MAGNETIC TAPE EQUIPMENT

Since the Allies' discovery in 1944 of the "magnetophones" created in Germany during World War II (1), the technology of magnetic recording has evolved to the point that in the developed world there are few people who have not had recent access to a magnetic tape recording/reproducing system. The prevalence of the consumer video cassette recorder (*VCR*) is the most obvious example, but the audiocassette recorder, whether stand-alone or in a vehicle, is still in use although it is fading relative to digital alternatives. In addition, the magnetic tape drive is also the basis of most consumer video camera, the "Camcorder," that is now found in many homes. There are hosts of competing professional video, audio, and data recording systems used as video and data source devices, music recorders, and content editing systems. In business and industry, the use of magnetic tape drives as computer data repositories is also very common. These include the local backup device to the home computer, the server/network backup system, the instrumentation data recorder, and the data archive or warehouse prevalent in many corporate environments.

Table 1 lists the range of the magnetic recording tape equipment industry with a rough classification as to application and utility.

This article will first explain some of the basic principles of magnetic recording on tape, followed by a description of the three fundamental methodologies of helical recording, linear recording, and the older but still used transverse recording.

The formats and tape handling techniques that underlie these three methods will be illustrated by descriptions of various, but not by any means all, of the devices in current use.

BASIC ELEMENTS OF MAGNETIC TAPE DRIVES

Device Fundamentals

Figure 1 shows, at the most conceptual level, the basic elements of a magnetic tape drive. The components that are present in almost all modern drives include the following:

1. *A tape medium*. This varies in width generally from 4 mm to 2 in. and is used in a wide variety of thicknesses. Tape technology is addressed elsewhere in this encyclopedia; extensive technical reviews are available (2).
2. *Magnetic recording and reproducing heads.* The density of the recorded information is largely set by the transfer function of the record/read stylus as well as the properties of the medium. The critical parameters include the frequency response function, the physical wear properties, the record gap dimensions, and the resulting signal-to-noise ratio (*SNR*) achieved by the head–tape interface. Details of recording heads are given elsewhere in this encyclopedia and elsewhere (3).
3. *Ancillary magnetic heads.* These provide additional functions depending on the application, timing control, servo control marks, bulk or local erase functions and so on.
4. *Methods to hold the tape and heads in intimate contact while moving relative to each other.* Contoured tape head assemblies and/or heads incorporated into rotating drums are used. The air foil attributes of the interface is critical (4) as are the resulting wear properties on the drum and tape medium (5). The head drum assemblies can rotate at rates above 5000 rpm.
5. *A control method for the tape tension, as the drive is used in read / write and often fast seek modes.* Tension arms and or pinch rollers or capstans have been used to control tape movement as well as through the use of push–pull motor control.
6. *Drive motors to move the tape over the heads or, on occasion, lift the tape from the heads.* Speeds vary from a few inches per second to several hundred inches per second. Also used to control tape tension.
7. *Guides to control the tape position relative to the heads and spools.* Fixed guides, roller guides, and airflow lubricated guides are used.
8. *Tape spools;* sometimes provided in the cartridge and sometimes split between cartridge and drive. Critical issues involve the ability of the tape-guiding and tension control system to ensure that the tape spools up uniformly and with good parallelism with the spool flanges so that tape damage is avoided.
9. *An automated loading and ejection system that accepts the cartridge and positions it appropriately over the drive spindles.* Associated with this is a mechanism that pulls the tape out and locates it over the drum or threads it ready for alignment.
10. *Sensing systems*—for example, to ensure that the cartridge is inserted correctly, to lock out unallowed write functions, to sense potential tape damage events, to detect potential harmful environments, and to feed back to servo systems as below.
11. *Servo systems*—for example, to drive the magnetic heads to follow the data tracks, to control tape tension, to control tape speed, to control the various timing elements in a drive, and so on.
12. *A preamplifier circuit to improve the signal picked up by the read head.* Critical is the frequency response and gain of the preamp together with its noise characteristics.
13. *A detector to detect the amplified signal.* Traditional peak detect systems have been used; but more recently, methods that permit more sophisticated analysis of the preshaped read pulse are in use. These are, in particular, maximum-likelihood type detectors as described below (6).
14. *A coding method, together with encoding and decoding circuitry.* This translates the detected signal into data bits that are conveniently and efficiently processed by the data channel. Code selection is very important and is discussed below (7).
15. *A read / write channel.* Circuitry that takes the processed signal and applies it to the write head, and/or

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Table 1. Some Magnetic Tape Equipment Formats and Applications

Name	Application	Recording Method	Tape Width	Digital Analog
VHS	Consumer video	H	0.5 in.	A
Beta	Consumer video	H	0.5 in.	A
Digital beta	ProVideo	H	0.5 in.	D
R DAT	ProAudio	H	4 mm	D
8 mm	Consumer and ProVideo	H	8 mm	A
8 mm	Data	H	8 mm	D
D2	ProVideo and data	H	19 mm	D
D3	ProVideo and data	H	0.5 in.	D
DLT	Data	L	0.5 in.	D
3480/90	Data	L	0.5 in.	D
QIC	Data	L	0.25 in.	D
QIC wide	Data	L	0.315 in.	D
4 mm	Data and audio	H	3.8 mm	D
Type C	ProVideo	H	1 in.	A
DCRSi	Data	T	1 in.	D
DST	Data	H	19 mm	D
DCT	ProVideo	H	19 mm	D
BetaSP	ProVideo	H	0.5 in.	D
Quad	ProVideo	T	2 in.	A
U Matic	ProVideo	H	0.75 in.	A
DDS	Data	H	4 mm	D
AIT	Data	H	8 mm	D
LTO/U	Data	L	0.5 in.	D
LTO/A	Data	L	8 mm	D
Travan	Data	L	0.315 in.	D
3590	Data	L	0.5 in.	D

L, Linear; H, helical; T, transverse; D, digital; A, analog.

accepts the read signal from the head in read mode.

16. *A data channel.* This is the circuitry and software that does the coding, processes the coded signal to provide error detection and correction functions, and provides data in a form that can be understood and interpreted by the interface and controller.
17. *Cache memory or buffer.* Embedded memory that can be used for internal drive functions, generally for smoothing data flow, and so on.
18. *Controller.* Usually a microprocessor that provides the logic controls for the above electronic functions. Associated with this is the firmware, or otherwise nonaccessible code that provides the housekeeping functions intrinsic to the drive.
19. *Interface.* The standardized connection to the external world that allows drive integration through universally understood links. Both the read and write data enter and exit through the interface, as do standard control functions.

Several of these basic elements are similar to those used in other data storage or data processing systems. The data channel and error correction systems, for example, for example. Other elements are discussed in other parts of this text. In the following sections the descriptions of existing tape drive technology will illustrate some of these aspects. Other topics are treated separately. General references for tape recorder technology are given in Refs. 8 through 10.

