

Mark IIIA/IV/VLBA Tape Formats, Recording Modes and Compatibility

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1. Introduction

The Mark IIIA, VLBA and Mark IV VLBI data-acquisition systems are all based on the Metrum (formerly Honeywell) Model 96 transport using 1" wide reel-to-reel tape. Although the data-format on tape is very similar among these systems, there are significant differences in details that must be noted in order to successfully process data from these systems. The purpose of this memo is describe the tape and data formats of each of these systems in significant detail.

2. Mark IV Tape Format and Recording Modes

The Mark IV VLBI Data-Acquisition System is an upgrade to the original Mark IIIA system that was designed primarily for two purposes, 1) expansion of maximum data rate from 224 Mbits/sec to 1024 Mbits/sec and 2) full compatibility with all VLBA channel-bandwidth and data-multiplex modes. For this purpose, an entirely new formatter was designed for the Mark IV system, and modifications were made to BBC's and the tape transport.

The Mark IV system can record up to 64 simultaneous tracks (expandable to 128 tracks) at a maximum data rate of 16 Mbits/sec/track (18 Mbits/sec/track with parity) for maximum total data rate of 1024 Mbits/sec (expandable to 2048 Mbits/sec). The data along each track is physically continuous, but are divided into logical frames, each frame being a self-contained unit containing synchronization, timing and auxiliary information as well as sampled data. In the Mark IV system, as in the VLBA system (but unlike the Mark IIIA system), data from a single video-converter (baseband-converter) channel may be distributed to multiple tracks; conversely, data from several channels may also be multiplexed onto a single track. Therefore, in order to completely understand the Mark IV tape format, we must understand both the format along a single track (*longitudinal track format*) and the format laterally across the simultaneously-written tracks (*transverse track format*). These are described in Sections 2.1 and 2.2, respectively.

2.1 Longitudinal Data Format

The continuous stream of bits along each single track is logically divided into Tape Frames. Each Tape Frame consists of 22,500 bits divided into 4 fields (see Figure 1):

- Field 1. Auxiliary-data Field (64 bits + 8 odd-parity bits)
- Field 2. Sync Word (32 bits + 4 even-parity bits)
- Field 3. Time Code & CRC (64 bits + 8 odd-parity bits)
- Field 4. Data Field (19840 data samples + 2480 odd-parity bits)

Fields 1,2, and 3 are collectively known as the Header and replace 160 data bits that otherwise would have been written in that position. The first replaced data bit has a time tag corresponding precisely to the time code in the header; the actual first present data bit has a sample time 160 sample times later than the header time.

2.1.1 Time Code & CRC

The Mark IV time code (identical to the Mark IIIA time code) is a 48-bit BCD time code followed by a 12-bit CRC check code and is identical to the Mark IIIA time code and CRC check code. The time code consists of the following 12 BCD digits, in order of writing on tape:

Digit	Definition
1	Unit year
2	Day-of-year - 100's digit
3	Day-of-year - 10's digit
4	Day-of-year - 1's digit
5	UT hour - 10's digit
6	UT hour - 1's digit
7	UT minute - 10's digit
8	UT minute - 1's digit
9	UT second - 10's digit
10	UT second - 1's digit

11	UT second - 0.1 digit
12	UT second - 0.01 digit
13	UT second - 0.001 digit

Table 1: Mark IV Time-Code Definition

Each time-code BCD digit is written to tape in order msb-to-lsb.

The 12-bit CRC-12 cyclic redundancy code is computed over the data bits (not including parity) of Auxiliary-Data Field, Sync Word, plus the 52 bits of the Time Code (148 bits total) using the generating polynomial $x^{12} + x^{11} + x^3 + x^2 + x + 1$ (initialized to zero). This 12-bit CRC code is placed in the last 12 bits of Field 3. [Example: Aux-data - 0000 002D 0330 0000; Sync-word - FFFF FFFF, Time-code - 4053 2143 3805 5; CRC - 284 (all hex)]

The phasing of Tapes Frames with respect to formatter time is always such that a frame boundary occurs on a minute mark. Frame-lengths (in formatter time) range from 1.25 msec (written at 18 Mbits/sec/track) to 160 msec (written at 125 kbits/sec/track) in octave steps. Since the time code has a resolution of only 1 msec, the actual time-tag must be inferred for frame periods of 1.25 msec and 2.50 msec, according to the following table:

Time-code msec	Implied Time msec
0	0
1	1.25
2	2.5
3	3.75
4	illegal
5	5.0
6	6.25
7	7.50
8	8.75
9	illegal

Table 2: Mark IV Implied Time Code

The Implied Time indicated at the beginning of a Frame indicates the formatter-time of the first sample replaced by the first bit of Field 1 (Aux Data)¹. Therefore, the first bit of the Data Field is a sample taken 160 sample periods after the Implied Time.

2.1.2 Auxiliary Data Field

Each Tape Frame begins with a 64-bit Auxiliary Data Field. We can write the aux-data field as 16 hex characters in the form (and in the order written to tape):

aaaabbbrrsstuu

where

aaaa:	bits 15 -0	nominal headstack 1 position in microns; 4 BCD digits; 0000-3999 positive micron positions (bcd encoded) 4000-7999 negative micron positions (bcd encoded); (4000, 7999 indicate positions of 0, -3999 respectively)
bbbb:	bits 15-0	nominal headstack 2 position in microns; 4 BCD digits; (encoded same as 'aaaa')
rr:	bits 7-6	(track specific);

¹This is strictly true only for non-multiplexed data. For multiplexed data where a single sample stream is distributed to 2 or 4 tracks, the actual UT sample time of the data bits may be offset by 0,1,2 or 3 sample times. See discussion on Transverse Tape Format.

	bits 5-0	headstack number (0-3 corresponds to headstacks 1-4) (<i>track specific</i>); Track number/ID (2-33 BCD, corresponding to VLBA track numbers); see Appendix.
ss:	bits 7-0	Identifies source of data in frame (<i>track-specific; frame-specific if barrel-roll active</i>); Data ID ² (0-255 binary)
	Bits 7-6:	Fan-out sub-channel number
	00	First data bit in frame was taken at the frame-header-time
	01	First data bit in frame was taken at the frame-header-time plus one sample interval
	10	First data bit in frame was taken at the frame-header-time plus two sample intervals
	11	First data bit in frame was taken at the frame-header-time plus three sample intervals
	Note:	Bits 7-6 are 00 in all fan-in modes. In <i>all</i> modes (including all fan-out and fan-in modes), bits 5-0 of the Data-ID subfield specify the source of <i>first data bit</i> in the frame.
	Bit 5:	0 'Sign' bit 1 'Magnitude' bit
	Bit 4:	0 Upper-sideband (USB) output of BBC 1 Lower-sideband (LSB) output of BBC
	Bits 3-0	Video-converter-number minus 1 (Mark IV BBC's are numbered 1-16)
tt:		Formatter status and error flags ("1" if TRUE)
	bit 7	time sync error
	bit 6	internal clock error
	bit 5	processor time-out error
	bit 4	communication error
	bit 3	spare
	bit 2	spare
	bit 1	track-roll (barrel-roll) enabled
	bit 0	sequence suspended for command processing
uu:	bits 7-0	system ID (must contain at least one '0'); msb-to-lsb ³

All aux-data BCD digits and binary subfields are written to tape in order msb-to-lsb.

The Data Identifier sub-field (bits 23-16) identifies the data in the *following* Data Field (unlike the VLBA, which defines the Auxiliary Data Field to be at the end of a tape frame, and so identifies the data in the *prior* Data Field). When barrel-rolling is enabled (see below), the Data Identifier field (bits 23-16) is also rolled so that it always properly identifies the data in the following Data Field.

²The connections from BBC's to the 32 samplers are hard-wired, so that the identification of the sampler unambiguously defines the source of the data. Furthermore, the data from a single sampler must be designated as the 'sign' data stream or the 'magnitude' data stream, which may fan-out to as many as 4 tracks each. Therefore, 8 bits are sufficient to uniquely identify the data source in the frame. When multiple data-streams are fanned-in to a single frame, the Data Identifier subfield indicates the source of the data corresponding to the first data bit in the frame.

³ In order for better compatibility with the VLBA correlator, Jon Romney has requested that all tapes processed at the VLBA correlator should have at least two zeros in the 'system ID' field. The Mark IV formatter has been modified to allow an override of the standard 'system ID' code in order to accommodate this request.

2.1.3 Sync Word

The Sync Word is an invariant pattern of four identical bytes, each consisting of eight '1's' followed by a '0'. These 4 bytes are the *only* instance of even parity in the frame. Explicitly, the Sync Word is (in the bit order written to tape):

1111111011111110111111101111111011111110

The detection of a sync word should *unconditionally* synchronize the decoder. The sync word has been designed in three ways to have a very low probability of being falsely detected during the 'data' portion of the frame as a result of poor recordings or tape flaws. First, the sync word alone violates the odd parity of the rest of the frame. The fact that the sync word is made up of four repeated bytes of even parity insures that odd parity is violated by *any* 9-bit segment of the sync word. Secondly, the sync word contains as many "1's" as possible within the even-parity constraint so that the chance that a tape flaw will 'create' a sync word is minimized. And lastly, the sync word is specified to be flanked on either side by a byte with at least one '0'; this averts the possibility that an otherwise-legitimate all-1's byte will be recognized as a sync byte as the result of a single parity error, causing the sync word to be detected with a ± 1 byte offset. The fact that the sync word is easily destroyed by a tape flaw is not important because the sync word need not be detected in each frame in order for the decoder to remain synchronized. Loss of format synchronization (bit-slip) is unambiguously detected (and synchronization simultaneously re-established) when the decoder finds a sync word at the 'wrong' intra-frame bit count. The format is such that bit-slip can be detected and corrected by monitoring parity in more than one position, but bit-slip is sufficiently rare that complicating the decoder to speed up recovery is not warranted.

2.1.4 Data Field

The primary content of each Frame is the Data Field, which carries 19,840 sampled VLBI data bits. Data is encoded in NRZM format ('1' = flux change; '0' = no flux change).

Each sample is encoded according to the following table:

Voltage (mv) ⁴	Tape (aka 'MSB') (aka 'LSB')		MkIV corr chip inputs		MkIV formatter rear-panel outputs	
	'Sign'	'Mag'	'Sign'	'Mag'	'Sign'	'Mag'
>200	1	1	0	1	1	1
0→200	1	0	0	0	1	0
0→-200	0	1	1	0	0	0
<-200	0	0	1	1	0	1

Table 3: Mark IV Sample-Encoding Definition

When 1-bit sampling is used, only the 'sign' bit is relevant. The Mark IIIA, Mark IV and VLBA systems all use the same data-encoding algorithm on tape.

The precise sampling epoch is determined for each data bit by counting from the first bit of Field 1 (auxiliary data), whose epoch is in turn determined by the time-code as described above. The time interval between adjacent data bits with a frame depends on factors not directly relevant to the frame format, such as sampling rate and fan-in/fan-out factor.

