HIGH DENSITY DIGITAL RECORDING WITH VIDEO TECHNIQUES[*]

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Summary A digital recorder which writes or reads digital data at 8 megabits per second and has a storage capacity of 84 billion bits per reel of tape is described. The packing density is in excess of I million bits per square inch on conventional one-inch magnetic tape. The high packing density and transfer rate was achieved through the combination of phase-encoded digital electronics with a helical scan video transport. The use of the helical scan technique permitted extremely efficient utilization of the tape and permitted inclusion of other features, such as high-speed search (400 ips), individually addressable records, and self-threading and cartridge-loading capability.

Introduction The development of a sophisticated document storage and retrieval system necessitated the use of a mass digital memory capable of storing large amounts of digital data with an extremely fast transfer rate in both read and write modes.

Current recorder technology in the computer industry is 1600 bits per inch on 9 tracks of one-half inch tape, yielding a packing density of approximately 28,000 bits per square inch of tape with a transfer rate of approximately 1,400,000 bits per second. The systems requirement for the document storage and retrieval system was a magnetic tape unit with a packing density of at least 1 million bits per square inch of tape and with a transfer rate of 8 megabits per second in both read and write modes.

Special-purpose longitudinal transports have increased packing densities up to 500,000 bits per square inch utilizing 20,000 bits per linear inch per track and with up to 28 tracks on one-inch tape. However, it was not felt that extending the longitudinal approach to accommodate the packing density, the required record time, or to achieve the on-line reliability, was feasible in the longitudinal technique. The helical scan video recorder had, over the years, proven reliable in the handling of wideband analog data and in achieving long record times on single reels of tape. A helical recorder can provide a three-hour record time for a recorded bandwidth of up to 5 megacycles. Therefore, a

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[*] This development program was performed under contract to Trans-A-File Systems Company, Cupertino, California

development program was launched to utilize the wideband capability of the video recorder with high-density digital electronics.

This paper describes the development of a helical scan digital recorder and covers the technical details of the transport design, signal electronics, control logic, and other pertinent features.

System Considerations The helical scan recorder was selected over the longitudinal technique because of the following considerations:

Simplicity--The helical scanner has a relative head-to-tape speed of 723 ips. Therefore, an 8 megabit data stream can be handled on one data channel without the necessity of splitting up the data into parallel tracks to accommodate a slower relative head-to-tape speed. Using only one data channel, the requirement for multiple channels of read and write electronics, along with the associated input and output buffering system and other support electronics, could be eliminated. A major advantage accruing to the helical technique is the simplicity of the data read/write head. In order to even approach the writing capability of the helical digital recorder, a longitudinal recorder would have to employ a 28-track, narrow-gap head stack, which is expensive, prone to be troublesome in an on-line operation because of tape contaminations and head wear patterns (causing one or more tracks to lose intimate head-to-tape contact), and the expense and complexity of replacement. The helical scan technique employs one ferrite head which historically has lasted well in excess of 2,000 operational hours and can be replaced in the field in less than one minute at a cost of approximately $300.

Efficiency--The greatest advantage enjoyed by the helical scan approach, when compared to other drive techniques, is its efficiency of tape utilization. The IVC video recording format employs a 6-mil head recording scan tracks on 9.5 mil centers. Since the helical head goes completely across the tape, the helical scan recorder can achieve in excess of I million bits per square inch of tape while not exceeding a recording density of 11,000 bits per linear inch on the individual scan tracks. This density, combined with the superior helical 7 scan head-to-tape contact, allows an error rate of less than 1 in 10^7 to be directly achieved without recording redundancy or error correction codes.

Capability--A prime goal was the ability to search large volumes of data at high rates. The helical scan technique allows a recording of an 8 megabit data stream at a lineal tape speed of 6.91 ips (the relative head-to-tape speed is 723 ips). In the search mode, however, the longitudinal tape speed is increased up to 400 ips, and individual data records can be addressed and located at very high speeds. The rate of the data search at 400 ips exceeds 400 million bits per second.