Applications

The applications that tape drives have been put to can also be used as a method to classify them. The following is not intended to be fully comprehensive but does illustrate the major classes.

Analog Audio Recording. This technology uses classical alternating-current (*ac*) bias recording methods (11), but the equipment can vary from the standard "audio cassette deck" with a two-track format and a tape speed of 48 mm/s, to a 32-track 2-in.-wide tape format used by professional audio engineers. In this recording method the tape is moved over the three ring heads—erase, read, and record. The read signal is amplified, integrated, and equalized. The equalization corrects for the falloff in response at the higher frequencies. An ac bias of about 100 kHz is used to linearize the otherwise highly nonlinear recording process.

Digital Audio Recording. Rotating head audio recording systems that are based on conventional digital-bit-based recording (R-DAT) complement the CD (nontape) music distribution technology. Very frequently the master recordings are done on 2 in. ac-bias recorders and then converted to digital data sometimes using multiple channels to achieve the necessary data rate of about 1 Mbit/s. The R-DAT format uses azimuth recording and a track following servo. Digital PCM encoding methods are also in use as well as FM pulse code modulation. Stationary head digital recording (DASH) formats are also used with lower tape speeds but more limited signal-to-noise ratios. A half inch tape drive typically has 24 tracks, uses ferrite heads, and operates at 30 in./s (12).

FM Video Recording. The basic FM recording principle can be simply illustrated by Fig. 2, where the video information is recorded by frequency modulation (8).

The large bandwidth requirement of video information placed significant burdens on the development of video tape recorders that were only solved with the advent of the transverse scanning four-headed "Quadruplex" recorder

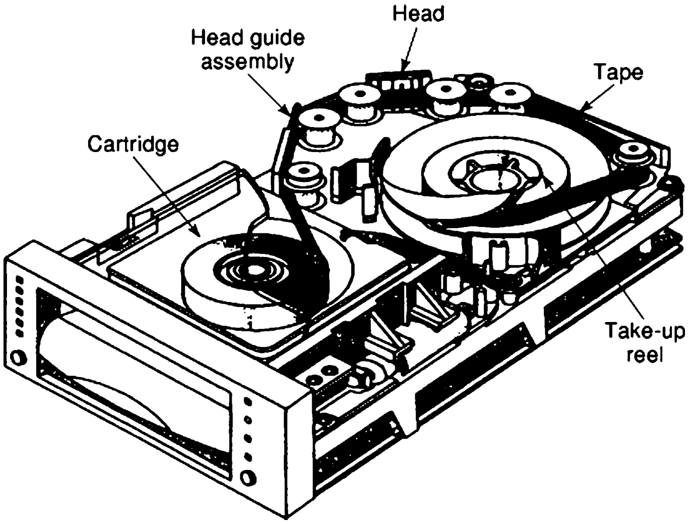


Figure 1. Basic elements of a magnetic tape drive. The example shown is a linear tape drive (DLT) where the drive has the take-up spool and the cartridge has the supply spool.

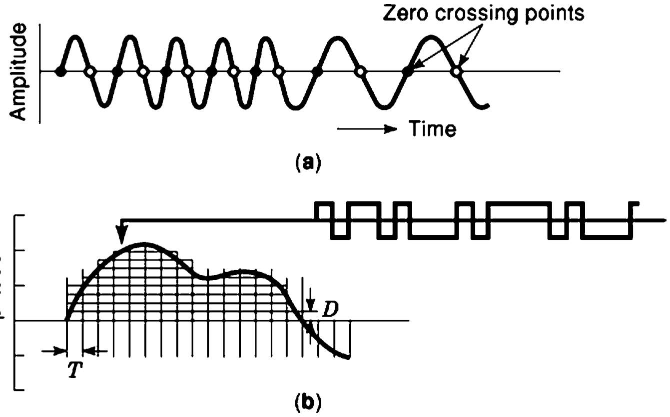


Figure 2. (a) The frequency modulation (*FM*) recording method and (b) the associated pulse code modulation (*PCM*) technique.

developed by Ampex in 1956 (13). This was later replaced by the angled scan (helical) system that used a rotating drum with the long tracks written across 1 in. tape by the use of the acute record angle. In both of these cases the drum speed allows very high effective tape-head speeds, 1600 in./s for example, while the actual tape speed is a stable, controllable, 5 in./s. This, among other factors, opens up the available bandwidth, although other issues such as time base stability are still significant. The SNR of analog video is proportional to the relative head to tape speed and to the square root of the track width. The bandwidth of the record process is between 1 MHz and 15 MHz, with the white carrier level at 10 MHz and the black level at 8 MHz. Cameras for video recording are based on very similar principles and in consumer products generally use the same formats as the playback devices. (VHS, 8 mm, Compact VHS, etc). In the professional camera arena, Super VHS is used and the Beta format is very successful (Beta SP). All these cameras are based on the use of helical scan technology, which is detailed below.

Digital Video Recording (14). The essence of digital video recording is in the coding method. Common is pulse code modulation where the differences in the zero crossing points in the signal shown in Fig. 2 is sampled, quantized into discrete bits made up of integer intervals, and then coded into a binary format. In order to achieve the total information content in a typical TV picture, a bit rate approaching 90 Mbit/s is needed; when ECC bits and so on, are added, the bit rate is closer to 100 Mbit/s. Very-high-density recording is needed for this process. This, while readily achieved in the professional arena (the D2 Digital Video recorder for example), remains a challenge for consumer applications. The recording bandwidth for an 8-bit/sample quantizing system, and a sampling frequency of three times the color subcarrier, is 0.1 MHz to 86 MHz. The incompatibility between composite-signal-based NTSC, PAL, and SECAM broadcast standards is carried forward into the digital video arena, but the development of a component-based coding scheme now allows for compatibility. In this method the luminance signal and the two color difference signals are separately coded. With 8-bit quantization a total data rate of 216 Mbit/s is needed, and this is now available. Digital cameras have also been developed for the professional market with the Beta format predominating.

Digital Data Recording. Digital data are recorded on magnetic media using coded binary formats and mapped onto the medium in a "non-return-to-zero" (*NRZ*) form where the maximum and minimum number of zeros allowed between ones is constrained. These run-length-limited (*RLL*) codes are very similar to the code methods used by communication systems and magnetic and optical discs. These codes allow for effective high-density recording with simple error correction methods applicable. Digital data magnetic storage is characterized by the need for very low error rates after correction, 10^{-17} for example, and the hosts of competing technologies all have this in common. Originally based on an open-reel nine-track form, this application is now largely based on cartridge and cassette tape systems with linear recording, helical scan recording, and even transverse recording devices used. This is discussed below in more detail.

