed to go too high. Since the head efficiency increases as the head wears down the write current may need to be periodically reduced.

6.6.5 Tracking Errors

The exact path the tape follows when it passes over the headstack is quite repeatable and is known as the tracking signature. However there are differences between the forward and reverse signatures and the signature on the first and later passes of a tape. The differences between forward and reverse are largely the result of variations in the elastic anisotropy in the tape. A constant forward-reverse offset is the result of machine alignment errors but is not a problem as it is eliminated by the head position calibration procedure. The difference between the first and later passes of the tape is the result of strains which are introduced during environmental cycling of the tape during shipping. If necessary, the tracking shift on the first pass can be eliminated by "prepassing" the tape before use. The prepass can be done well in advance since no excessive strains

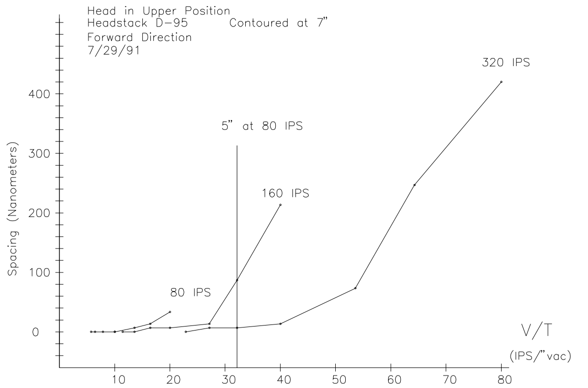

Figure 6.9: Spacing due to head flying

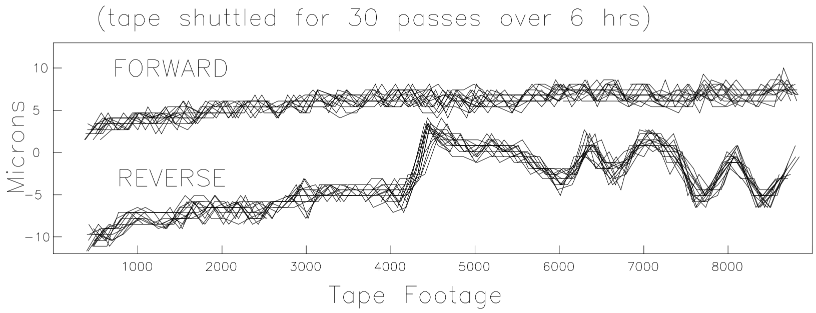

Figure 6.10: Tracking signature on a forward recording

are built up on the tape reel pack unless the tape is subject to large environmental changes. The tracking signature in figure 6.10, from playback of the forward recording in the reverse direction, shows that the elastic anisotropy signature is largely repeatable. The slitting signature is confined to a scale along the tape of a decimeter or less and is not resolved in figure 6.10. Separate tests show the difference in slitting signatures between forward and reverse to be about 10μm peak-to-peak.

The "DC" tracking changes which occur with transport alignments are given in table 6.2 on the next page.

6.6.6 Headlife and Humidity

The rate at which the head wears down is very strongly dependent on humidity. For Sony DIK tape the wear rate (Rogers and Hinteregger 1993) increases from 0.004 microns per hour at a relative humidity (RH) of 30% to 0.02μm hr^{-1} at 60% RH and 0.09μm hr^{-1} at 100% RH. The head life is determined by the time it takes to reduce the depth of gap from its initial value of about 38μm to zero. The

Table 6.2: The tracking shifts with transport alignments

		Tracking sensitivity in μm arcsec^{-1}		
Alignment	Direction	Shift in forward dir.	Shift in reverse dir.	Notes
Capstan tilt	left	0.2	0.2	a
Capstan tilt	up	0.5	0.5	a
Idler tilt	left	0.5	0.5	a
Idler tilt	up	0.03	−0.03	a
Capstan taper		0.5	0.5	b
Upper headstack tilt up	tilt up	−0.06	0	a
Lower headstack tilt up	tilt up	0	−0.06	a