Another unique capability is to address, locate, and rewrite individual scan lines without disturbing the data on either side of the rewritten scan line.

Mechanical Design In terms of tape speed, rotational velocity of the scanner, tape geometry, and reel size, the digital helical scan recorder is identical to the standard video model; however, the handling of digital data and the implementation of cartridge self-threading capability imposes additional requirements which necessitated major changes in the control logic, tape reeling servoes, and tape path.

Tape Handling The transport is designed to accept a tape cartridge which comprises a standard one-inch wide, 12-1/2" reel, a stiff leader, and a plastic outer housing to protect the tape against contaminants, critical in the protection of the high-density digital recorded data.

The tape path is shown schematically in Figure I. Following the tape path, as the tape moves in the forward direction, the tape is spooled from the fixed reel into the tension sensing assembly. The tension sensing assembly consists of two fixed-position rotating guides, and a third rotating guide mounted on the end of a short low-inertia arm. Tape tension is set by a very low rate spring (essentially a constant-force spring), which maintains a constant tape tension on the fixed reel side of the machine. The position of this arm is sensed optically by a lamp and photo transistors. Its position is controlled by the fixed reel motor.

The tape then passes through a tape sensing block. This block senses a reflective strip on the polyester side of the tape indicating the “beginning” of the tape. This prevents the tape from unthreading from the fixed reel. This block also includes a broken tape sensor and tells the tape self-threading logic that the tape has passed through the scanner and capstan pinch roller assembly.

After passing over the fixed heads, the tape enters the scanner assembly, which contains the rotating heads that read and write scan track data. The tape then goes around the scanner in a spiral helical wrap, forming the Greek letter “ $\propto$”.

The tape, moving in the forward direction, next passes another sensing block, which senses the “end-of-tape” marker and broken tape.

The tape passes through another tension sensing assembly before entering the cartridge. The tension sensing assembly on the tape cartridge side of the machine is almost identical to the assembly on the fixed reel side of the machine. The only difference is that in the forward read mode or write mode, it maintains the tape at a higher tape tension than the fixed reel tension assembly to overcome friction losses by the tape in the scanner assembly.

In the Forward Search mode, the tension sensing arm on the tape cartridge side of the machine is locked in a fixed position, and the tape cartridge reel motor is used to control the tape speed.

In the Reverse Search mode, the functions of the tape, cartridge and the fixed reel are interchanged. The fixed reel motor determines the tape velocity, and the tape cartridge furnishes hold-back tension.

The discrete command functions available on the recorder are as follows:

Logic Commands Load (thread tape) A tape cartridge is installed on the machine. When the Load command is given, the tape is automatically threaded through the tape path. After completing the load operation, the recorder is ready to accept the next tape motion command, which will normally be a Reverse Search command to rewind the tape to the beginning.

Reverse Search and Forward Search In these modes, the tape moves at high speed in either the forward or reverse direction, with a maximum search speed of 400 ips. In a typical system, address information is recorded on the longitudinal tracks for identifying the location of the high-density digital data. The addresses containing identification data are numerically ordered. During a typical search sequence, the tape controller keeps count of the difference between the ordered address corresponding to the tape position and the ordered address corresponding to the location of the requested data on the tape. Using this information, the controller commands the tape to run at the maximum search speed of 400 ips until the difference between present and requested address changes below a preselected minimum, at which point the tape is caused to decelerate on a controlled profile so as to arrive at the requested address in minimum time. The acceleration and deceleration that the tape experiences are constant and are determined by internal control circuitry. To insure long tape lif, the acceleration is set in the range of 200/in sec^2 (0.52g) to 240/in sec^2 (0.62g). The time required to accelerate the tape from a stopped condition to the maximum search speed of 400 ips is 1.7 seconds for a preset acceleration of 240/in sec^2. The time required to decelerate along a controlled trajectory is approximately 2.7 sec. The controlled profile deceleration time is longer because of the necessity to control the tape speed at each intermediate Search speed to be sure of cueing the tape to the proper data location.