Instrumentation Data Recording. Originally developed from the technology of the audio recorder, this method of capturing long sequences of generally unstructured data, from telemetry or instrumentation data streams, now often uses pulse code modulation (*PCM*) methods. However, a base band linear method with ac bias is also in use utilizing a constant noise power ratio (*NPR*) method. Tape speeds can be very high, and very high densities can be achieved (3000 flux reversals/mm or fr/mm, for example). These recorders also incorporate error correction and detection methods.

More Intelligent Tape Drives. With greater electronic integration and more sophisticated firmware in modern tape drives these devices can now be built with many more intelligent features than existed in the past. Products can be built with new features including in-drive encryption to protect user data and on-board file system capability so the tape system can be used as a Network Attached Storage (NAS) device. The future of tape technology will depend upon greater capacity tapes giving economical storage for less-frequently used data as well as additional built-in intelligence to make the devices able to protect and manage their own content.

FUNDAMENTALS OF MAGNETIC RECORDING ON TAPE

Recording Physics

Figure 3 shows a ring-type magnetic recording head and medium (10). The inductive ring head consists of a core of soft magnetic material (low coercive field, small magnetic remanence) with a coil of wire wrapped around it. For an inductive write and read head the coil of wire conducts a current around the soft magnetic core during write to generate a magnetomotive force in the head core. This magnetomotive force generates a magnetic field in the core which circulates through the core until it reaches a nonmagnetic gap in the core adjacent to the hard magnetic (high coercive field, large magnetic remanence) recording medium. The magnetic field fringes out across the gap with some of the field directed toward the hard magnetic recording medium layer.

When the field from the head penetrates the hard magnetic medium surface, it moves the magnetic particles in the medium through their magnetic hysteresis loop. The final field which the medium particles experience from the head field as the head moves across the medium determines the direction of remanent magnetization in the medium. As the medium (e.g., a magnetic tape) moves under the gap of the head, the direction of current flow through the wire coil wrapped around the magnetic head core changes direction as directed by the changing voltages from the preamplifier electronics driving the head coil. This changing current direction leaves the magnetic recording medium with a known remanent magnetization pattern as shown in Fig. 4. In this way, information is written into the magnetic recording medium which can be accessed during the readback process (10).

As the current in the coil around the write head core changes, the direction of the magnetization changes from one direction to the other. The recording mode we have been describing is called longitudinal recording in which the medium is magnetized in the plane of the medium along the direction of medium motion.

The width of this transition region between the two remanent magnetization region in the magnetic recording region is called the transition width (usually described by a transition width parameter, a). This transition width is determined primarily during the write process and only changes a few percent due to demagnetization reduction effects during the playback process. The primary determinants of the transition width are the magnetic properties of the magnetic recording media (in particular the magnetic coercivity and the slope or magnetic squareness of the magnetic hysteresis curve near the coercive field value) and the sharpness of the field from the magnetic recording head in the medium. The sharpness of the recording head field is a function of the geometry of the head (especially the head gap length, g) and the distance between the recording head and the magnetic recording medium.

Once the information is written in the magnetic recording media, it can be accessed using magnetic playback processes. Various sorts of magnetic playback transducers can be used in a magnetic recording system from an inductive sensor to a magnetoresistive (*MR*) or giant magnetoresistive sensor to a Hall or similar semiconductor magnetic playback sensor. These playback transducers experience loss mechanisms which can lower the signal level recovered from the medium and hence increase the susceptibility to errors in signal recovery due to recording system noise. Figure 4 shows readback signals which would be recovered from the series of written magnetic transitions (10).

An inductive playback head may use the same head core as used for the write process or may use a separate magnetic core with gap lengths for the write and read head optimized for each process. Although this increases the cost and complexity of the head, it can allow higher recording densities and a more robust signal recovery system. Such a multigap record/playback system is common in tape recording systems.

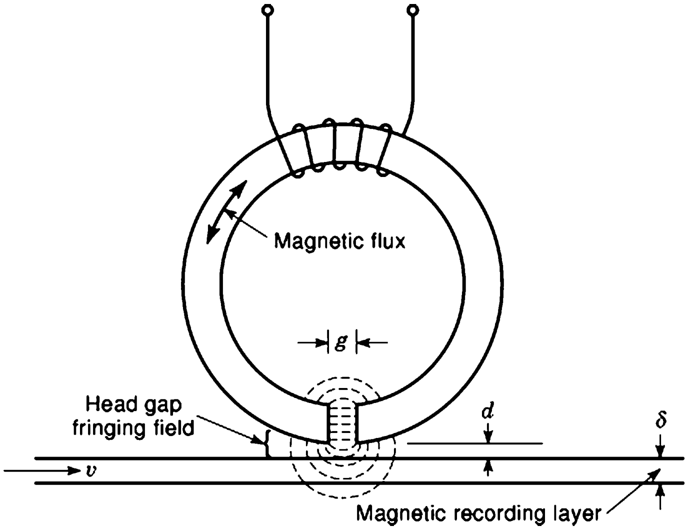


Figure 3. Magnetic recording head and media configuration. *g* is the gap size, *d* is the head-to-medium spacing, d is the recording layer thickness, and *v* is the surface velocity.

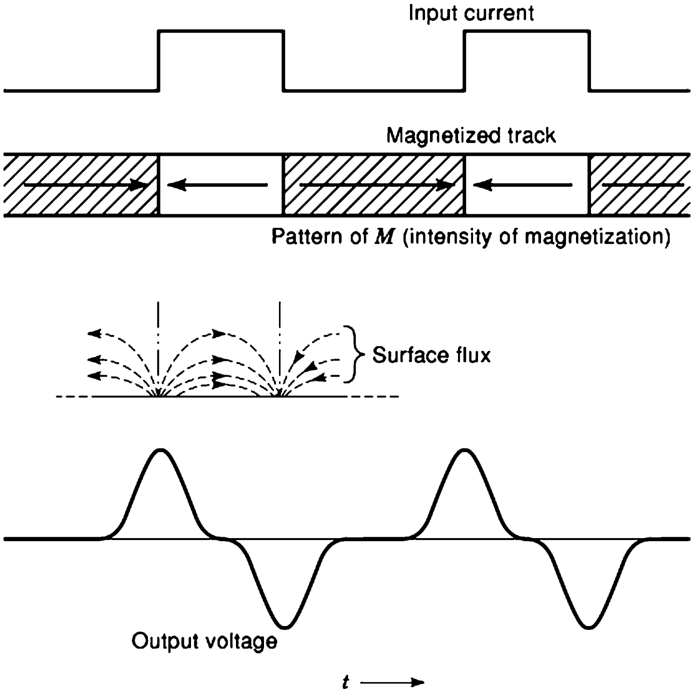


Figure 4. Pattern of magnetization in the medium recorded by the changing direction of input current through the record head. On the readback the surface flux from the medium is picked up by the read head, which generates voltage pulses for amplification.