Every data bit in the Data Field may, optionally, be modulated by a fixed pseudo-random sequence (compatible with VLBA⁵). This modulation pattern is generated by a 16-bit feedback shift-register algorithm, reset at the first bit of each Data Field, implemented by the following C function:

⁴With reference to 0 dBm total power into 50Ω for optimum SNR, which is provided by AGC within the Mark IV video converters (BBC's)

⁵ The VLBA formatter has the flexibility to program the actual pseudo-random code; the Mark IV formatter is designed to support only the pseudo-random code specified in the document "VLBA Longitudinal Track Format" by Jon Romney, 1990 November 16.

```

Unsigned mod_func()
{
    static unsigned ff[16] = {1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1};
    unsigned output, n;
        :
    output = ff[10] ^ ff[12] ^ ff[13] ^ ff[15];
    for ( n = 15; n > 0; n-- ) ff[n] = ff[n-1];
    ff[0] = output;
    return (output);
}

```

The generator advances by one step for every bit within a Data Field, including parity bits. A '1' output bit from the generator causes inversion of the data bit in the Data Field, but is ignored for parity bits⁶. One odd-parity bit is inserted after every 8 data bits. The use of odd parity bytes, together with the NRZM code, insures that at least one flux change is written per 9-bit byte and guarantees that transitionless runs can be no longer than 16 bit-cells.

2.2 Transverse Data Format

2.2.1 Data-Multiplexing

The Mark IV system can multiplex the data samples from one channel to several tracks (so-called 'fan-out'), and can also multiplex the data samples from multiple channels onto a single track (so-called 'fan-in'). The use of fan-in/fan-out allows the use of sample rates higher than can be support on a single tape track, and also allow the data-recording modes to be adjusted for improved correlator efficiency.

2.2.1.1 Definitions

Before discussing the details of fan-in and fan-out, we need to discuss the concept of a *bit stream*. When doing 1-bit sampling of a signal, only a single *bit stream* (sign bits) is created; when doing 2-bit sampling, the sign and magnitude *bit streams* are considered as two independent bit streams as far as the recording system is concerned.

A single *bit stream* may be 'fanned-out' to k tracks, where k may be 1, 2, or 4. When operating in this mode, bits $0,k,2k,3k,\dots$ are written to one track, bits $1,k+1,2k+1,3k+1,\dots$ are written to the second track, etc., so that the bit-rate/track is reduced by a factor of k from the original *bit-stream* rate. Since the maximum data-rate/track of Mark IV is 16 Mbits/sec, data collected at 32 Msamples/sec *must* be multiplexed in this fashion. Note that *tracks* in this discussion refer to *non-barrel-rolled tracks*; any barrel-rolling is applied on top of the data-multiplex format.

Multiple *bit streams* may be 'fanned-in' to a single track. In the Mark IV and VLBA systems, 2 or 4 bit streams may be fanned-in to a single track. In such a case, every second or fourth bit within the Data Field of a tape frame are from the same *bit stream*.

The so-called '*fan-out ratio*' is defined as the *bitstreams/track*. For both the Mark IV and VLBA systems, the fan-out ratio can have the values of 0.25 (1 bit-stream to 4 tracks), 0.5, 1, 2, 4 (4 bit-streams to 1 track). For the Mark IIIA system, the fan-out ratio is constrained always to be 1.

2.2.1.2 Capabilities of Mark IV Formatter

The Mark IV formatter has been designed as a plug-in replacement for the Mark IIIA formatter which is compatible in all essential respects with the VLBA formatter. The major difference is that the Mark IV formatter can only write the Mark IIIA tape-frame format (except for aux-data).

2.2.1.2.1 Signal Switching and Multiplexing Modes

The Mark IV formatter can accommodate up to 32 video-signal inputs, an USB and LSB channel from each of 16 Mark IV video-converters. The 14 original video-converters are numbered VC1 through VC14. Mark IV systems which have been upgraded with additional video-converters will have video-converters VC15 and VC16 in addition. The following table summarizes the multiplex capabilities of a fully-configured (capable of writing to 128 tracks) Mark IV formatter:

⁶ Just to insure against any ambiguity, the pseudo-random generator output for the first 45 bits of the Data Field can be written as '00000000P00110110P00001111P01111011P10110110P.....', where '0' indicates no bit-inversion, '1' indicates bit-inversion, and P represents parity bit.

Fan-Out/In Mode (bitstrms:tk)	Bits per sample	Accessible VC's	Output track mapping	#heads req'd at full capacity	Max data-rate at full capacity (Mbits/sec)	Comments
1:4	2	1-8	Arbitrary	128	1024	512 Mbits/sec max with 2 headstacks (64 tracks).
1:4	1	All	Arbitrary	128	1024	512 Mbits/sec max with 2 headstacks (64 tracks).
1:2	2	All	Arbitrary	128	2048	1024 Mbits/sec max with 2 headstacks (64 tracks).
1:2	1	All	Arbitrary	64	1024	
1:1	2	All	Arbitrary	64	1024	
1:1	1	All	Arbitrary	32	512	
2:1	2	All	Arbitrary	32	512	Single track contains data from single U or L chan. Data Field bit order is sign,mag from single VC.
2:1	1	All	Arbitrary	16	256	Single track contains U/L chans from single VC. Data-Field order is sign-L, sign-U.
4:1	2	All	Arbitrary	16	256	Single track contains data from U/L of single VC. Data Field order is sign-L,mag-L,sign-U,mag-U.
4:1	1	Adjacent VC pairs	Arbitrary	8	128	Data from adjacent odd(N) and even (N+1) VC pair on one track. Data Field order is odd-sign-L,odd-sign-U, even-sign-L,even-sign-U.

Table 4: Capabilities of Mark IV Formatter

2.2.1.2.2 Raw Sample-Data Outputs

Raw sample data at 32 Msamples/sec (only) from the USB and LSB signals of two selected BBC's is available on a rear-panel connector of the Mark IV formatter. One set of USB/LSB samples may be selected from among BBC's 1,2,3,4,9,10,11,12 and the other from among BBC's 5,6,7,8,13,14,15,16. Also available on the same connector is the sample clock, a 1 PPS marker, and a frame boundary marker. These raw-sample data streams may be used by external systems for such purposes as real-time data-analysis or piggyback connections to other recording systems. Please note that these samples are encoded in true sign and magnitude coding, as indicated in **Table 3**.

2.2.1.2.3 Barrel-Rolling

The Mark IV uses two headstacks of 32 tracks each, for a maximum of 64 simultaneously-written tracks on a tape. Data is written to these 64 tracks through a 64x64 cross-point switch which can be arbitrarily reconfigured according to 16 independent user-definable maps. Starting at a minute mark, Map 0 is used to configure the cross-point switch. After every n frames, the map number is incremented, coming back to Map 0 after incrementing through m maps; where m (≤ 16) is user-definable. By declared convention, n is required to divide evenly into the #frames/minute so that the pattern is repeated exactly every minute. This process is used to implement what is called *barrel-rolling*. The purpose of barrel-rolling is to spread a single data stream over many tracks to minimize the damage due to the prolonged loss of a single track.

The Mark IV supports all VLBA barrel-rolling modes. In normal operation, it is expected that Mark IV recordings will primarily use VLBA-compatible barrel-roll sequences (see Section 3.2.1).

2.2.2 Data-Multiplex Track-Assignment and Barrel-Roll Conventions

Mark IV will support all the standard fan-out track-assignment conventions used by the VLBA (detailed in Section 3.2.3.1) with obvious extensions to 16 video-converters and 64 or 128 tracks.

Barrel-Roll: Mark IV will support the standard VLBA barrel-roll conventions (detailed in Section 3.2.1).

2.3 Recorder Characteristics

The Mark IV system utilizes the Metrum Model 96 transport which has been heavily customized with headstacks, headstack-positioning capabilities and data electronics. This section outlines the major physical characteristics of the Mark IV system and the physical format of data on tape.

2.3.1 Transport

The Mark IV system is based on the Metrum (formerly Honeywell) Model 96 tape transport. Although the basic tape-moving part of the transport remains nearly original, significant modifications have been made in the tape-path mechanical components in order to meet the requirements of the Mark IV system. Table 5 lists the basic characteristics of the Metrum 96 transport as configured for the Mark IV system. The English company Penny and Giles also manufactures tape transport which is designed to be fully compatible with the Mark IV and VLBA data-acquisition systems.

		Comments
Tape width	1 inch (25400 um)	Transport can be easily adapted to narrower tapes
Tape length	arbitrary	Typically 9000 ft of 25um thickness tape on 14" diam reel or 18000 ft of 16um thickness tape on 14" diam reel.
Tape speed limit	+/-360 ips	
Recording/playback speed	+/-0 to 330 ips	Typically, recording speed is adjusted with data rate to maintain a constant bit density along each track. Playback speed may be selected independent of recording speed.
Tape-guiding type	Edge	Guided along single edge of tape
Tape-tracking repeatability (properly aligned Metrum Model 96)	<5 um	May be systematic forward/reverse (tape motion) tracking offset of up to ~30 um, but headstack-position is calibrated to compensate.

Table 5: Metrum Model 96 Transport Characteristics

2.3.2 Headstack

Each Mark IV system is outfitted with two identical headstacks, each independently mounted and movable in a direction transverse to the direction of tape motion. Both headstacks may be used for recording while one headstack may also be used for playback. Table 6 lists the basic characteristics of the standard Mark IV headstack manufactured by Metrum (detailed specification is given in Mark IV memo 144):specification are given in Mark IV memo 144). Note that the same headstack is used for Mark IIIA, Mark IV and VLBA. The English company ICT also manufactures (for Penny and Giles) headstacks which are designed to be fully compatible with the Metrum headstacks.

		Comments
#heads	36	Mark IV uses only inner 32 heads. Mark IIIA uses only inner 28 heads. VLBA can use all 36 heads.
Head numbering	0-35	Head 0 is furthest from Metrum transport deck plate. Head 35 is nearest Metrum transport deck plate.
Head width (gap width)	38 um	Width of single written track
Gap length	.35+/- .035 um	Capable of writing in excess of ~75000 flux transitions per inch on suitable tape with suitable drive current.
Head pitch (spacing)	698.5 um (27.5 mils)	36 heads span 24485.5 um (between outer edges of heads 0 and 35), theoretically allowing a range of headstack motion of +/-457.25 um around a centered headstack position while keeping all 36 heads on tape.
Headstack life	>5000 hrs typical	Requires relative humidity at headstack of <40%. Headstack life significantly degraded at higher values of relative humidity.

Table 6: Mark IIIA/Mark IV/VLBA Headstack Characteristics

2.3.3 Headstack Positioner

Each headstack is mounted on an independent headstack-positioning device. Table 7 lists the basic characteristics of the ‘inchworm’ positioner used on the Metrum 96 transport. A positioning device used on the Penny and Giles transport, operating on a ‘squash-plate’ principle, is designed to be compatible.

		Comments
Positioner range (Inchworm mechanism)	+/-1397 um minimum	Corresponds to +/-2 head pitches around center position. Can position to any value within this range.
Positioner precision/repeatability	+/-2 um typical	Accuracy over full span is poorer, depending on calibration, but generally not important since repeatability is high.