Read or Write All reading and writing of data is done at 6.91 ips longitudinal tape speed. The input and the output data rate is 8 megabits per second.

Electrical Design A discussion of the recorded tape format will be helpful in understanding the recording of the digital data and the address and control tracks.

The helical scan recorder offers the advantage of being able to space share the same portion of magnetic tape between the address and the data tracks without crosstalk or interference if the wavelengths involved on the address tracks are different by an order of magnitude from those on the data track, and if the data track's longest wavelength to be recorded does not fully penetrate the oxide coating. In the helical scan digital recorder, the address track information is recorded longitudinally at a digital density of 600 bits per inch, which produces a shortest fundamental wavelength on tape of 3.3 mils. The scan track data information is recorded at 11,000 bits per inch, which produces a maximum wavelength on tape of 364 microinches.

Using the spacing and thickness loss formula developed by R. L. Wallace, Jr., of the Bell Systems[**], the scan track data information will penetrate the tape oxide to a maximum effective depth of approximately 56 microinches, giving a 3-1/2 db loss of address track information through erasure, and a loss of an additional 1 db due to effective spacing of the address track information from the address read head. In practice, a 6 db loss in address track output is experienced, the additional 1-1/2 db being due to complete erasure of the surface high-frequency transition information in the 600-bit per inch address data.

Tape Geometry The tape geometry of the overwriting process of the address and data tracks is shown in Figure II. The helical scan digital recorder has five longitudinal tracks which are recorded on tape prior to the scan data track information. Each of these tracks is 44 mils wide and spaced on 140 mil centers. The number of longitudinal tracks could be increased to 14 if the need should arise for additional low-density digital information without sacrificing the present address system error rate performance of 1 error in 10^9 bits.

The track nearest the edge of the tape is the status or update track, providing the capability to be rewritten at any time to allow the address information to be current after editing any of the scan data tracks. Data on all address tracks are in NRZI format.

The second track is the clock track, which is common NRZI clock for both the permanent address and the status address information. The third track is the permanent address track, which identifies individual data tracks or block of data tracks, depending upon the system usage.

The fourth track is a control track which contains pulses written at a 60 Hz rate to allow synchronization and registration of the scan head with the scan data tracks during the read process. The fifth track is a spare track in the present application.

[**] Reproduction of Magnetically Recorded Signals, by R. L. Wallace, Jr.; The Bell System Technical Journal, Vol. 30, No. 4, p. 1145, October 1951, Part II

The helical wrap of the tape around the head scanner assembly causes the data tracks to be written on tape at a 4.75° angle, as noted in Figure II. Each data track is 6 mils wide. They are separated by a 3 -1/2 mil guardband and are spaced on 9.5 mil centers.

High Density Digital Data on Scan Tracks Figure ITT is a timing diagram of the scan digital data tracks to allow writing and reading high density digital information on the helical scan recorder. The helical scan rotary head is synchronized to a 60 Hz source. This synchronization process causes the rotary head to make exactly one pass across the tape diagonally per 60 Hz cycle and thereby maintains the relationship of the rotary head with reference to the edge of the tape itself. All signals must be synchronized with the same 60 Hz source to properly write digital data on a scan track. A Prepare To Write Video Data signal must become true 6 to 10 milliseconds prior to the 60 Hz sync point at which writing will commence in order for the Read/Write head to be switched to the write electronics before writing current commences. This timing allows the scan erase head to fully erase the track to be recorded, as the scan erase head precedes the Read/Write by 120°, or one-third of a scan line. It will be noted in the timing diagram that the scan erase signal becomes true approximately 2.9 milliseconds after the fall of the 60 Hz square wave, which indicates the middle of a scan period and will go low, terminating erase during the final third of the scan time for which the Prepare To Write Video signal goes false at the midpoint. This prevents the scan erase head from erasing into the next scan track, which may be occupied by an earlier recording.