The heads used in tape recording may have several adjacent magnetic cores, each with its own magnetic write and read transducers. Each of these adjacent cores is referred to as a head track, and the head is called a multitrack head. Such a multitrack head allows several adjacent tracks of information to be written on and read off the recording medium in parallel, thus increasing the speed with which the recorded information is accessed.

If we assume in playback a sinusoidal recording pattern on the magnetic recording medium described by

$$M_x(x) = M_0 \sin(kx)$$

and if the playback transducer is an inductive head whose head field (which is the write head field and the read head sensitivity due to reciprocity theory), we get an inductive playback voltage generated by the flux from the magnetic transition picked up by the head core and passing through the wire coil wrapped around the head core. If we assume that the head fields are described by the Karlqvist field equations (15), this output voltage is described by

$$E(x) = \frac{\mu_0 v w M_0 H_g g k\delta}{\mathrm{NI}} \exp(-kd) \times \left(\frac{1-\exp(-k\delta)}{k\delta}\right)\left[\frac{\sin\left(\frac{kg}{2}\right)}{\frac{kg}{2}}\right]\cos(kx)$$

This equation shows several terms that lower the signal output levels. Figure 5 shows that the most significant of these signal amplitude loss terms is the spacing loss (which is an exponential loss), followed in order of effect on the playback by the medium thickness loss (which may be significant for particulate coated tape media) and the gap loss (10).

Recording System Design

The basic magnetic recording system can be represented by the block diagram shown in Fig. 6.

The writing process is driven by a current driver in the preamplifier circuit. The input signal to the preamp is often preconditioned to account for known nonlinearities in the magnetic recording process. An example of this preconditioning is precompensation in which the time interval between adjacent transitions is modified to correct for expected shifts in the transition location due to fields generated by adjacent transitions. The write process including input signal conditioning is shown in Fig. 7(a) (16).

A special form of preconditioning of the write signal, called write equalization, is required to use MR heads with thick particulate tape media. MR read heads are commonly used in modern digital tape systems. Write equalization reduces the flux-amplitude differences between high and low densities so that the magnetoresistive sensor remains within its linear operating region. It also provides significant high-frequency boost during write (and thus narrower pulses), thus avoiding reduced signal-to-noise that results from read equalization (17).

In the readback process the voltage output from the head is fed into a amplifier which magnifies the signal and system noise up to that point in the circuit (including head, media, and circuit noise). The amplified signal can then be filtered to remove any systematic interference and equalized in a manner to make the signal easier to detect in the channel circuitry. Figure 7(b) shows the typical readback process prior to the channel detection.

Information is recorded onto the tape according to special codes which match the recorded transition characteristics to the data channel used for reading back the recorded information. Table 2 shows some of the modulation codes used in magnetic recording (7).

Encoded information is read out from the head passing over the tape. The signal enters the recording channel where it is detected and corrected (using error correction techniques) if needed. One of the most popular modern types of recording channels is the partial response class 4 (*PR4*) channel and its derivatives EPR4 and E^2PR4. This channel requires shaping the pulses coming out of the playback head so they match a perfectly shaped pulse and can detect recorded information at very high densities if there are no nonlinear interference phenomena such as nonlinear superposition of pulses or nonlinear transition shift. This shaping technique is called read equalization. Figure 8 shows a PR4 channel with a maximum likelihood detector used to reduce the error in the read-back signals (18).

Figure 9 shows the effect of a PR4 equalizer on the frequency response of the channel (8). The equalizer boosts the high-frequency response so as to turn the Lorenzian-shaped isolated pulses from the recorded media into the more complex pulse shapes needed for sampling and decoding by the PRML channel.

Table 3 lists the user information density per recorded transition on the tape for two of the more popular codes used for PRML channels, compared to the older peak detect channels (18).

SPECIFIC EQUIPMENT IMPLEMENTATIONS OF MAGNETIC TAPE RECORDING

The three basic mechanisms for magnetic recording will now be described in some detail; these are transverse, linear, and helical scan recordings.

Transverse Recording

The origin of today's video recording industry lies in the 1956 introduction of the Ampex rotating head device. This technology allowed the use of a head to tape speed of 38 m/s (1500 in./s) while keeping the tape speed down to 38 cm/s and allowed a record time of 1 h. The recording was done by four heads with rotating drum writing transversely on the tape as shown in Fig. 10.

The limitations of this technology include the fact that each transverse track can only record a fraction of the one field, and complex switching is needed to assemble a complete field. Banding is produced by any amplitude or phase differences between the picture segments. Since it is necessary to use a 2 in. tape width, tape cost is very high. These limitations led to the helical scan technology detailed below. The standardized head and track format is shown in Fig. 11 (19).

This transverse method of recording has survived in a 1-in. form factor in the extremely high-performance digital data recorder called the DCRSi (Ampex Corporation). This data recorder used mostly for surveillance and related image capture applications has perhaps the highest data rate of any equivalent tape recorder (240 Mb/s). Of interest here is also the fact that the detector used maximum likelihood methods (Viterbi technology) (20) well before any other recording system.

Linear Recording

As shown in Fig. 12, the principle is the recording of a linear track of data produced when a tape is moved linearly over a stationary head. The recording can be simple parallel or serpentine; the latter allows bidirectional performance.

Nine-track open-reel methods originated this technique but have been supplanted by cartridge formats such as the 0.5 in. IBM 3480/3490 devices illustrated in Fig. 13.

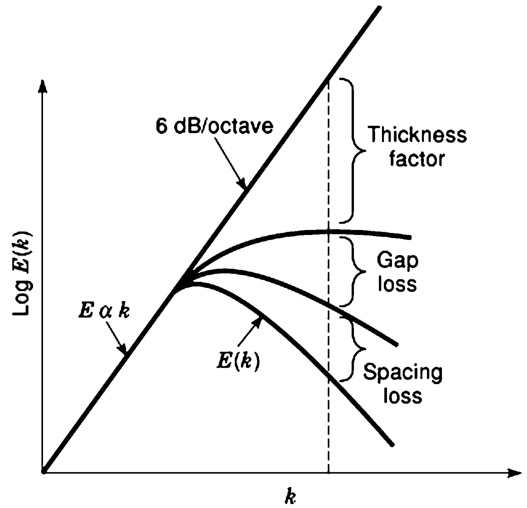


Figure 5. Significance of various reproduce loss terms as a function of wavenumber, *k*.

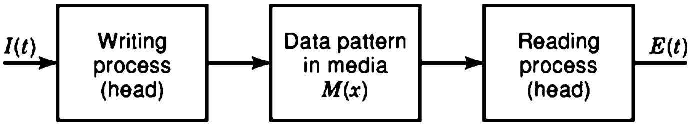


Figure 6. Block diagram of a basic magnetic recording system.