Table 7: ‘Inchworm’ Headstack-Positioner Characteristics

2.4 Physical Recording-Format Conventions

2.4.1 Longitudinal

The only selectable longitudinal recording parameter is the bit density along each track, which is entirely controlled by the selection of the per-track-data-rate and the recording tape speed. The magnetic encoding on each track is so-called ‘NRZ’ in which a flux transition corresponds to a ‘1’ and the lack of a transition corresponds to a ‘0’, therefore the bit density corresponds to the flux-transition density of all-‘1’s data. The Mark IV system is designed for a longitudinal density of 56,250 bits/inch/track; this density is required at a data rate of 18 Mbits/sec/track in order to limit tape speed to 320 ips, the upper limit of recording speed on the Mark IV system; lower per-track-data-rates use correspondingly lower tape speeds. Lower longitudinal densities may be used at lower per-track-data-rates; in particular, the Mark IIIA system typically uses 33,333 bpi/track. Some older tapes will not support the 56,250 bpi longitudinal density; in such case, density is normally reduced to 33,333 bpi/track (however, the 18 Mbits/sec/track data rate is not supported at this density).

2.4.2 Transverse

The transverse format of the tape (placement of the tracks) is completely controlled by the position of the headstack and the subset of available heads which are enabled for writing on each pass of the tape over the headstacks. The Mark IV plans to adopt a 16-pass recording mode similar to the 14-pass mode adopted by the VLBA (see Section 3.4.2), although the details of the headstack-position conventions are not yet fully decided.

3. VLBA Tape Format and Recording Modes

3.1 Longitudinal Data Format

The VLBA standard tape format is illustrated in Figure C-1. The primary differences compared to the Mark IV tape format are:

1. The VLBA uses non-data-replacement tape frame; that is, the time, sync and auxiliary data are spliced into the data stream instead of replacing a small amount of data as in Mark IIIA and Mark IV. This increases the frame length by 160 bits + 20 parity bits compared to the Mark IIIA/IV frame.
2. The auxiliary-data field is considered to be at the *end* of the tape frame, so that frame-specific parameters within the aux-data must be referred to the data field immediately *prior* to the aux-data field.
3. The encoding of the time and aux-data are somewhat different and are detailed below.

The following details of the VLBA longitudinal tape format are taken from VLBA document A56000N003 (*VLBA Longitudinal Track Format*, J. D. Romney, 1990 November 16) with some clarification (G. Peck, private communication). For additional information on sampling and recording modes supported by the Very Long Baseline Array, see the documents *Basic VLBA Recording Modes*, R. C. Walker, 1993 January 20 and *Standard VLBA Observing Modes*, J. D. Romney, 1993 January 27 (both available at ftp.aoc.nrao.edu). Longitudinal Format

3.1.1 Time Code & CRC

The VLBA Time code spans eight bytes (48 bits), organized as 12 BCD digits, designated T1-T12, plus a two-byte (16 bit) CRC error-detection pattern. All BCD digits in the time-code field are written to tape in the order msb-to-lsb. There are three sub-fields in the time-code field:

MJD - Modified Julian Date

The three least-significant digits of the Modified Julian Date, as defined in Section B of the "Astronomical Almanac":

J (T1)	MJD	(100's digit)
J (T2)	MJD	(10's digit)
J (T3)	MJD	(1's digit)

Seconds

The time interval elapsed since the beginning of the given MJD, expressed in seconds to a precision of 0.1 milliseconds. An implicit decimal point follows the unit seconds digit at T8:

S (T4)	Seconds (10000's digit)
S (T5)	Seconds (1000's digit)
S (T6)	Seconds (100's digit)
S (T7)	Seconds (10's digit)
S (T8)	Seconds (1's digit)
s (T9)	Seconds (0.1's digit)
s (T10)	Seconds (0.01's digit)
s (T11)	Seconds (0.001's digit)
s (T12)	Seconds (0.0001's digit)

CRC

A "CRC-16" cyclic redundancy code is computed on the data bits (not including parity bits) of the first six time code bytes, using the generating polynomial $x^{16} + x^{15} + x^2 + 1$ (initialized to zero). The 16-bit output is written to the final two bytes of the 64-bit Time Code field.

3.1.2 Auxiliary Data

The VLBA auxiliary data comprises eight bytes (64 bits) organized as 16 BCD digits. All BCD digits in the aux-data field, unless stated to be *bit-reversed*, are written to tape in the order msb-to-lsb. *Bit-reversed* digits are written in order of lsb-to-msb. The ranges shown are appropriate to current plans for the VLBA recording system. The auxiliary data field can be written as 16 BCD digits of 4-bits each:

SSRHPPPTTGBSCD00

These 16 digits are also referenced as A1 through A16, in order from left to right, and written onto tape in the same order, except that each of the digits 'TGBSCD' are *bit-reversed* (i.e. written lsb→msb; indicated by underscore). The auxiliary parameters can be grouped into four logical sub-fields:

Station Identification - A unique identification code assigned to each station

S (A1)	Station Code (10's digit)
S (A2)	Station Code (1's digit)

Recorder Parameters - Recorder and Headstack which wrote this track (though current VLBA implementation uses only single headstack), and sign and magnitude of the absolute headstack position commanded for that headstack

R (A3)	Recorder#	0 - 1
H (A4)	Headstack#	0
P (A5)	Position Sign	0:+ 8:-
P (A6)	Position (100's digit)	
P (A7)	Position (10's digit)	
P (A8)	Position (1's digit)	

DAR Parameters - Data-acquisition rack ('D-rack') parameters; *all digits in this sub-field are bit-reversed.*

Parameters marked 'BR' change every frame as a result of barrel roll.

T (A9) Track		0 - 7	(see Appendix A)
G (A10) Group		0 - 4	(see Appendix A)
B (A11) Bit ⁷	(BR)	0: 'Magnitude' bit 1: 'Sign' bit	
S (A12) Sideband	(BR)	0: lower 1: Upper	
C (A13) Converter	(BR)	0 - 7 (corresponding to BBC's 1-8, respectively)	
D (A14) DAR#		0 - 1 (currently only single DAR)	
A15		0	
A16		0	

3.1.3 Sync Word

The VLBA sync word is identical to the Mark IIIA and Mark IV sync word (see Section 2.1.3).

3.1.4 Data Field

The VLBA Data Field is very similar to the Mark IV Data Field, with the following points to be noted:

1. The first bit of the VLBA Data Field has a sample-time corresponding exactly to the immediately-preceding Time Code. Since the format is non-data-replacement, the last bit of the VLBA Data Field (assuming no fan-in/fan-out is active) has a sample-time corresponding to one-sample-period before the next Time Code field.
2. Sample encoding is identical to Mark IV sample encoding (see Section 2.1.4).
3. Optional pseudo-random-code modulation of the Data Field is identical to Mark IV (see Section 2.1.4).

3.2 Transverse Data Format

The VLBA transverse format is essentially identical to the Mark IV, except that:, in addition to the 32 heads per headstack supported by Mark IV, the VLBA formatter support 4 additional heads called 'system tracks'. The 36 available heads are labeled 0-35, with the center 32 heads (2-33) corresponding to the 32 heads of a Mark IV headstack. The VLBA 'system tracks' are intended to serve as additional support tracks for such things as spares and cross-track parity.

3.2.1 Barrel Roll Conventions

'Barrel-Rolling' is the periodic reassignment of bit streams to tracks in a cyclic pattern. The purpose of barrel-roll is to minimize susceptibility to a bad head or bad track by spreading the data over many tracks.

For purposes of barrl-rolling, the 32 formatter 'data' outputs⁸ (2-33) are divided into 4 groups of 8 outputs or 2 groups of 16 outputs. *At each frame*, the barrel-roll steps to the next step in the barrel-roll sequence; the barrel-rolling sequence is reinitialized on every even second mark. Formatter 'system' outputs (0-1 and 34-35) are not barrel-rolled. The block diagram of the VLBA formatter in **Error! Reference source not found.** may help to clarify the available internal data paths.

Though the barrel-rolling capability of the VLBA formatter is very flexible, only a simplified subset of possible barrel-rolling modes is normally used. The following guidelines (George Peck, personal communication) have been adopted by the VLBA in assigning barrel roll modes:

⁷When multiple data-streams are present in a single frame ('fan-in' mode), the 'BSC' (Bit, Sideband, Converter) subfields indicate the source of the first data bit in the frame.

⁸ The 36 VLBA formatter outputs 0-35 are divided into 'data' outputs (2-33) and 'system' outputs (0,1,34,35). The 'data' outputs normally contain sampled data, while the 'system' outputs serve special purposes, such as cross-track parity or duplicating a pre-barrel-rolled data stream to compensate for a bad track. In particular, formatter 'system' outputs 0,1,34,35 have access to pre-barrel-rolled 'data' tracks 2-9, 10-17, 18-25 and 26-33, respectively, and may be used to duplicate any data track within their respective track groups; in addition, each 'system' output has access to all of the seven flavors of cross-track parity. Normally, formatter outputs 0-35 correspond directly to recorder tracks 0-35, but the recorder also allows some internal track duplication; in particular, each of the four 'system' tracks has access to formatter outputs 0-35 (see VLBA Data Acquisition Memos 71 and 238).

1. Barrel roll is disabled if the total number of tracks is not divisible by 8.
2. The 8-track barrel-roll is an 8-step sequence that is enabled when -
 - the total number of tracks is divisible by 8 but not by 16, OR
 - the tape-writing rate is ≤ 2 Mbits/sec/track and the total number of tracks is divisible by 16.

The details of the standard VLBA 8-track barrel-roll sequence for even tracks is given in Table 8, where 'home' (or Roll Step 0) is the track to which a particular bit stream is written on each frame starting on an even second tick; subsequent 'roll steps' indicate the tracks to which that same bit stream is directed in succeeding frames; the sequence repeats until it is reset on the next even second tick. For the odd-track roll sequence, add one to all track numbers in Table 8.

Home track	Output Track							
	Roll Step 0	Roll Step 1	Roll Step 2	Roll Step 3	Roll Step 4	Roll Step 5	Roll Step 6	Roll Step 7
2	2	16	14	12	10	8	6	4
4	4	2	16	14	12	10	8	6
6	6	4	2	16	14	12	10	8
8	8	6	4	2	16	14	12	10
10	10	8	6	4	2	16	14	12
12	12	10	8	6	4	2	16	14
14	14	12	10	8	6	4	2	16
16	16	14	12	10	8	6	4	2
18	18	32	30	28	26	24	22	20
20	20	18	32	30	28	26	24	22
22	22	20	18	32	30	28	26	24
24	24	22	20	18	32	30	28	26
26	26	24	22	20	18	32	30	28
28	28	26	24	22	20	18	32	30
30	30	28	26	24	22	20	18	32
32	32	30	28	26	24	22	20	18

Notes: 1. The 'Home track' is the track that would be written if no b-r.
2. For odd-track sequence, add 1 to every track number in table.

Table 8 Standard VLBA 8-track barrel-roll sequence for even tracks

3. The '16-track' barrel-roll is a 16-step sequence that is enabled when
 - the total number of tracks is divisible by 16
 - tape writing speed is ≥ 4 Mbits/sec/track.