Notes: [a] Positive shift is towards precision back plate. [b] Larger diameter near back plate produces positive shift. [c] I/O roller, reel table, and front door alignments have no effect on tracking. [d] Idler roller (in place of fixed post) improves tracking by making it less sensitive to misalignments and tape elastic anisotropy variations—by a factor of about 4.

exact mechanism for the role of water in the wear process in not fully understood. It has been shown that the wear rate depends on the relative humidity in the immediate vicinity of the head. This suggests that it is the presence of water molecules being dragged across the head that increases the wear rate rather than some slowly reversible chemical reaction with the tape. The theory of evaporation shows that the thickness of the layer of water molecules condensed on a surface is dependent on the RH, and measurements of surface resistivity show that the layer thickness increases sharply above 50% RH.

6.6.7 Thin Tape and Edge Damage by Frictional Heating

A severe problem has been encountered in the use of thin tapes at high speed. The edges can be easily damaged by frictional heating. Figure 6.11 shows the appearance of edge damage. While the damage does not appear very severe the thickening of the tape edges leads to instabilities in the tape pack on the reel which in turn produce a "bumpy" wind that will eventually result in "dropping" of the tape loops in the vacuum buffers. The problem has been solved, although it has yet to be shown that the solution is complete, by a redesign of the tape path. This redesign involved (Bhushan, Hinteregger and Rogers 1994) reducing the edge guiding forces as much as possible and utilizing a guide of low-friction and high thermal conductivity.

6.6.8 Tape Reel and Shipping Canister

The VLBA uses 14-inch diameter glass reels. The supply reel has a flange separation of 1″at the hub and flanges are chosen so that the reel is "convex" having an even smaller peripheral flange separation. This less than standard flange separation helps prevent scatter-wind and edge damage during tape shipment. The

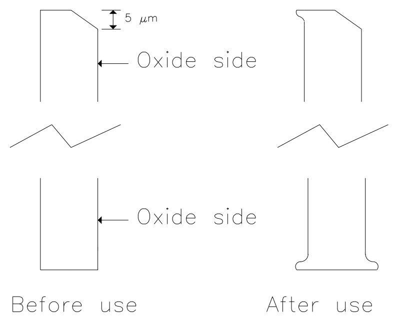

Figure 6.11: Appearance of edge damage

take-up reel is an industry standard, non-self-packing, glass reel. The shipping canister supports the tape at the hub to prevent any rotational torque being applied which might disturb the pack. The canister also has soft material on each side to cushion lateral shock which can cause a shift in the pack. A normal, well-wound, tape pack is quite strong and behaves like a solid disk of plastic if the reel flanges are removed. However, excessive shock or environmental cycling can cause the pack to shift with some damage. Many tests have been made to ensure that the packaged tape is as robust as possible. However, the experience is that extreme shock (several 100 g) and temperature ranges ($-40°$ to $60°$ C) can occur during shipping. Upon receipt at the site or processor, the tapes should be allowed to reach room temperature before being used on the transport.

6.7 Future VLBI Recording Systems

6.7.1 Expansion Paths for the VLBA Formatter

The current VLBA formatters as presently configured can write with a maximum of 32 data tracks plus 4 system tracks per pass for a maximum data rate of 256 Mb/s. This rate can be doubled to 512 Mb/s by plugging additional modules into the formatter. VLBA sites will be equipped with this expansion in 1995. Another factor of 2 can be gained if the circuitry can be upgraded to record at 16 Mb/s per track. The recorder should be able to support 16 Mb/s per head with only minor changes so that 1 Gb/s could be recorded with 2 recorders running simultaneously.