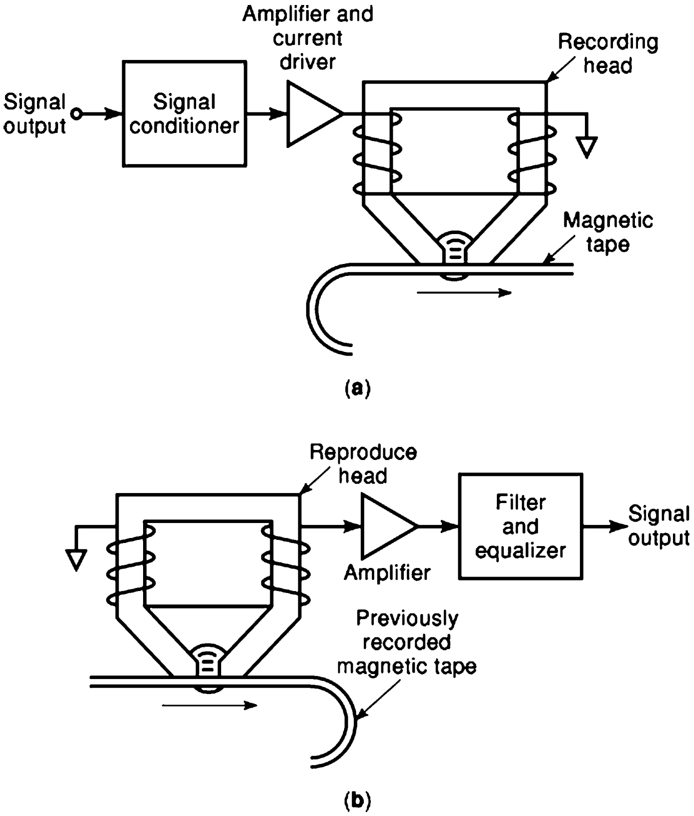


Figure 7. (a) Tape recording write process including signal conditioning and the current driver. (b) Tape recording read processes including amplifier and signal conditioning prior to the playback channel.

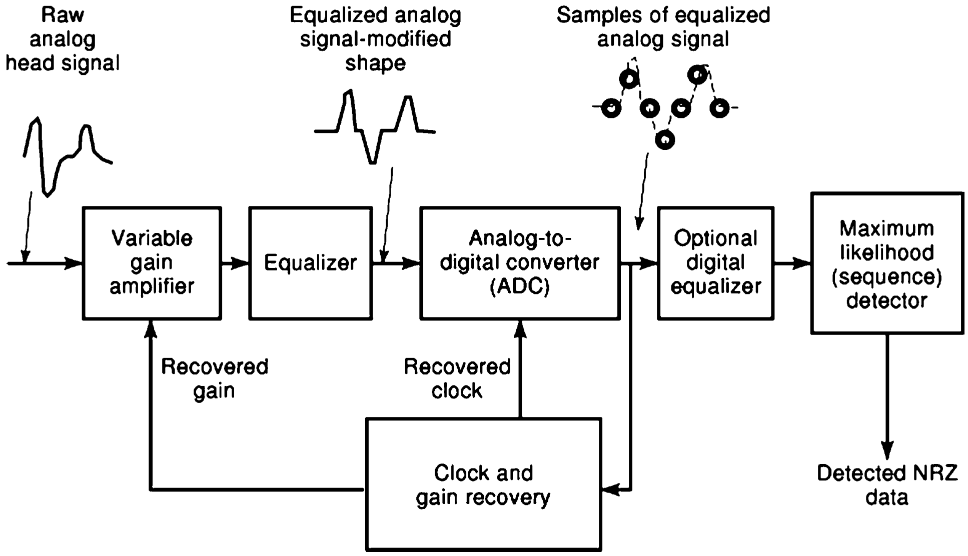


Figure 8. PR4 channel with maximum likelihood detector for error correction.

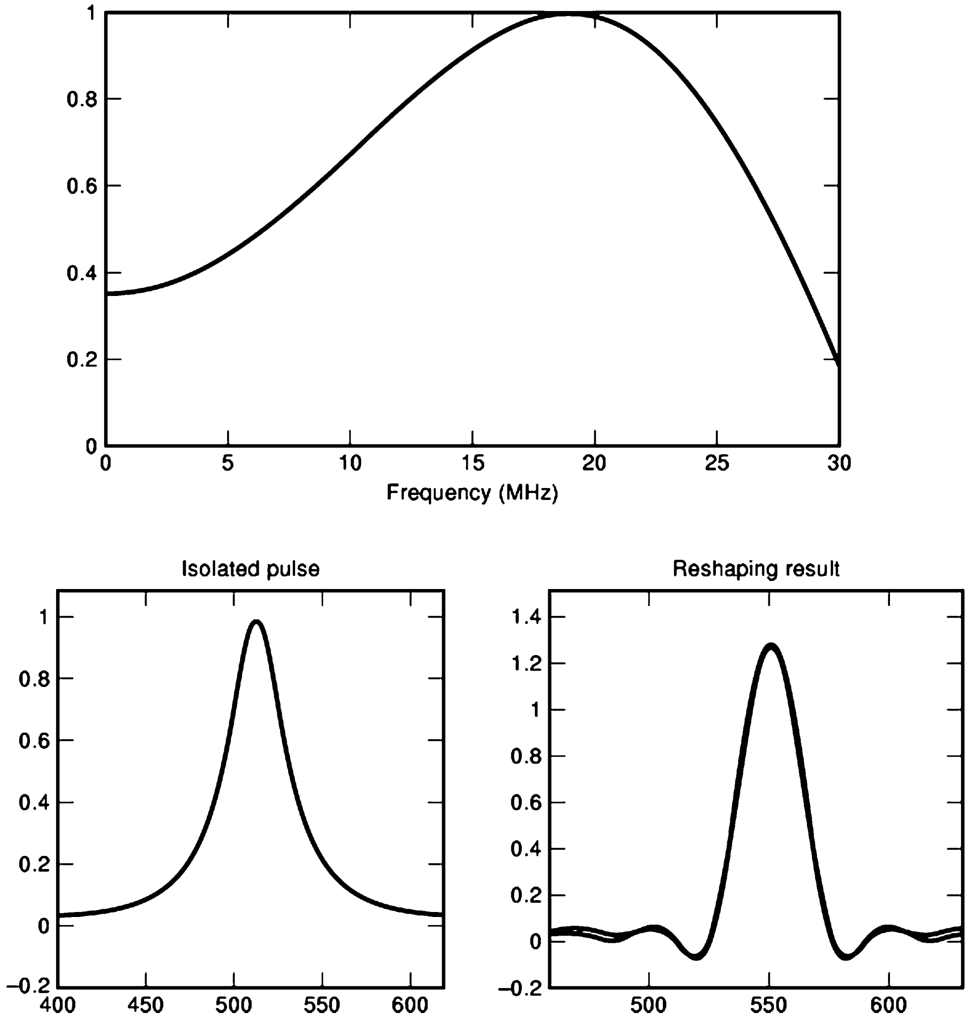


Figure 9. The equalizer circuit changes the frequency characteristics to shape isolated pulses into the complex shape required for accurate detection by the detector.