The details of the standard VLBA 16-track barrel-roll sequence for even tracks is given in Table 9, where 'home' (or Roll Step 0) is the track to which a particular bit stream is written on each frame starting on an even second tick; subsequent 'roll steps' indicate the tracks to which that same bit stream is directed in succeeding frames; the sequence repeats until it is reset on the next even second tick. For the odd-track roll sequence, add one to all track numbers in Table 9.

Home track	Output Track															
	Roll Step 0	Roll Step 1	Roll Step 2	Roll Step 3	Roll Step 4	Roll Step 5	Roll Step 6	Roll Step 7	Roll Step 8	Roll Step 9	Roll Step 10	Roll Step 11	Roll Step 12	Roll Step 13	Roll Step 14	Roll Step 15
2	2	16	14	12	10	8	6	4	18	32	30	28	26	24	22	20
4	4	2	16	14	12	10	8	6	20	18	32	30	28	26	24	22
6	6	4	2	16	14	12	10	8	22	20	18	32	30	28	26	24
8	8	6	4	2	16	14	12	10	24	22	20	18	32	30	28	26
10	10	8	6	4	2	16	14	12	26	24	22	20	18	32	30	28
12	12	10	8	6	4	2	16	14	28	26	24	22	20	18	32	30
14	14	12	10	8	6	4	2	16	30	28	26	24	22	20	18	32
16	16	14	12	10	8	6	4	2	32	30	28	26	24	22	20	18
18	18	32	30	28	26	24	22	20	2	16	14	12	10	8	6	4
20	20	18	32	30	28	26	24	22	4	2	16	14	12	10	8	6
22	22	20	18	32	30	28	26	24	6	4	2	16	14	12	10	8
24	24	22	20	18	32	30	28	26	8	6	4	2	16	14	12	10
26	26	24	22	20	18	32	30	28	10	8	6	4	2	16	14	12
28	28	26	24	22	20	18	32	30	12	10	8	6	4	2	16	14
30	30	28	26	24	22	20	18	32	14	12	10	8	6	4	2	16
32	32	30	28	26	24	22	20	18	16	14	12	10	8	6	4	2

Notes: 1. The 'Home track' is the track that would be written if barrel-roll is disabled.
2. For odd-track barrel-roll sequence, add 1 to every track number in table.

Table 9: Standard VLBA 16-track barrel-roll sequence for even tracks

3.2.2 Cross Track Parity

The VLBA formatter can form cross-track parity on groups of 8 or 16 formatter ‘data’ outputs and direct these (post barrel-roll) cross-track-parity data streams to the formatter ‘system’ outputs. In particular, cross-track parity from ‘8-track’ groups 2-9, 10-17, 18-25 and 26-33 may be written to any of the formatter ‘system’ outputs 0,1,34 or 35. Additionally, cross-track parity from ‘16-track’ groups 2-17, 10-25 and 18-33 may be written to any of the formatter ‘system’ outputs. The purpose of the cross-track parity data streams is to compensate for the loss of a single track of data within the group of tracks protected by the cross-track parity. This use of this feature has been designed into the VLBA correlator, but the author is unaware of its use to date.

3.2.3 Data-Multiplex (Fan-In/Fan-Out) Format

Although the VLBA formatter has extreme flexibility in the selection of fan-out track assignment, simple conventions have been adopted for standard recording modes, as outlined below. The user may arbitrarily assign any BBC-sideband to any CHANNEL. Special fan-out track assignments for special modes are not necessarily precluded.

3.2.3.1 Data-Multiplex Track-Assignment Conventions

The fanout conventions adopted by the VLBA are given in the tables below. For fan-out modes, the bit ordering for a single data stream is from the top to the bottom of an individual column in a table.

Fan-out mode 1:4 with 2-bit sampling

CHAN a		CHAN b		CHAN c		CHAN d	
Sign	Mag	Sign	Mag	Sign	Mag	Sign	Mag
2	10	3	11	18	26	19	27
4	12	5	13	20	28	21	29
6	14	7	15	22	30	23	31
8	16	9	17	24	32	25	33

Table 10: Track Assignment for 1:4 Fanout with 2-bit Sampling

Fan-out mode 1:4 with 1-bit sampling

CHA N a	CHA N b	CHA N c	CHA N d	CHA N e	CHA N f	CHA N g	CHA N h
Sign	Sign	Sign	Sign	Sign	Sign	Sign	Sign
2	3	10	11	18	19	26	27
4	5	12	13	20	21	28	29
6	7	14	15	22	23	30	31
8	9	16	17	24	25	32	33

Table 11: Track Assignment for 1:4 Fanout with 1-bit Sampling

Fanout mode 1:2 with 2-bit sampling

CHAN a		CHAN b		CHAN c		CHAN d		CHAN e		CHAN f		CHAN g		CHAN h	
Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g
2	6	3	7	10	14	11	15	18	22	19	23	26	30	27	31
4	8	5	9	12	16	13	17	20	24	21	25	28	32	29	33

Table 12: Track Assignment for 1:2 Fanout with 2-bit Sampling

Fanout mode 1:2 with 1-bit sampling

CH N a	CH N b	CH N c	CH N d	CH N e	CH N f	CH N g	CH N h	CH N i	CH N j	CH N k	CH N l	CH N m	CH N n	CH N o	CH N p
Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n	Sig n
2	3	6	7	10	11	14	15	18	19	22	23	26	27	30	31
4	5	8	9	12	13	16	17	20	21	24	25	28	29	32	33

Table 13: Track Assignment for 1:2 Fanout with 1-bit Sampling

Fanout mode 1:1 (i.e. no fanout) with 2-bit sampling

CHAN a		CHAN b		CHAN c		CHAN d		CHAN e		CHAN f		CHAN g		CHAN h	
Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32
CHAN i		CHAN j		CHAN k		CHAN l		CHAN m		CHAN n		CHAN o		CHAN p	
Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g	Sig n	Ma g
3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33

Table 14: Track Assignment for 1:1 Fanout with 2-bit Sampling

Fanout mode 1:1 (i.e. no fanout) with 1-bit sampling

This mode is essentially the Mark IIIA-compatible mode with 1 channel/track. Typically, 16 even tracks are recorded in one tape direction and 16 odd tracks in the other tape direction to emulate the standard Mark IIIA recording modes (see Appendix B).

Notes:

1. A 'channel' may be any USB or LSB output from any BBC.
2. For each multiplexed channel, the sample bit taken at the Time Code+0 is written as the first bit in the Data Field of the lowest-numbered track; the sample bit taken at Time Code+1-sample-period is written as the first bit in the Data Field of the lowest-numbered-track+2, etc.

3.2.3.2 Fan-In Track-Assignment Conventions

As of this writing, fan-in track-assignment conventions have not yet been stated by NRAO. Fan-in modes are not yet supported by the VLBA correlator.

3.3 Recorder Characteristics

3.3.1 Transport

The VLBA transport is mechanically identical to the Mark IV transport, although the control electronics has been significantly modified. Control of the VLBA system is with the MCB (Monitor and Control Bus).

3.3.2 Headstack

The VLBA uses a single headstack which is identical to the Mark IV headstack (see Section 2.3.2), except that all 36 heads are supported. The headstack can be electronically switched between read and write capability.

3.3.3 Headstack Positioner

The VLBA headstack positioner is identical to the Mark IV headstack positioner (see Section 2.3.3).

3.4 Physical Recording-Format Conventions

3.4.1 Longitudinal

Like the Mark IV, the longitudinal bit density along a track is determined entirely by the writing data rate and the tape speed. Although the design density of the VLBA system is ~56,250 bpi/track, operations are currently being done at ~33,000 bpi/track. Since the maximum per-track-data-rate of the VLBA system is ~9 Mbits/sec, all recording modes can be supported at ~33,000 bpi. Note that the recording speed must be slightly different for the 'data-replacement' and 'non-data-replacement' formats in order to keep the longitudinal density constant. Plans currently exist to increase the density to ~56,000 sometime in 1996.

3.4.2 Transverse

The design specification for the VLBA is 16 passes of the tape writing all 36 tracks. Currently, the VLBA is operating in a 14-pass mode (i.e. 14 passes with all 36 head writing on each pass), with the possibility to upgrade to a 16-pass mode in the future.

Error! Reference source not found. illustrates the layout of recorded tracks across the tape for the '14-pass' operating mode. This mode requires that the headstack be positioned to 14 different positions in such a way that there is non-interference between adjacent tracks. Seven of the positions are recorded in the forward direction, spaced at 48 μm ; with a 38 μm track width; this provides a 10 μm guard band between these tracks. The forward-tape-motion headstack positions have been chosen to be -319, -271, -223, -175, -127, -79 and -31 μm (by convention, negative headstack positions are away from the transport deckplate; headstack position '0' is calibrated to center the headstack on the tape). This can be visualized as a group of seven adjacent parallel stripes on the tape all written by the same head. This group of seven stripes is widely separated from the group written in the same-tape-motion-direction by adjacent heads; the space in between, as explained in the next paragraph, is for a group of seven tracks written in the reverse-motion direction.

The reverse-tape-motion headstack positions are also chosen with a spacing of 48 μm ; in particular, the headstack positions are 31, 79, 127, 175, 223, 271 and 319 μm . This groups the reverse-direction tracks written by head n into seven parallel stripes straddled on the positive-headstack-position side by the forward-written tracks laid down by the head n and on the negative-headstack-position side by the group of seven parallel tracks written in the forward direction by head $n-1$. Note that the forward-motion group of tracks is separated from the reverse-direction group of tracks by 24 μm (track edge to track edge), providing a larger guard band 14 μm larger between the forward/reverse track groups than between tracks within the same group. This recognizes the fact that the forward-direction/reverse-direction tracking signature of the transport is generally poorer than repeatability in the same tape-motion direction.

Note that multiple passes may be written at the each headstack position (in the same tape-motion direction) so long as exclusive sets of heads are recorded on each pass.

4. Mark IIIA Tape Format and Recording Modes

4.1 Longitudinal Data Format

The Mark IIIA tape-frame format is identical to the Mark IV format except for the auxiliary-data information. The auxiliary-data field in each case contains 64 bits (16 hex numbers). Both are protected by the 12-bit CRC code in the header block (as is the time code). Of course, the Mark IIIA system is limited to 1 bit/sample and 1 chan/track, so there is no capability to support fan-in or fan-out as on the Mark IV and VLBA systems.

4.1.1 Time Code & CRC

The Mark IIIA time code and CRC fields are identical to the Mark IV time code and CRC fields (see Section 2.1.1).