The 8. 1 MHz data clock signal must commence as soon as the 60 Hz sync time for the scan track to be written and must continue as long as high-density digital information is to be written. Refer to the timing diagram, line labeled “Write Mode Data Track”. The encoded digital data commences 411 microseconds after the 60 Hz sync point with a preamble portion, followed by a block of digital encoded data, in turn followed by a postamble prior to the subsequent 60 Hz sync which will repeat the sequence if Prepare To Write Video is still true.

Near the end of the preamble portion, the Send Video Data line from the recorder will fall, indicating to the data source that the digital data should be sent to correspond with the data clock being continuously transmitted. The Send Video Data pulse is generated from the shift register which produces the unique end-of-preamble code. By selecting different tap locations on this shift register, it is possible to vary the timing of the Send Video Data pulse in half-bit increments of the 8.1 MHz clock period. In this way, variations in cable delay from system to system may be eliminated from affecting system operation and from causing loss of synchronization of the internally generated preamble and the external data stream.

The timing relationships discussed give rise to a pattern on tape such as shown in Figure II for a typical scan track. It will be noted that the 1.011 millisecond preamble begins while the scan head is passing over the status or update address track area of the tape. This portion at the beginning of the scan track will be completely erased if the status track is updated; therefore, there must be sufficient preamble remaining on tape after the status track area to enable synchronization of the playback decode with the tape data prior to encountering data. This is accomplished by the second half of the preamble, which always lies on the tape at a distance sufficient from the status track to not be erased during status track update.

A postamble is written during the final 495 microsecond period, where the reproduced data level will decrease as the track nears the very edge of the tape and playback performance is degraded

The preamble and the Postamble, therefore, buffer the data portion from the edges of the tape, where marginal reproduce performance is encountered, causing only the strongest data signal portion to be used for data recording.

Digital Data Encode Process The digital level information and 8.1 MHz clock are combined into a phase-encoded signal utilizing a phase-encoded technique in which a transition occurs in the middle of each bit cell containing a ONE and between adjacent bit cells containing ZEROS.

Digital Data Decoder The digital decode scheme to convert the phase-encoded information back into digital level and clock information in its original form consists of an internal clock which is phase-locked to the read head output and allows the digital data to be read directly from the tape output. The voltage slope of the waveform in the first half of a digital time period is compared with the waveform slope in the second half of the time period. If the slopes are different, the output is interpreted as a “1”, or if they are the same, as a “0”. Playback peaks are detected and provided to synchronize an internal VCO clock. This internal VCO clock is then directed to the slope comparison circuit. The decoder achieves proper clock phase synchronization with the preamble on tape at the beginning of each data scan track.

Address Track Timing The longitudinal tracks are activated 4-1/2 milliseconds before the 60 cycle sync pulse, which begins a data block of scan lines. The longitudinal write amplifiers are turned off one millisecond prior to the 60 Hz sync pulse which terminates the last scan line of the final block to be written. In addition, even parity is maintained on both the clock and the permanent and status address tracks, and write amplifiers are always initialized to saturate the tape in the same manner at the beginning of each write command. No errors are generated as a result of adding blocks of data to an existing partially written tape. This timing overlap relationship is satisfactory for the present system, which utilizes blocks of 13 scan lines for an addressable data file. Should it be desirable to address individual scan lines, the overlap time period would necessarily be reduced to minimize the loss of the 69 bits geometrically available per scan track.

Address Track Encoding and Decoding The input data for the permanent address and status address tracks is in the form of standard digital level and clock. These data are converted to NRZI for recording on the permanent address and status address tracks. The clock information, which is common for both tracks, is recorded on the clock track wherein a flux transition occurs for each digital bit recorded on the permanent address of status address tracks.