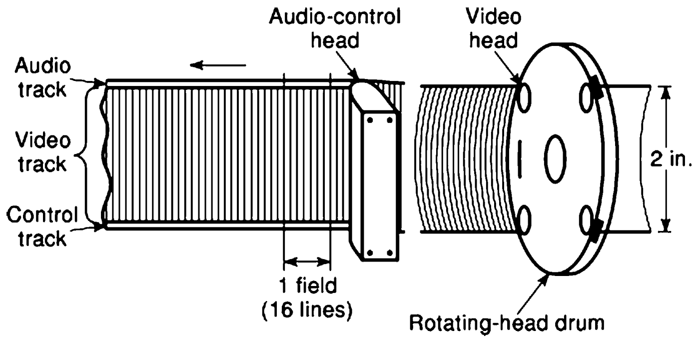


Figure 10. The transverse recording method. A rapidly rotating drum scans the tape surface vertically while the tape moves longitudinally at a much slower speed. The heads are embedded in the drum.

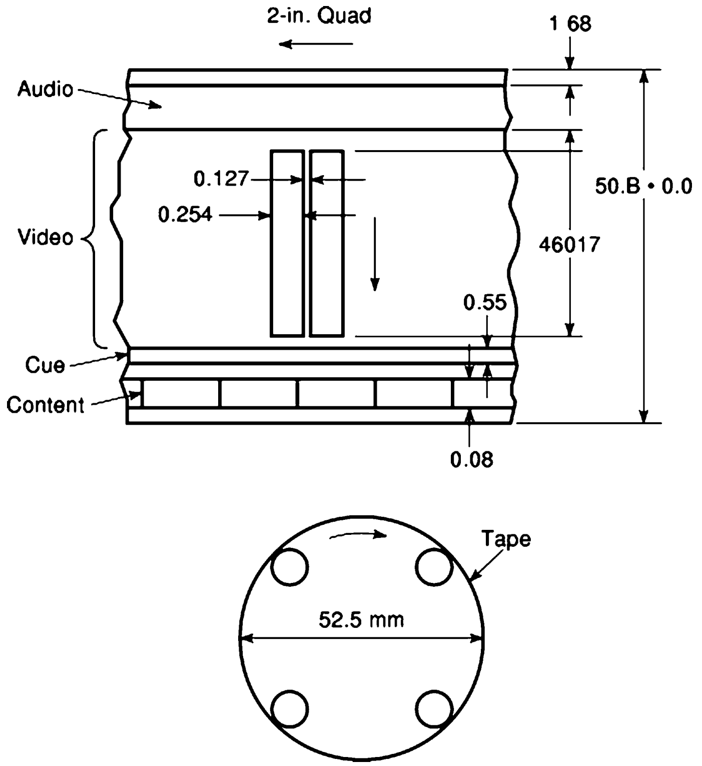


Figure 11. The 2 in. quad standard format. The universally accepted definitions of recorded data on tape for this format. The standard allows for interchange between differing versions of equipment that meet the standard.

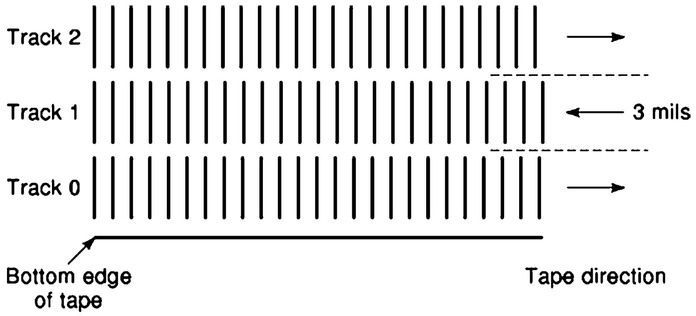
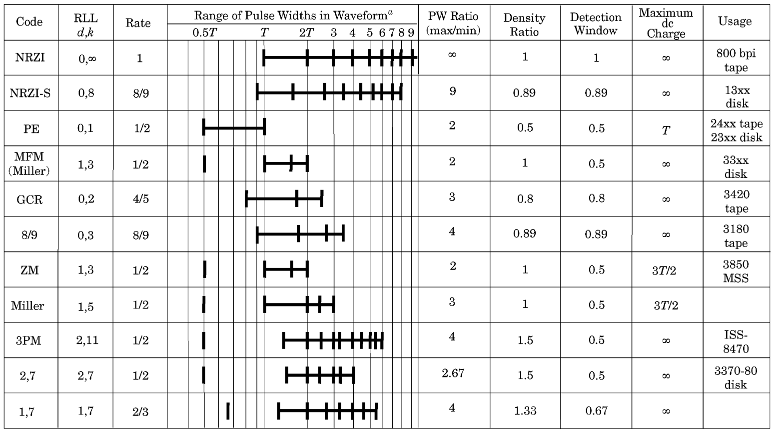


Figure 12. Linear tape recording formats. The information is written in a parallel data stream longitudinally along the entire tape length. It can also be interleaved in an alternating bidirectional form called serpentine.

Table 2. Modulation Codes Used in Magnetic Recording



Code	RLL d,k	Rate	Range of Pulse Widths in Waveform[a]	PW Ratio (max/min)	Density Ratio	Detection Window	Maximum dc Charge	Usage
			0.5T T 2T 3 4 5 6 7 8 9					
NRZI	0,∞	1		∞	1	1	∞	800 bpi tape
NRZI-S	0,8	8/9		9	0.89	0.89	∞	13xx disk
PE	0,1	1/2		2	0.5	0.5	T	24xx tape 23xx disk
MFM (Miller)	1,3	1/2		2	1	0.5	∞	33xx disk
GCR	0,2	4/5		3	0.8	0.8	∞	3420 tape
8/9	0,3	8/9		4	0.89	0.89	∞	3180 tape
ZM	1,3	1/2		2	1	0.5	$3T/2$	3850 MSS
Miller	1,5	1/2		3	1	0.5	$3T/2$	
3PM	2,11	1/2		4	1.5	0.5	∞	ISS-8470
2,7	2,7	1/2		2.67	1.5	0.5	∞	3370-80 disk
1,7	1,7	2/3		4	1.33	0.67	∞	

[a] The left-hand vertical bar denotes the pulse width of the clock.