6.7.2 Recorder Improvements

6.7.2.1 Thinner Tape

13-micron tape is already becoming available and 10-micron tape is expected within a year. The recording industry is currently developing tape with stronger substrates like PEN (polyethylene naphthalate) polyaramid, and PBC (polybenzoxazole), which have a much higher Young's modulus than the PET (polyethylene terephthalate) substrate used in the current tape. Also, the new substrates have a higher glass transition temperature so that the heat produced in the edge guiding contact is less likely to result in edge damage. While tape as thin as 1.5 microns would increase the footage on a VLBA reel to 280,000 feet (85 Km) it will probably be some years before such thin tape is available at reasonable cost. The D1 tape currently being used by the VLBA is very similar to VHS tape used for home video. Until very thin tape is in home use, it is unlikely to be affordable. Digital high resolution TV will require a new generation of VCRs and VLBI will stand to benefit from these consumer product developments.

6.7.2.2 Higher Data Rates

The VLBA transport is limited to a maximum speed of 320 IPS (8 m/s) which corresponds to a data rate of 16 Mb/s (excluding parity) at a density of 56,000 bits per inch. As previously mentioned, the VLBA formatter is limited to 8 Mb/s but could perhaps be upgraded. Future developments however, are more likely to go in the direction of more heads as a means of increasing the data rates.

6.7.2.3 Next Generation of Heads

Haystack Observatory is currently pursuing (Hinteregger 1993) the development of new headstacks or head-arrays, as they are now called. The next generation of head-arrays will use thin film technology and photolithographic techniques to put more heads in the array at lower cost than the present headstack whose manufacture is so highly labor-intensive that they cost about $ 8000 each.

6.7.3 Mark IV

Mark IV is an upgrade path for the old Mark IIIA system. A new formatter has been designed to be physically compatible with the Mark III "VLA"-style electronics rack. This new formatter has many of the features of an expanded VLBA formatter and has a maximum output rate of 1 Gb/s with expandability to 2 Gb/s. The Mark IV uses a recorder which is very similar to the VLBA recorder except that it has 2 headstacks and can write at a maximum rate of 1 Gb/s. (The VLBA recorders can be expanded by adding modules and another headstack to meet the Mark IV standard.) Table 6.3 on the following page summarizes the characteristics of Mark III, IV, and VLBA.

6.8 Summary and Conclusions

Owing to the special requirements of high data rate, high storage capacity and no need for error corrections, VLBI recording systems have been custom designed.

Table 6.3: Comparison of recording systems

	Mark III	Mark IV	VLBA
#BBC's	14	14	8
Maximum sample rate (Msamples/sec)	8	32	32
#bits/sample	1	1 or 2	1 or 2
#tracks	28	64	36[a]
Maximum data-rate/track (Mbits/sec)	8	16	8
Multiplex fan-out (chans:track)	1:1 only	1:1, 1:2, 1:4, 1:8	1:1, 1:2, 1:4, 1:8
Multiplex fan-in (chans:track)	None	2:1, 4:1	2:1, 4:1
Barrel-rolling	N	Y	Y
Data-modulation	N	Y	Y
Data-replacement format	Y	Y	N[b]

Notes: [a] 32 data tracks plus 4 'system' tracks. [b] Can also write Mark IIIA/Mark IV-compatible non-data-replacement format.

The VLBA recording system is very flexible and can be easily upgraded to take advantage of new tape and head technology.

Acknowledgments

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 Mark IIIA and 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 Corporation) under the leadership of Harry Allen. The formatter was designed by J. I. Levine of Haystack Observatory.

References

Bertram, H. N. 1986. "Fundamentals of the magnetic recording process". *IEEE Proc.* **74**, 1494.

Bhushan, B., Hinteregger, H. F., & Rogers, A. E. E. 1994. "Thermal considerations for the edge guiding of thin magnetic tape in a longitudinal tape transport". *Wear* **171**, 179.

Broten, N. W., Legg, T. H., Locke, J. L., McLeish, C. C., Richards, R. S., Chisholm, R. M., Ghush, H. P., Yen, J. L., & Galt, J. A. 1967. "Long baseline interferometry: A new technique". *Science* **156**, 1592.