4.1.2 Auxiliary Data

The Mark IIIA auxiliary data field is common across all tracks and can be written as 16 hex digits (in the order written to tape):

vwxwxyzFFaabb

where

vv:	hex 'FF' for forward calibration (odd passes) hex 'FE' for reverse calibration (even passes) hex 'FD' for uncalibrated position Note: In the VLBA emulation of Mark IIIA, 'vv' is binary-encoded to be the VLBA track number (4-31, corresponding to Mark IIIA tracks 1-28); see Appendix A.
wxyz:	0000-3999 positive micron positions (bcd encoded) 4000-7999 negative micron positions (bcd encoded); (4000, 7999 indicate positions of 0, -3999 respectively)
FF:	hex characters FF
aa:	Formatter status and error flags bit 7 time sync error bit 6 primary power fail bit 5 framing error bit 4 timing error bits 3-2 input source bits 1-0 formatter mode
bb:	bits 7-0 hardware ID

The first 48 bits of the aux-data (ttwxwxyzFF) are software-controllable; the last 16 bits (aabb) are fixed by the Mark IIIA formatter. The apparently-peculiar encoding of head position is an attempt to remove DC bias from the aux-data field, which sometime causes decoding problems on older playback drives at the correlators. Mark IIIA systems using control software other than that provided by NASA Goddard Space Flight Center may not write the first 48 bits of the aux-data field in the manner described.

4.1.3 Sync Word

The Mark IIIA sync word is identical to the Mark IV sync word.

4.1.4 Data Field

The Mark IIIA Data Field is identical to the Mark IV Data Field, but with the following restrictions:

1. Only 1-bit sampling is supported.
2. No fan-in or fan-out modes are supported (i.e. 1 channel maps to 1 track at all times)
3. No data-modulation is supported.

4.2 Transverse Data Format

The Mark IIIA formatter writes to the center 28 heads 36 heads available on the headstack; the headstack is identical to the Mark IV and VLBA headstack. Each head is assigned to a single BBC USB/LSB channel according to the recording mode; no multiplexing or barrel-rolling is supported.

4.3 Recording Modes and Track Assignments

The Mark IIIA formatter supports four fixed mappings of video-converter channels to tracks, designated modes A-D, according to the following table:

VLBA Track#	Mark 3A Track#	Mark 3A Group#	Mode A	Mode B	Mode C	Mode D	Mode E
4	1	1	U1	U1	U2	U1	U1
6	3		U3	U3	U4	U1	U3
8	5		U5	U5	U6	U1	U5
10	7		U7	U7	U8	U1	U7
12	9		U9	U9	U10	U1	U9
14	11		U11	U11	U12	U1	U11
16	13		U13	U13	U14	U1	U13
18	15	3	L1	L1	U1	U1	U1
20	17		L3	L3	U3	U1	U3
22	19		L5	L5	U5	U1	U5
24	21		L7	L7	U7	U1	U7
26	23		L9	L9	U9	U1	U9
28	25		L11	L11	U11	U1	U11
30	27		L13	L13	U13	U1	U13
5	2	2	U2	U1	U2	U1	U1
7	4		U4	U3	U4	U1	U3
9	6		U6	U5	U6	U1	U5
11	8		U8	U7	U8	U1	U7
13	10		U10	U9	U10	U1	U9
15	12		U12	U11	U12	U1	U11
17	14		U14	U13	U14	U1	U13
19	16	4	L2	L1	U1	U1	U1
21	18		L4	L3	U3	U1	U3
23	20		L6	L5	U5	U1	U5
25	22		L8	L7	U7	U1	U7
27	24		L10	L9	U9	U1	U9
29	26		L12	L11	U11	U1	U11
31	28		L14	L13	U13	U1	U13

Table 15: Mark IIIA Data-Recording Modes and Track Assignments

Notes:

1. U - Upper sideband output from video-converter
2. L - Lower-sideband output from video-converter
3. Mode A - 28 track recorded in one pass for wideband continuum
4. Mode B - 14 track recorded in each pass for continuum
5. Mode C - 14 track per pass using all the upper-sideband outputs from all 14 video-converters
6. Mode D - 1 track recorded per pass for spectroscopy

Mode E is a 'software mode' which is realized by alternating between hardware modes B and C and enabling a single group of tracks on each pass.

4.4 Recorder Characteristics

4.4.1 Tape Transport

The Mark IIIA tape transport is essentially identical to the Mark IV transport (see Section 2.3.1). Note, however, that the mechanical upgrade needed to support 'thin' (≤ 16 μm thickness) tape, which is mandatory on Mark IV systems, may not be implemented on all Mark IIIA systems. Such unupdated systems may cause damage to 'thin' tape and should not be used with thin tape.

4.4.2 Headstack

The Mark IIIA uses two headstacks, each mounted on an independent positioner. One headstack is dedicated to writing and the other to playback. Both headstacks are identical to the Mark IV headstacks (see Section 2.3.2), except that only the central 28 heads (numbered 4-31) are used.

4.4.3 Headstack Positioner

The Mark IIIA headstack positioners are identical to the Mark IV headstack positioners (see Section 2.3.3).

4.5 Physical Recording-Format Conventions

4.5.1 Longitudinal

The Mark IIIA system is generally operated at 33,333 bpi/track, which results in tape recording speeds of 270 ips and sub-octaves (135 ips, 67.5 ips, etc.). Only Mark IIIA systems which use 'thin' (≤ 16 μm thickness) tape, which has better magnetic performance, may use the higher bit densities supported by the Mark IV and VLBA systems; such systems must have installed the mechanical upgrade to properly support 'thin' tape.

4.5.2 Transverse

The Mark IIIA has traditionally written tapes with two different sets of headstack positions, depending on the number of tracks recorded. Mode A (28-tracks) is recorded in a 12-pass format as detailed in **Error! Reference source not found.** Modes B and C (14-track modes) are written in a 24-pass format as detailed in **Error! Reference source not found.**

5. Standard Recording Modes and Inter-Compatibility

Error! Reference source not found. and **Error! Reference source not found.** give parameters for the set of 'standard' Mark IV and VLBA recording modes⁹. Each mode is given a designation of the form:

$$\langle \text{total data rate} \rangle - \langle \# \text{channels} \rangle - \langle \# \text{bits/sample} \rangle$$

For example, mode 128-4-2 indicates a recording rate of 128 Mbits/sec, covering 4 channels sampled at 2 bits. For purposes of this designation, a channel is a single USB or LSB output from a video converter (BBC). **Error! Reference source not found.** covers the most-common continuum observing modes and **Error! Reference source not found.** covers the most-common spectroscopic modes. Note that *all* 'standard' VLBA observing modes are included in these tables. Also included are several 'Mark III compatibility' modes which should be considered when operating Mark IV and Mark IIIA simultaneously.

Note that the three-number mode designator can be ambiguous with respect to the details of fan-out, tape-speed and data-rate/track. For example, the 64-4-2 mode can be recorded on 8 tracks at 8 Mbits/sec/track or on 16 tracks at 4 Mbits/sec/track. In these cases, care must be taken to specify the *actual* recording mode by specifying fan-out or tape-speed or data-rate/track.

Compatibility with the following other VLBI data-acquisition systems (DAS) is indicated for each mode:

1. VLBA-8: standard VLBA system with 8 BBC's and either one or two tape drives
2. VLBA-14: 'geodetic' VLBA system augmented to 14 BBC's for full compatibility with the Mark IIIA system.
3. Mark 3A: standard Mark IIIA with 14 BBC's

⁹The VLBA 'standard' modes are defined in 'Standard VLBA Observing Modes', J.D. Romney, 27 Jan 1993, and are a subset of the VLBA 'basic' modes which are defined in 'Basic VLBA Recording Modes', R.C. Walker, 20 Jan 1993.

Known or expected compatibility with correlators either existing or under-development is also indicated, along with the expected processing speed-up factors for each mode.

Many variations on the modes listed in **Error! Reference source not found.** and **Error! Reference source not found.** are supported by Mark IV and VLBA hardware, but their use should be limited to special circumstances to avoid non-standard configurations.

	Mode	Total	#chans	Bits/samp	Total BW	Smp Rate	Tk Rate	#tracks	Fan-Out	VLBA-8	VLBA-14	Mark 4	Mark 3A	VLBA	Mark 4	EVN	Mark 3A
	Designation	(Mbits/sec)			(MHz)	(Msamp/s)	(Mbits/sec)	(per pass)	(bitstream/ track)	(S=stndrd) DAS	(see Notes) DAS	DAS	DAS	Corr	Corr	Corr	Corr
														(speedup)	(speedup)	(speedup)	(speedup)
	512-16-1	512	16	1	256	32	8	64	0.25	S(2 drvs)	Y(2 drvs)	Y	-	1	-	1	-
	256-8-1	256	8	1	128	32	8	32	0.25	S	Y	Y	-	1	-	1	-
	128-16-1	128	16	1	64	8	4	32	0.5	Special	Y	Y	N	2	4	4	1
	128-16-1	128	16	1	64	8	8	16	1	Special	Y	Y	Y	1	2	2	0.5
	128-8-1	128	8	1	64	16	4	32	0.25	S	Y	Y	-	2	4	4	-
	64-16-1	64	16	1	32	4	2	32	0.5	Special	Y	Y	N	4	8	8	2
	64-16-1	64	16	1	32	4	4	16	1	Special	Y	Y	Y	2	4	4	1
	64-4-1	64	4	1	32	16	4	16	0.25	S	Y	Y	-	2	4	4	-
	32-2-1	32	2	1	16	16	4	8	0.25	S	Y	Y	-	2	4	4	-
	16-2-1	16	2	1	8	8	2	8	0.25	S	Y	Y	Y	4	8	8	-
	8-2-1	8	2	1	4	4	2	4	0.5	S	Y	Y	Y	4	8	8	-
	2048-32-2	2048	32	2	512	32	16	128	0.5	-	-	4 hdstks	-	-	1	1	-
	1024-16-2	1024	16	2	256	32	16	64	0.5	-	-	Y	-	-	1	1	-
	512-8-2	512	8	2	128	32	8	64	0.25	S(2 drvs)	Y(2 drvs)	Y	-	1	-	1	-
	512-16-2	512	16	2	128	16	8	64	0.5	Special	Y	Y	-	1	2	2	-
	256-8-2	256	8	2	64	16	8	32	0.5	S	Y	Y	-	1	2	2	-
Primary VLBA mode	128-4-2	128	4	2	32	16	4	32	0.25	S	Y	Y	-	2	4	4	-
VSOP mode	128-2-2	128	2	2	32	32	8	16	0.25	Special	Y	Y	-	1	2	2	-
	64-2-2	64	2	2	16	16	4	16	0.25	S	Y	Y	-	2	4	4	-
	32-2-2	32	2	2	8	8	2	16	0.25	S	Y	Y	1-bit only	4	8	8	-
	16-2-2	16	2	2	4	4	2	8	0.5	S	Y	Y	1-bit only	4	8	8	-
	8-2-2	8	2	2	2	2	2	4	1	S	Y	Y	1-bit only	4	8	8	-
Notes:																	
	1. VLBA-8 is 'standard' VLBA system with 8 BBC's (may have one or two tape drives).																
	2. VLBA-8 modes labelled as 'S' are 'standard' VLBA recording modes as described in "Standard VLBA Observing Modes" by J.D. Romney, 27 Jan 93.																
	3. VLBA modes labelled as 'Special' are accessible to VLBA system, but not among 'standard' modes defined by VLBA.																
	4. Mode 128-16-1 has highest bit-rate compatibility between Mark IIIA and VLBA, although in practice Mark 3A would probably record in mode 112-14-1 for tape-usage efficiency.																
	5. Mode 64-16-1 has 64 Mbit/sec compatibility between Mark IIIA and VLBA, although in practice Mark 3A would probably record in mode 56-14-1 for tape-usage efficiency.																
	6. Mode 512-16-2 is the only VLBA 512 Mbit/sec mode compatible with Mark IV correlator.																
	7. Mark 4 correlator cannot support modes which reproduce at >32 Msamples/sec at fixed 16 Mbit/sec/track playback rate.																
	8. Mark 4 DAS and VLBA-14 can be configured to be compatible with all Mark 3A modes.																
	9. Recording modes with more than 8 channels may require 2 passes through the VLBA correlator.																
	10. Mark IV systems require external filters to support BBC channel bandwidths of 0.25 and 1.0 MHz.																