A unique feature of the decoding process is the circuitry which determines the presence of peaks in the read head output which has a variable reference level related to tape speed to allow a constant percentage clipping level of the peaks during search velocity ramps. Address information may, therefore, be read error-free any time the tape is in motion at a speed above 3 inches per second, during acceleration, search at any speed, and during deceleration. This ability to read address information accurately during all search conditions allows one to target very accurately to a particular record if the address information contains ordering numeral data for each data block on tape.

Conclusion Utilization of helical scan technology, in combination with new digital electronics, has dramatically advanced the state-ofthe-art for digital magnetic tape recorders in terms of digital data rates and packing density. 84 billion digital bits of data per reel of tape allows an extremely large amount of data storage on-line. The transfer rate of 8 million bits per second can drastically cut the utilization time of the computer and will permit a much faster processing of data. Self threading and cartridge loading minimizes human error and will give longer tape life with fewer record errors. In some situations, the new capability will mean that a change can be made from analog data collection to digital techniques. Larger on-line libraries will now be possible. Very high data rate transfer between two communication points is now feasible. Certainly the Systems Engineer can now expand his thinking in terms of the manipulation of data and its management. The helical scan digital recorder will permit magnetic tape to maintain its competitive edge over other digital storage media in terms of flexibility, simplicity, and cost.

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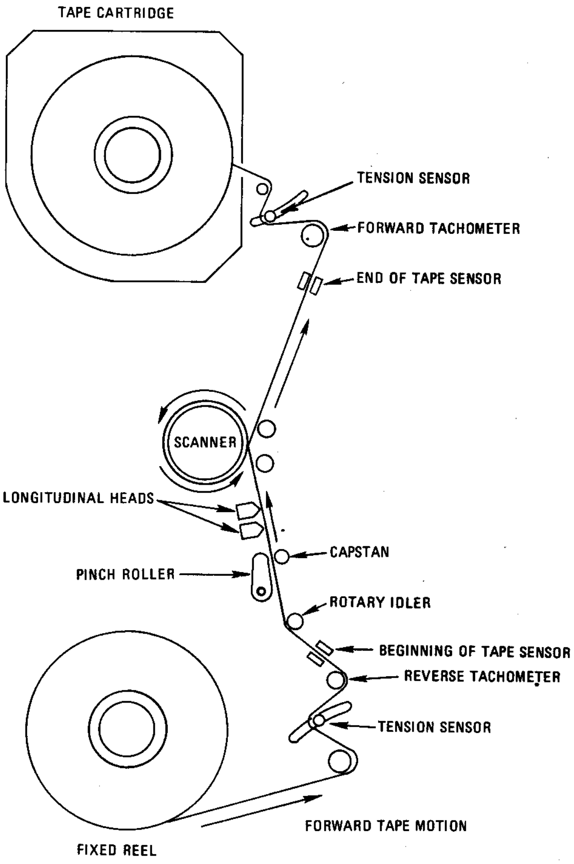
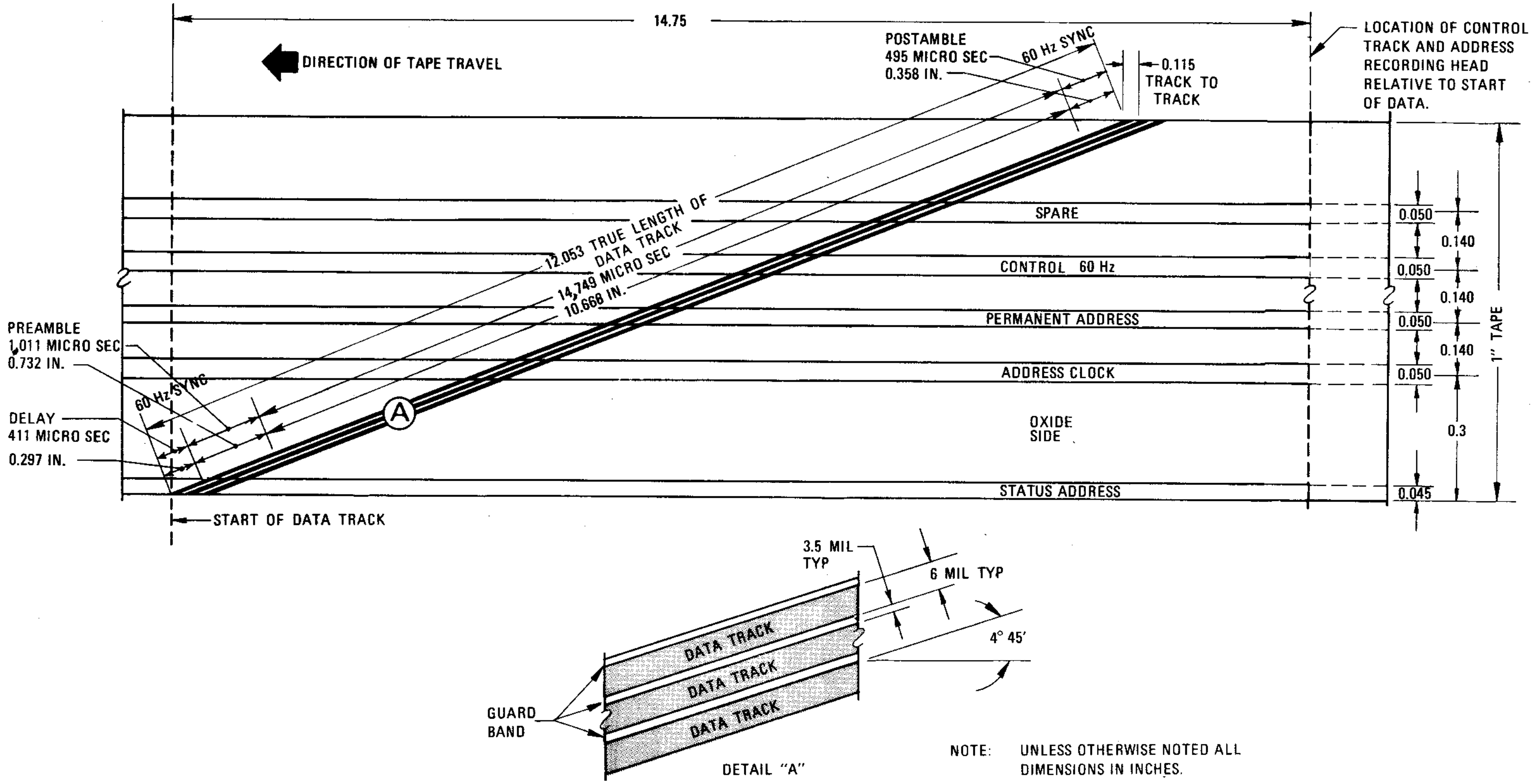