Clark, B. G. 1973. "The NRAO tape-recorder interferometer system". *IEEE Proc.* **61**, 1242.

D'Addario, L. 1984. "Minimizing storage requirements". VLB Array Memorandum 332, National Radio Astronomy Observatory.

Hinteregger, H. F. 1982. "The density upgrade: Mark IIIA (a future improvement of the Mark III VLBI system)". In W. E. Carter and A. Tusuchiya (Eds.), *Proc. Symp. No. 5, International Association of Geodesy, Geodetic Applications of Radio Interferometry.* Number NOS 95 in NOAA Technical Report. Rockville, MD, U. S. Department of Commerce: National Oceanic and Atmospheric Administration, p. 143.

Hinteregger, H. F. 1993. "Stepping up to gigabyte/sec recording at terabyte/in3 density: A plan for VLBI recorder development". Technical report, Haystack Observatory, Westford.

Hinteregger, H. F., Rogers, A. E. E., Cappallo, R. J., Webber, J. C., Petrachenko, W. T., & Allen, H. 1991. "A high data rate recorder for astronomy". *IEEE Trans. Mag.* MAG-27(3), 3455.

Hirabayashi, H., Inoue, M., & Kobayashi, H. (Eds.) 1991. *Frontiers of VLBI.* Tokyo: Universal Academy Press, Inc.

Huber, W. D. 1981. "Equalization of the D. C. null in high density digital magnetic recording". *IEEE Trans. Mag.* **MAG-17**, 3352.

Kawaguchi, N. 1991. "VLBI recording system in Japan". See Hirabayashi, Inoue and Kobayashi (1991), p. 75.

Rogers, A. E., & Hinteregger, H. F. 1993. "Measurement of magnetic tape abrasivity by interchanging tape thickness". *Trib. Trans.* 36(1), 139.

Rogers, A. E. E., Cappallo, R. J., Hinteregger, H. F., Levine, J. I., Nesman, E. F., Webber, J. C., Whitney, A. R., Clark, T. A., Ma, C., Ryan, J., E., Corey B., C., Counselman C., Herring, T. A., Shapiro, I. I., Knight, C. A., Shaffer, D. B., Vandenberg, N. R., Lacasse, R., Mauzy, R., Rayhrer, B., Schupler, B. R., & Pigg, J. C. 1983. "Very-long-baseline radio interferometry: The Mark III system for geodesy, astrometry, and aperture synthesis". *Science* **219**, 51.

Rogers, A. E. E., & Nesman, E. D. 1988. "1988". VLBA Acquisition Memo 108, National radio Astronomy Observatory.

Thompson, A. R. 1993. "An introduction to the VLBA receiving and recording system". VLBA Technical Report 15, National Radio Astronomy Observatory.

Whitney, A. R., Rogers, A. E. E., Cappallo, R. J., Hargreaves, J. E., Hinteregger, H. F., & Smythe, D. L. 1991. "The Mark 4 data acquisition system". In W. E. Carter (Ed.), *Proc. AGU Chapman Conference on Geodetic VLBI, Monitoring Global Change.* Number NOS 137 in NOAA Technical Report. Rockville, MD, U. S. Department of Commerce, p. 7.

Wietfeldt, R. D., & D'Addario, L. R. 1991. "Compatibility issues in VLBI". In T. J. Cornwell and R. A. Perley (Eds.), *IAU Coll. 131, Radio Interferometry: Theory, Techniques, and Applications.* Volume 19 of *ASP Conference Series.* San Francisco: Astron. Soc. of the Pacific, p. 98.

Wietfeldt, R. D., Newby, P. S., Baer, D., Cannon, W. H., Feil, G., Oeone, P., & Tan, H. 1991. "The Canadian S2 recorder for Radioastron". See Hirabayashi, Inoue and Kobayashi (1991), p. 75.

Wood, R. 1990. "A theoretical comparison of detection techniques on R-DAT". *IEEE Trans. Mag.* 26(5), 2157.