Table 16 Standard Mark 4 Continuum Modes and Compatibility with VLBA and Mark 3A

BW/line (MHz)	#lines	Mode Designation	Total (Mbits/sec)	#chans	Bits/samp	Total BW (MHz)	Smp Rate (Msamp/s)	Tk Rate (Mbits/sec)	#tracks (per pass)	Fan-Out (bitstreams/ track)	VLBA-8 DAS (S=stndrd)	VLBA-14 DAS	Mark 4 DAS	Mark 3A DAS	VLBA Corr (speedup)	Mark 4 Corr (speedup)	EVN Corr (speedup)	Mark 3A Corr (speedup)
52	1	256-4-2	256	4	2	64	32	8	32	0.25	S	Y	Y	-	1	-	2	-
28	1	128-2-2	128	2	2	32	32	8	16	0.25	S	Y	Y	-	1	-	2	-
16	1	64-1-2	64	1	2	16	32	8	8	0.25	S	Y	Y	-	1	-	2	-
8	1	32-1-2	32	1	2	8	16	4	8	0.25	S	Y	Y	-	2	4	4	-
4	1	16-1-2	16	1	2	4	8	2	8	0.25	S	Y	Y	1-bit only	4	8	8	-
2	1	8-1-2	8	1	2	2	4	2	4	0.5	S	Y	Y	1-bit only	4	8	8	-
1	1	4-1-2	4	1	2	1	2	2	2	1	S	Y	Y	1-bit only	4	8	8	-
0.5	1	2-1-2	2	1	2	0.5	1	2	1	2	S	Y	Y	1-bit only	4	8	8	-
52	2	512-8-2	512	8	2	128	32	8	64	0.25	S(2 drvs)	Y	Y	-	1	-	2	-
28	2	256-4-2	256	4	2	64	32	8	32	0.25	S	Y	Y	-	1	-	2	-
16	2	128-2-2	128	2	2	32	32	8	16	0.25	S	Y	Y	-	1	-	2	-
8	2	64-2-2	64	2	2	16	16	4	16	0.25	S	Y	Y	-	2	4	4	-
4	2	32-2-2	32	2	2	8	8	2	16	0.25	S	Y	Y	1-bit only	4	8	8	-
2	2	16-2-2	16	2	2	4	4	2	8	0.5	S	Y	Y	1-bit only	4	8	8	-
1	2	8-2-2	8	2	2	2	2	2	4	1	S	Y	Y	1-bit only	4	8	8	-
0.5	2	4-2-2	4	2	2	1	1	2	2	2	S	Y	Y	1-bit only	4	8	8	-
0.25	2	2-2-2	2	2	2	0.5	0.5	2	1	4	S	Y	Y	1-bit only	4	8	8	-
28	4	512-8-2	512	8	2	128	32	8	64	0.25	S(2 drvs)	Y	Y	-	1	-	2	-
16	4	256-4-2	256	4	2	64	32	8	32	0.25	S	Y	Y	-	1	-	2	-
8	4	128-4-2	128	4	2	32	16	4	32	0.25	S	Y	Y	-	2	4	4	-
4	4	64-4-2	64	4	2	16	8	2	32	0.25	S	Y	Y	1-bit only	4	8	8	-
2	4	32-4-2	32	4	2	8	4	2	16	0.5	S	Y	Y	1-bit only	4	8	8	-
1	4	16-4-2	16	4	2	4	2	2	8	1	S	Y	Y	1-bit only	4	8	8	-
0.5	4	8-4-2	8	4	2	2	1	2	4	2	S	Y	Y	1-bit only	4	8	8	-
0.25	4	4-4-2	4	4	2	1	0.5	2	2	4	S	Y	Y	1-bit only	4	8	8	-
16	8	512-8-2	512	8	2	128	32	8	64	0.25	S(2 drvs)	Y	Y	-	1	-	2	-
8	8	256-8-2	256	8	2	64	16	8	32	0.5	S	Y	Y	-	1	2	2	-
4	8	128-8-2	128	8	2	32	8	4	32	0.5	S	Y	Y	1-bit only	2	4	4	-
2	8	64-8-2	64	8	2	16	4	2	32	0.5	S	Y	Y	1-bit only	4	8	8	-
1	8	32-8-2	32	8	2	8	2	2	16	1	S	Y	Y	1-bit only	4	8	8	-
0.5	8	16-8-2	16	8	2	4	1	2	8	2	S	Y	Y	1-bit only	4	8	8	-
0.25	8	8-8-2	8	8	2	2	0.5	2	4	4	S	Y	Y	1-bit only	4	8	8	-

Table 17 Standard Mark 4 Spectroscopic Modes and Compatibility with VLBA and Mark 3A

6. Appendix A: Track Numbering and Aux-Data Track ID's in Mark IIIA, Mark IV, VLBA

There has arisen some confusion as to track numbering and track-identifying information in the Mark IIIA, Mark IV, and VLBA data-acquisition systems. The intent of this appendix is to help clarify this situation.

Track-Numbers vs. Head-Numbers

For purposes of convenience, and in deference to common usage, we will use the word 'track-number' when we really should be using the word 'head-number'. Because all three of these systems use movable headstacks and multiple passes, the true track-number quickly becomes ambiguous, but the 'head-number' within the headstack always remains unambiguously defined. We should note additionally that, due to the movable headstacks, a given track on the tape is potentially also readable by a neighboring head; so when we speak of 'head-number', at least in this note, we always mean the *writing* head-number.

Mark IIIA¹⁰

The Mark IIIA system uses 28 heads ('tracks'), numbered 1-28. On the Honeywell/Metrum transport, track 1 is closest to the front of the drive (closest to the user) and track 28 is closest to the deck plate; this is reversed on the Penny & Giles transport since the tape reels are mounted 'backwards'. The 28 tracks are divided into four groups, numbered 1-4. Group 1 contains the odd-numbered tracks in the range 1-13; Group 2 contains the even numbered tracks in the range 2-14; Group 3 contains the odd-numbered tracks in the range 15-27; Group 4 contains the even-numbered tracks in the range 16-28

The original Mark IIIA systems do not have the capability of writing track-specific data in the auxiliary-data field of each data-frame header, therefore no track-identification information is contained on tapes written on original Mark IIIA systems.

The VLBA system has the capability of emulating the Mark IIIA system, but includes the capability of writing track-specific identification information in the aux-data area of each data frame. When operating in this mode, the Mark IIIA aux-data field defined as 'vv' in Section 4.1.2 is written as a binary-encoded VLBA track number equal to the Mark IIIA track number plus 3 (see Table 15).

VLBA

The VLBA system uses 36 heads ('tracks'), numbered 0-35. Numbering order across the tape is similar to Mark IIIA. The 36 tracks are divided into four groups, numbered 0-3, within the VLBA tape recorder. Group 0 contains the even-numbered tracks in the range 0-16; Group 1 contains the odd-numbered tracks in the range 1-17; Group 2 contains the even-numbered tracks in the range 18-34; Group 3 contains the odd-numbered tracks in the range 19-35. The 'group' and 'track' hex digits A10 and A9 encoded into the VLBA auxiliary-data field are shown in Table 18; these 'group' and 'track' numbers are generated by the VLBA formatter and are somewhat different than the group numbers defined within the recorder.

Mark IV

The Mark IV system uses 32 heads ('tracks') in each of 2 headstacks for a total of 64 tracks, and is expandable to 4 headstacks. The tracks on each headstack are numbered 2-33, which correspond directly to VLBA tracks 2-33. The Mark IV track number is encoded into the aux-data field as a 6-bit BCD field. The headstack number is encoded into a 2-bit field in the aux-data.

Table 18 shows the track-numbering correspondence and aux-data track-ID fields in VLBA, Mark IV, Mark IIIA and VLBA emulation of Mark IIIA.

¹⁰ The older Mark III system is a subset of the Mark IIIA system. Both systems write 28 tracks, numbered in the same way, but the Mark III system has a fixed headstack and can write only a single pass on the tape.

Head #	VLBA			Mark IV		Mark IIIA	
	Track #	Aux-data 'Group' (Digit A10) (hex) ¹¹	Aux-data 'Track' (Digit A9) (hex) ¹²	Track#	Aux-data Track-ID (hex)	Track#	Aux-data Track-ID (hex) ¹³
0	0	4	2	-	-	-	-
1	1	4	0	-	-	-	-
2	2	2	0	2	02	-	-
3	3	0	0	3	03	-	-
4	4	2	1	4	04	1	04
5	5	0	1	5	05	2	05
6	6	2	2	6	06	3	06
7	7	0	2	7	07	4	07
8	8	2	3	8	08	5	08
9	9	0	3	9	09	6	09
10	10	2	4	10	10	7	0A
11	11	0	4	11	11	8	0B
12	12	2	5	12	12	9	0C
13	13	0	5	13	13	10	0D
14	14	2	6	14	14	11	0E
15	15	0	6	15	15	12	0F
16	16	2	7	16	16	13	10
17	17	0	7	17	17	14	11
18	18	3	0	18	18	15	12
19	19	1	0	19	19	16	13
20	20	3	1	20	20	17	14
21	21	1	1	21	21	18	15
22	22	3	2	22	22	19	16
23	23	1	2	23	23	20	17
24	24	3	3	24	24	21	18
25	25	1	3	25	25	22	19
26	26	3	4	26	26	23	1A
27	27	1	4	27	27	24	1B
28	28	3	5	28	28	25	1C
29	29	1	5	29	29	26	1D
30	30	3	6	30	30	27	1E
31	31	1	6	31	31	28	1F
32	32	3	7	32	32	-	-
33	33	1	7	33	33	-	-
34	34	4	3	-	-	-	-
35	35	4	1	-	-	-	-

Table 18: Correspondence of track numbers and aux-data track-ID field in various systems

¹¹Bit-reversed when written to tape (i.e. written lsb-to-msb)

¹²Bit-reversed when written to tape (i.e. written lsb-to-msb)

¹³Present on VLBA emulation of Mark IIIA system only

7. Appendix B: Tabular Summary of Primary Mark IIIA, Mark IV, VLBA Characteristics

The following table summarizes the salient characteristics of the Mark IIIA, Mark IV, and VLBA parameters relating to data and tape formats:

	Mark IIIA	Mark IV	VLBA
#BBC's	14	14 ¹⁴	8 ¹⁵
Max sample rate (Msamples/sec)	8	32	32
#bits/sample	1	1 or 2	1 or 2
#tracks (#supported heads)	28	64 ¹⁶	36 ¹⁷
Head spacing within headstack	698.5 um	698.5 um	698.5 um
#passes (all heads enabled)	12	16	16
Max data-rate/track (Mbits/sec) ¹⁸	8	16	8
Bit density (bpi/track)	~33,000	~56,000	~56,000 ¹⁹
Multiplex fan-out (bitstreams:trk)	1:1 only	1:1, 1:2, 1:4 ²⁰	1:1, 1:2, 1:4 ²⁰
Multiplex fan-in (bitstreams:trk)	None	2:1, 4:1	2:1, 4:1
Barrel-rolling	N	Y	Y
Data-modulation	N	Y	Y
Support of non-data-replacement	N	N	Y ²¹
Longitudinal track-frame length (Aux+Sync+Time+CRC +Data+Parity) [in bits]	64A +32S +52T +12C +19840D (+2500P)	64A +32S +52T +12C +19840D (+2500P)	32S +48T +16C +20000D +64A ²² (+2520P)

Table 19: Comparison of Mark IIIA, Mark IV and VLBA Major Characteristics

¹⁴Expandable to 16 BBC's

¹⁵A few VLBA systems have been augmented to 14 BBC's for better compatibility with Mark IIIA.