Table 3. User Densities for Various PRML Codes

Method	User Density (1, 7) Rate 2/3 Code	User Density (0, 4/4) Rate 8/9 Code
Peak detection (70% resolution)	1.33	0.88
Peak detection (80% resolution)	1	0.66
PR4	1.1	1.46
EPR4	1.33	1.77
E^2PR4	1.54	2.05

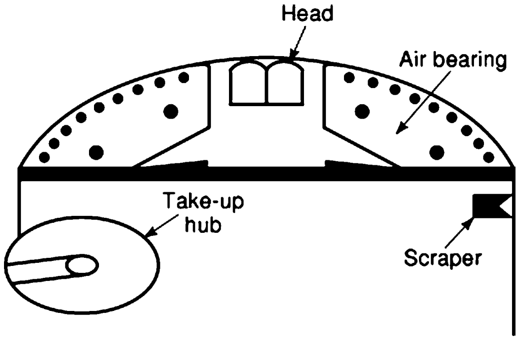


Figure 13. Typical tape head and handling configuration for the linear IBM 3480/3490 equipment family.

Typically the tapes are chrome oxide, and there can be 36 tracks with tape speeds up to 80 in./s and data rates of 3.0 MB/s. More recently the 3590 technology has been introduced that uses metal particle tape and multitrack magnetoresistive heads. Native (uncompressed) sustained data rates of 6.6 MB/s and 144 tracks are achieved. The increased data rate is accomplished through the use of a track following servo which takes 8 steps over the 144 tracks (128 data tracks and 16 servo tracks). The head itself has 16 data tracks and 2 servo gaps.

An alternate solution is based on the DLT (or the competing LTO) format; the cartridges have a supply reel but no take-up reel, which is permanently mounted in the drive. Figure 1 is an illustrative outline of a basic DLT drive. Up to 128 tracks are written in multiple linear passes down the entire length (1800 ft) of the tape. The inability to provide track to track cross-talk rejection, as will be discussed below, meant that a guard band had to be provided, as shown, this limits capacity. Hence symmetric phase recording (Fig. 14) was developed that allows 208 tracks on the 0.5 in. tape. A switchable head that pivots in the drive achieves the azimuth-type recording. The ability to electronically reject data derived from the opposing azimuth angle allows close packing on the tracks and eliminates the need for the guard band.

The head stack switches to vertical when reading older formats ensuring backward compatibility. The four read/write channels are set up with a parallel channel architecture. This allows the drive to perform a read after write command and automatically re-record data on a parallel channel if it finds an error.

The heads in this drive format have been typically metal in gap (*MIG*) heads as discussed elsewhere. More recent versions utilize magnetoresistive (MR) heads. Additionally, to wipe accumulated debris off the surface of the tape, raised edges are fabricated on the edge of the head stack

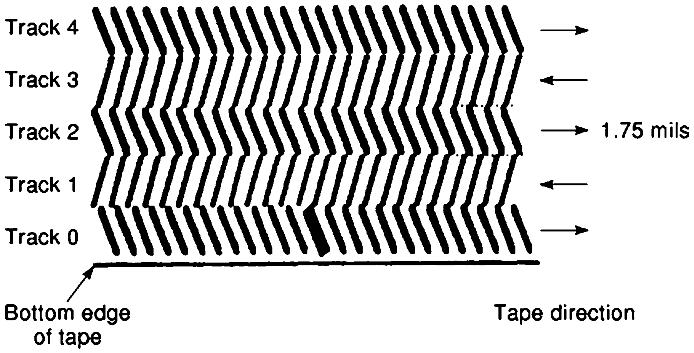


Figure 14. Symmetric phase recording—azimuth-syle linear recording. The opposing angle of the adjacent information simplifies the rejection of cross-talk between tracks.

to act as scourers and to remove loose material. The head has to be contoured to the tape, this is to achieve intimate contact and is often achieved through a wearing process with special abrasive tapes.

Tape handling in these linear formats is critical. Since the take-up reel is internal and fixed, it is possible to use very low tape tension and achieve low head and tape wear. The head guide assembly is shown in Fig. 15. The drive head is the only contact point for the magnetic tape surface; and the six guides, or rollers, only touch the back surface. The drive motor is tachometer-controlled with one motor pulling the tape, while the other applies an opposing force to maintain optimal tension. To minimize stops and starts these drives, and others, use a form of memory cache buffering. Adaptive methods allow the system to adjust block sizes to match the host data rate. Data are compacted as they enter the cache buffer at a rate that matches the rate at which it is written to the tape. This helps keep the drive streaming as much as possible and reduces delays due to repositioning.

A further linear format of interest is the quarter-inch cartridge (*QIC*) form factor. In this device the cartridge itself performs several of the functions that otherwise are performed by the drive—for example, tape guidance and tension control. Bit densities of 106 kbpi and flux densities of 80 kfrpi are achieved. The coding is 1,7 RLL, and the track pitch up to 65 mm. In more recent versions, metal particle (*MP*) tapes are used with coercivities of 1659 Oe.

Helical Scan Recording

To achieve the recording of one video field continuously on tape, it is clearly desirable to lengthen the track: This is difficult in transverse formats; but if the tape can be recorded diagonally, it can be done. To do this the tape is physically wrapped around a very rapidly rotating drum in a helical-shaped tape path (21). This is shown in Fig. 16.

When this is combined with the concept of azimuth recording (22), this has proved the most effective way of achieving high-density recording of both digital and analog information.

Figure 17 shows the NTSC standard for head and track formats for VHS tape recorders, the most common consumer video tape recorder. Other helical scan standards include: type C—1 in.; U matic—0.75 in.; 8 mm, video and DDS; 4 mm; 19 mm (D2, DST, DCT), beta—0.5 in. and many other lesser used formats.

A critical design element in helical scan design is the ensuring of alignment of the horizontal sync pulse. This ensures machine-to-machine compatibility and stability.

To ensure this, it is necessary to link the tape speed V_m, the drum diameter d, and the helix angle θ_0.

The tape speed is then given by

$$V_m = \frac{\pi d \alpha F}{2(n_h \pm \alpha)\cos\theta_0}$$

where F is the field frequency, n_h is the number of horizontal sync pulses on one video track (262.5—NTSC), and α is the number of horizontal sync pulses between the adjacent track edges.