TAPE PATH AND MAJOR ELEMENTS IN TAPE PATH

Figure I



NOTE: UNLESS OTHERWISE NOTED ALL DIMENSIONS IN INCHES.

Figure II

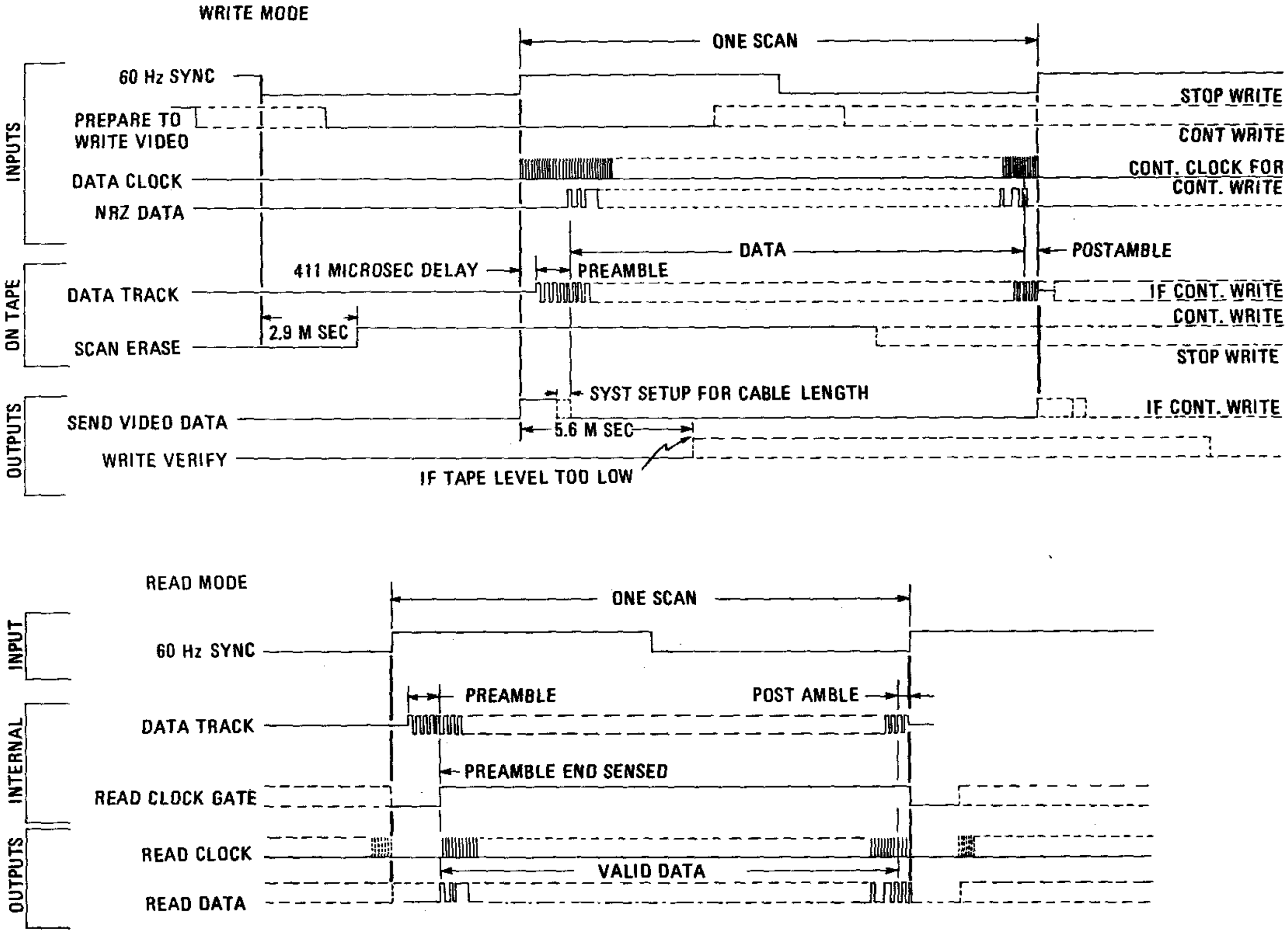

WRITE MODE
ONE SCAN
INPUTS
60 Hz SYNC
PREPARE TO WRITE VIDEO
DATA CLOCK
NRZ DATA
STOP WRITE
CONT WRITE
CONT. CLOCK FOR CONT. WRITE
DATA
POSTAMBLE
411 MICROSEC DELAY
PREAMBLE
ON TAPE
DATA TRACK
SCAN ERASE
2.9 M SEC
IF CONT. WRITE
CONT. WRITE
STOP WRITE
SYST SETUP FOR CABLE LENGTH
OUTPUTS
SEND VIDEO DATA
WRITE VERIFY
5.6 M SEC
IF CONT. WRITE
IF TAPE LEVEL TOO LOW
READ MODE
ONE SCAN
INPUT
60 Hz SYNC
PREAMBLE
POST AMBLE
INTERNAL
DATA TRACK
PREAMBLE END SENSED
READ CLOCK GATE
OUTPUTS
READ CLOCK
VALID DATA
READ DATA

Figure III