¹⁶Expandable to 128 tracks (4 headstacks total), for a maximum total data rate of 2048 Mbits/sec

¹⁷32 data tracks plus 4 'system' tracks.

¹⁸Actual Mark III/IV bit-rate/track is 9/8 times data-rate/track due to addition of byte-parity bits. Actual VLBA bit-rate/track is slightly greater than 9/8 times data-rate/track due to non-data-replacement format.

¹⁹As of mid-1995, VLBA was still in transition from 33,000 to 56,000 bpi/track.

²⁰A single sample bit-stream (sign or magnitude) can be fanned out to a maximum of 4 tracks. Therefore, data from 2-bit channels can actually be fanned-out to a total of 8 tracks. Mark IV and VLBA are the same in this respect.

²¹Can also write Mark IIIA/Mark IV-compatible data-replacement format

²²Aux-data field is defined to be at *end* of frame in VLBA tape-frame format.

8. Appendix C: Revision History

Revision 1.0, 27 December 95:

Original issue, largely based on Mark IV memo 205.6

Revision 1.1, 4 January 96:

Fix several minor typos

Revision 1.11, 8 May 98:

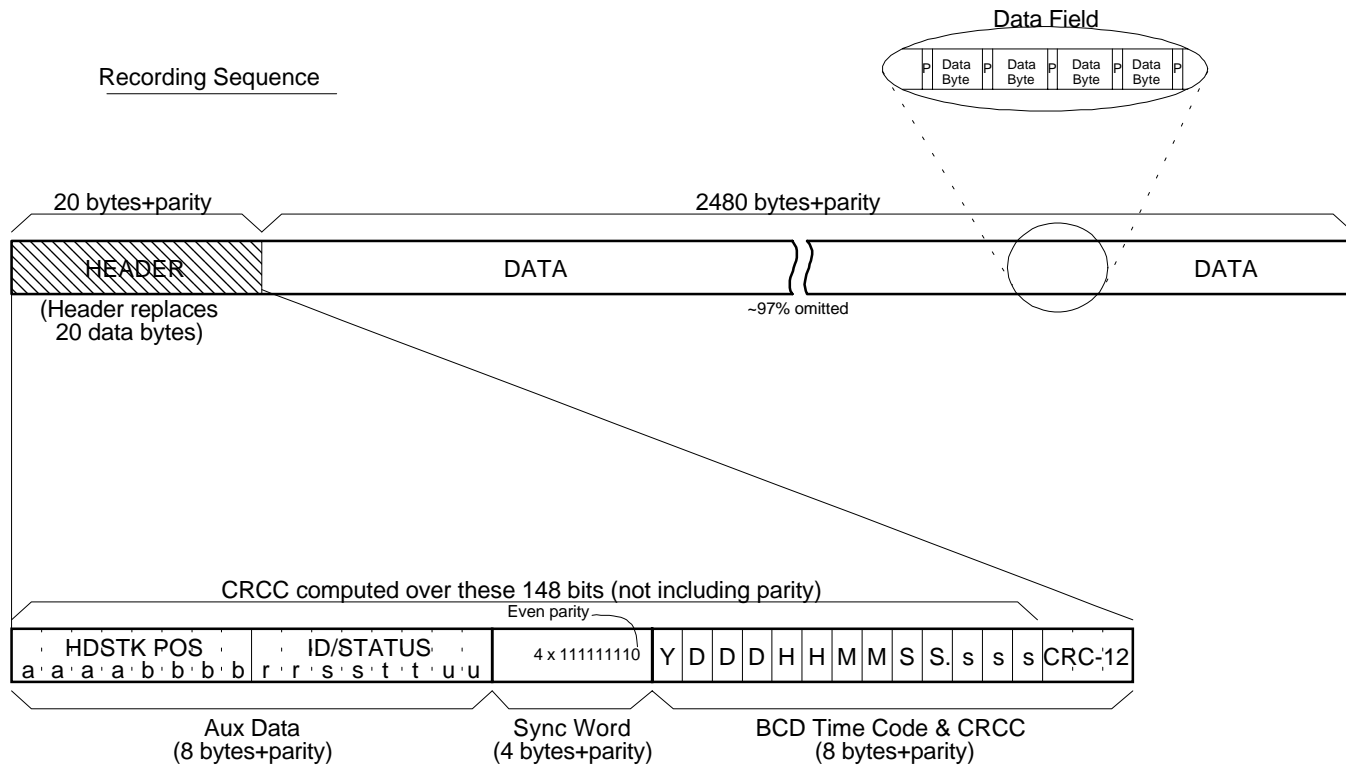
Fix several minor typos; add additional modes to Table 15

Revision 1.12 28 August 98:

Expand Table 3 to include encoding for MkIV corr chip and MkIV formatter rear-panel outputs.

Revision 1.2 28 September 2000:

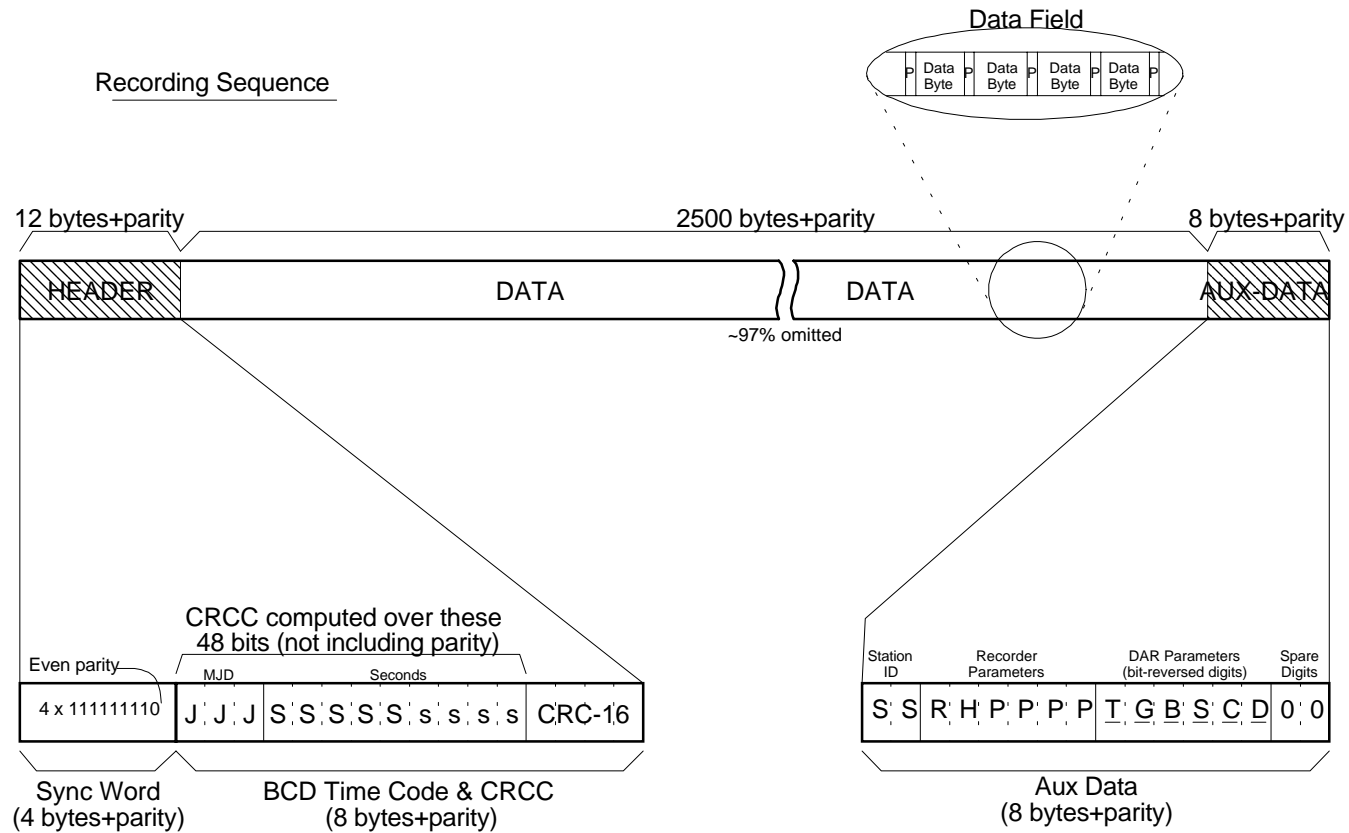
Amend barrel-roll tables to be consistent with actual VLBA sequences.



- Notes:
1. Parity always ODD except Sync Word.
 2. Byte to either side of Sync Word must contain at least one '0' (two '0's requested by VLBA correlator).
 3. Mark III tape frame format is identical except for contents of Aux Data field.