The actual recorded track angle is then given as the resultant of both head and tape movements:

$$\sin\theta = \frac{\sin\theta_0}{[1 \pm 2(2V_m/\pi F d)\cos\theta_0 + (2V_m/\pi F d)^2]^{1/2}}$$

The azimuth angle ϕ must be minimized in helical scan recording or the effective head gap length increases (by $1/\cos\phi$). Today the VHS standard azimuth angle is 6°. The ratio of the cross-talk, C, and the signal, S, can be calculated for azimuth recording from the following equation for azimuthal loss.

$$L_{az} = 20\log_{10}\left(\frac{\pi w/\lambda \tan(2\phi)}{\sin[(\pi w/\lambda)\tan(2\phi)]}\right)$$

where λ is the recorded wavelength, w is the video track width, and 2ϕ is the angular difference in the head gaps.

If the video track and the play back head are misaligned by Δw, then the *C*/*S* ratio is given by

$$C/S = 20\log_{10}\left(\frac{\sin[(2\pi\Delta w/\lambda)\tan(2\phi)]\Delta w}{(2\pi\Delta w/\lambda)\tan(2\phi)(w-\Delta w)}\right) \text{ dB}$$

A critical factor in helical scan recording is the maintaining of the proper spacing between the heads, drum, and tape. The heads are furthermore protruding from the plane of the drum as it rotates. While is necessary to maintain good head to tape contact, the drum to tape contact can be wearing to both components. Furthermore, variation in output signal can occur as the spacing varies. This problem has been studied using Reynolds equations and finite element

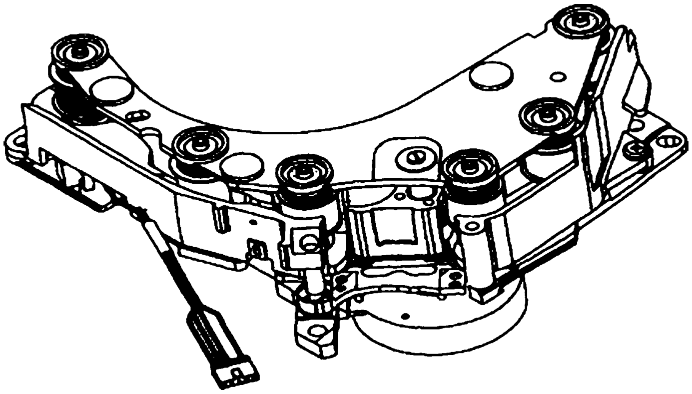


Figure 15. Linear (DLT) head guide and tape handling assembly. Note the six guiding rollers that control tape position.

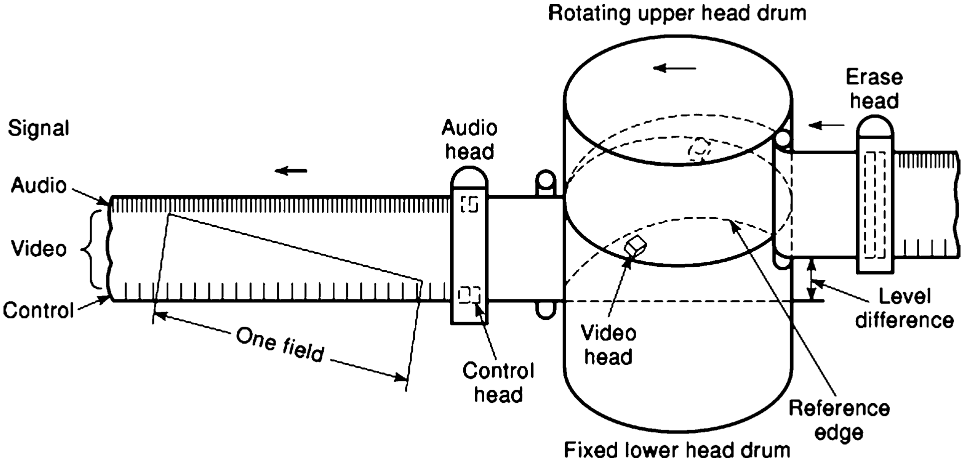


Figure 16. Basics of helical scan recording. The tape is wrapped around a rotating drum so that angled recoding can be achieved with consequent long tracks.

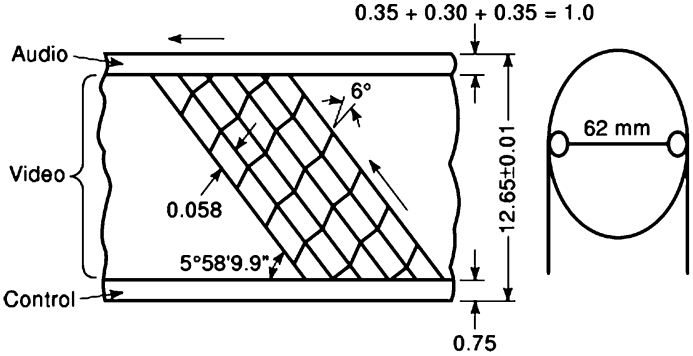


Figure 17. NTSC standard head and track format for helical scan as used in VHS recording for consumer applications.

analysis (5). When the tape is running over the drum, the displacement is determined by the shape of the head, the relative velocities, and the tape tension.

Numerous tape path configurations are used in helical scan. As an illustration Fig. 18 shows the tape path over the scanner and head in an 8 mm format. Note the use of a servo head in this format.

The use of complex servo systems has been an enabling technology for magnetic tape recording. Numerous schemes exist including pilot tones where the use of frequency components read by the head are used to control its position. Also used are embedded servos where there is information literally embedded among with all the other data; these are used in helical audio formats. In the 8 mm technology where all the information on the tape is high frequency, the servoing is often accomplished by a piezoelectric bimorph that is driven by an error signal. Similar technology is used in 19 mm helical scan where the au-

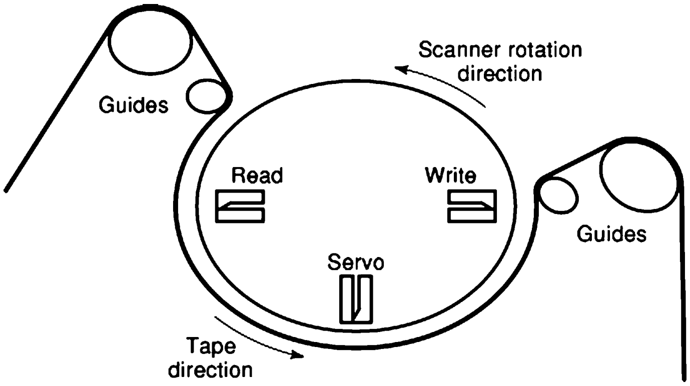


Figure 18. The 8 mm helical scan tape path. This well-established consumer and professional format uses the helical heads and a servo system to control head position.

tomatic scanning and tracking (*AST*) system uses heads driven by voice coil actuators (23).

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THOMAS M. COUGHLIN
DAVID H. DAVIES
Coughlin Associates,
Atascadero, CA
DataPlay, Inc., Boulder, CO