ARW
8 Dec 95

Figure 1: Mark IV Tape Frame Format

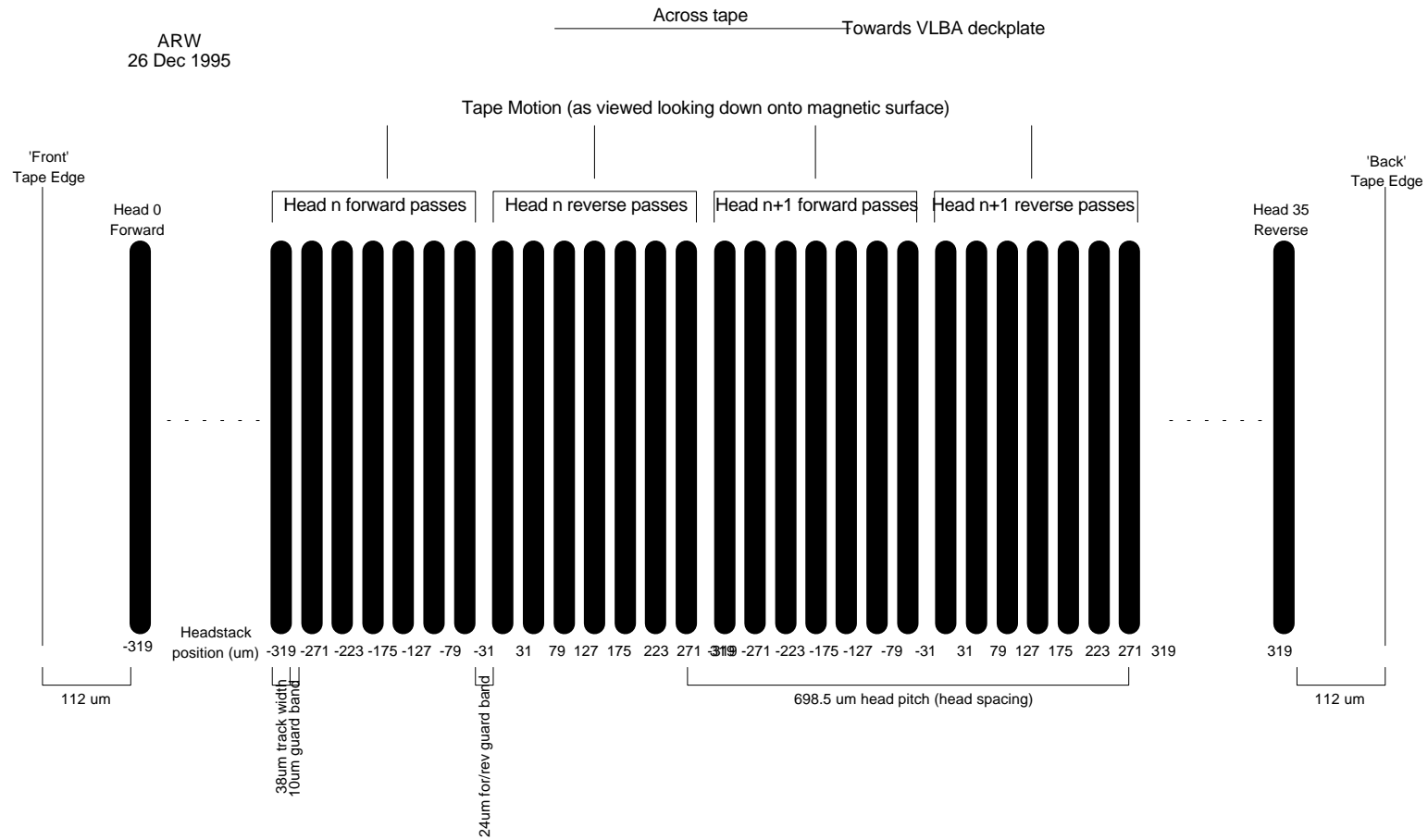


- Notes:
1. Parity always ODD except Sync Word.
 2. BCD digits in Time-Code and Aux-data, except those labelled reversed, are written to tape in order msb-to-lsb.
 3. Byte to either side of Sync Word must contain at least one '0'.

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26 May 1994

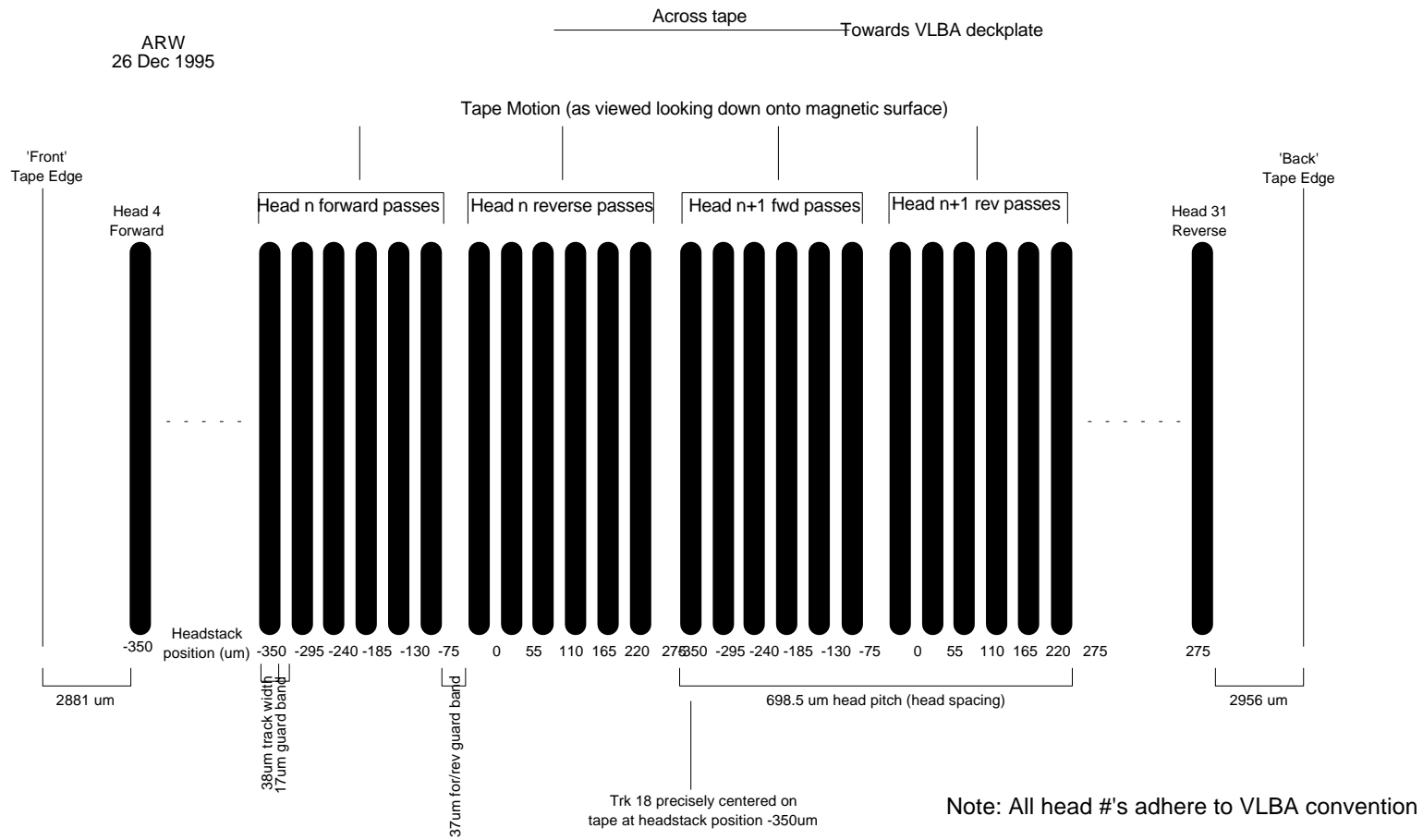
Figure 2: VLBA Tape Frame Format

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26 Dec 1995



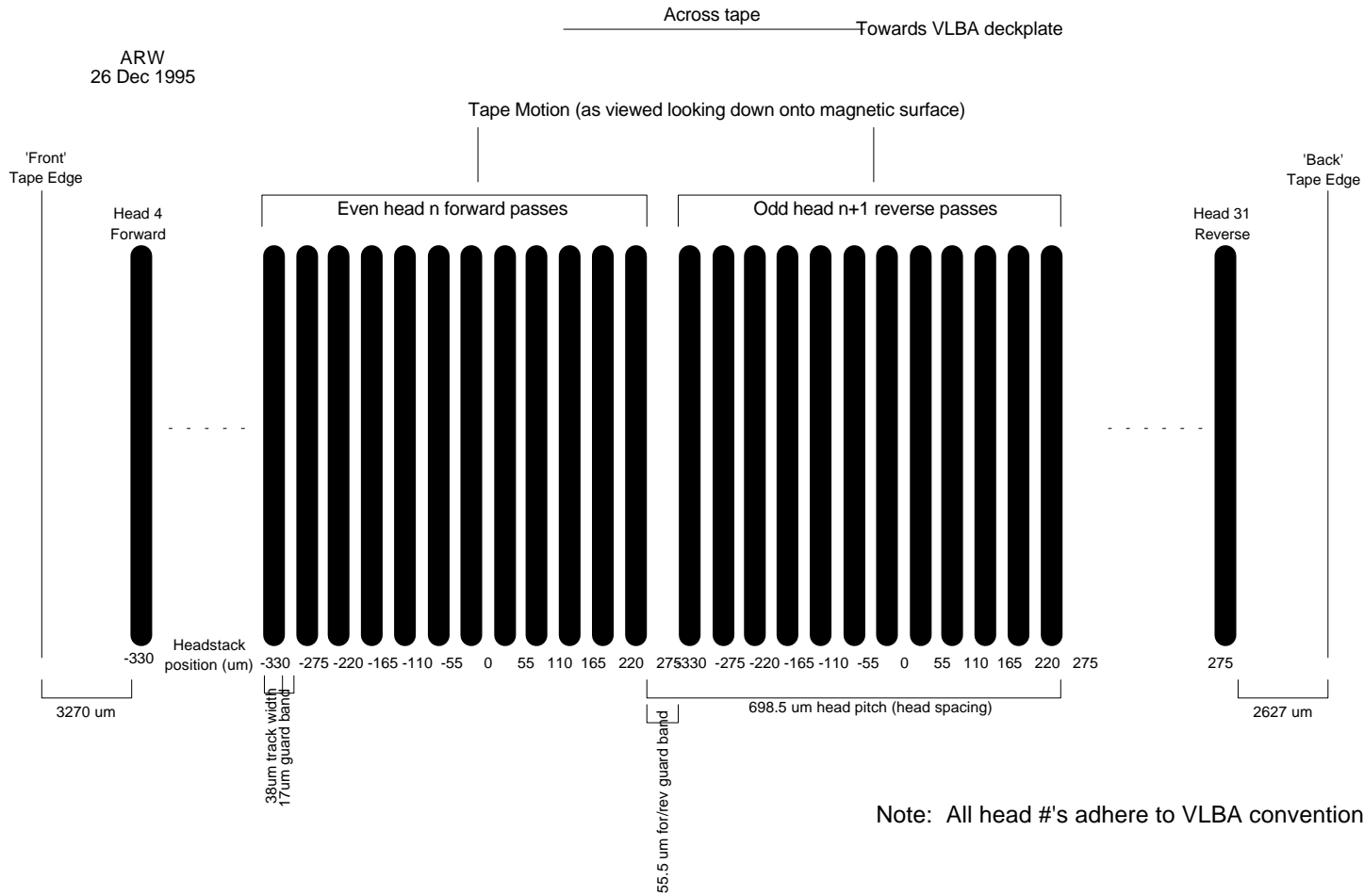
**Figure 4: VLBA Track Layout on Tape for 14-pass Operation
(track #'s are VLBA convention)**

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**Figure 5: Mark IIIA Mode A Standard Layout on Tape
(12 28-track passes)**

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**Figure 6: Mark IIIA Mode B,C Standard Layout on Tape
(24 14-track passes)**