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A Magnetic Digital Recording System for Field Use

C. McCoy, Jr., and H. L. Peterson

Electronics Branch
Sound Division

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Present-day data processing relies heavily on digital techniques. The use of magnetic digital recorders for the acquisition of field data, to be processed by digital computers at a later time, is both accurate and convenient.

This report discusses a digital recording system for field use. The system has been in use for over three years and has presented little or no operational difficulties. Five basic sections make up the recording system in the following order: analog, sampling and quantizing, magnetic tape assembly, visual monitor, and system control.

The analog section consists of eight bandpass filters which feed the chopper-stabilized dc amplifiers capable of 66-db maximum gain. The eight amplifiers are coupled to eight isolation transformers which serve to eliminate any dc bias before the signals are fed to the next section.

The sampling-and-quantizing section consists of an 8-channel multiplexer which receives the signals from the eight isolation transformers and samples them either in parallel or sequentially. At the time of sampling, the instantaneous voltage values are held on eight sample-and-hold circuits for sequential processing by an analog-to-digital converter. The converter encodes the value held on each circuit into binary digits consisting of ten bits and a plus or minus sign (11-bit word). This will give the analog sample a quantized value of one part in 1024, plus and minus, representing about 0.1 percent resolution.

The magnetic tape assembly section consists of a 16-channel dual-head, digital recorder which accepts the binary output from the converter.

The visual monitor section of the system makes use of the dual-head recorder to visually check the information written on the tape. The previously binary coded words are decoded into step analog voltages by means of a digital-to-analog converter and displayed on an oscilloscope. A parity section of the monitor checks the magnetic tape for possible dropouts and coding errors. When an isolated power supply is used to drive all electronics and an rf isolation transformer is inserted between the tape drive electronics and the line voltage, parity errors are reduced from a high of 30 or 40 per reel of tape to one or zero per reel.

The system control section is the heart of the system and employs commercially available digital modules and a crystal control pulse generator.

Included in this report is a discussion of multiplexers, analog-to-digital converters, and digital tape recorders. Included, but not all inclusive, are some rules for the selection of analog-to-digital converters with regard to resolution and accuracy. Techniques for minimizing noise pickup when using high-gain dc amplifiers and for isolation from rf noise generated by large tape transports are discussed.

The implementation of digital logic for controlling, formating, parity error checking, and visual display of data while writing on tape has also been included in this report.

INTRODUCTION

Developing adequate techniques for data acquisition and the handling of field experiments, so that data may be recorded in the field and processed later in the laboratory for statistical analysis, has always been a difficult problem. The conventional analog tape recordings suffer from the problems of "wow" and "flutter," which tend to degrade the original data, and the technique used in selecting and handling data that has been recorded in real-time is very often tedious.

Today, the low frequencies employed in underwater acoustical research have made possible the development and application of many new techniques to the problem of data processing. Present studies utilize the inherent flexibility of digital techniques, with great reliability in digital recording, to study signal coherence, signal-plus-noise background statistics, and reverberation characteristics.

The use of digital magnetic recorders for data acquisition is a natural outgrowth of digital processing. Since much acoustic data is handled, sorted, and analyzed by digital means, direct recording of field data in digital form is frequently the most effective method for acquiring the data.

NRL Problem S01-06; Project RF 001-03-44-4054. This is an interim report; work on the problem is continuing. Manuscript submitted September 19, 1963.

GENERAL DESCRIPTION OF RECORDING SYSTEM

The recording system is comprised of five basic sections (see Fig. 1). The first section is analog; the second is sampling and quantizing; the third is the magnetic tape assembly; the fourth is a visual monitor section; and the fifth section contains the system control.

The analog section consists of eight bandpass filters* which feed the chopper-stabilized dc amplifiers capable of 66-db maximum gain. The amplifiers are coupled to eight isolation transformers which serve to eliminate any dc bias before the signals are fed into the next section.

The second section does the sampling and quantizing. An 8-channel multiplexer receives the signals via the eight isolation transformers and samples them either in parallel or sequentially, depending on programming. It holds the instantaneous voltage values at the time of sampling on eight sample-and-hold circuits for sequential processing by the analog-to-digital converter. The converter encodes the value held on each sample-and-hold circuit into binary digits consisting of ten bits and sign (11-bit word). This will give the analog sample a quantized value of one part in 1024, plus and minus, representing about 0.1 percent resolution. The encoding is a ripple-down (serial) process, and when completed it triggers the next sample-and-hold circuit for its analog sample. This process continues until all sample-and-hold circuits have been encoded, and then the cycle repeats itself on receipt of the next sample pulse.

The digital numbers, or 11-bit words, are then fed in parallel from the converter to magnetic tape. The magnetic tape assembly, comprising the third section of the system, is a 16-channel, dual-head, digital recorder with manual and remote control features. The tape recorder accepts the binary output from the converter, and each data word of ten bits plus sign is mapped into one character word across the tape, including its associated parity bit and a clock bit to identify the word position (see Fig. 2). A group-marker bit is placed alongside each group of eight words, since all of these words were taken from the eight sample-and-hold circuits that sampled at the same instant. A file-code-marker bit is placed in another channel to mark off groups of 100 words for later use in the laboratory processing.

The fourth stage of the system is the visual monitor and parity check. By utilizing a dual-head recorder, a visual check may be made just after the information has been written on tape. The binary words are decoded into step analog voltages by a digital-to-analog converter, and these step voltages can be displayed directly on an oscilloscope, or fed first through an appropriate filter, and the resulting analog voltage can be viewed. A word selector decoder enables one to view any or all of the eight channels that are being recorded. The parity section of the monitor checks the magnetic tape for possible dropouts and coding errors. The converter provides the parity bit along with each conversion, and the total number of bits in each word should be an odd number. The use of odd or even parity is arbitrary and is generally the choice of the manufacturer of the converter. In the present case the parity checker inspects each word for an odd number of bits, and if a word fails to have an odd number of bits, a count is tallied in a binary counter used to indicate the number of errors for a given reel of tape.

The fifth and final stage of the recording system is the control section, built from commercially available digital modules. This control section, along with an associated crystal control pulse generator, is the heart of the system. The controller starts and stops the tape recorder and sets the tape speed, supplies the sampling pulses for the multiplexer, and gates the output of the analog-to-digital converter onto the magnetic tape. It supplies a clock pulse with each recorded word, a marker pulse, and the file mark. It also gates the digital-to-analog converter for monitoring and supplies the trigger for the parity-check circuit.

DETAILED DESCRIPTION OF RECORDING SYSTEM

Analog Section

The analog section of the recording system is divided into three parts (see Fig. 3). The analog inputs are fed to eight bandpass filters, one for each channel. These are Burnell filters having a

*Although narrow bandpass filters were used in this system, they need not be incorporated in a digital recording system. This would depend entirely on the frequency range of interest.

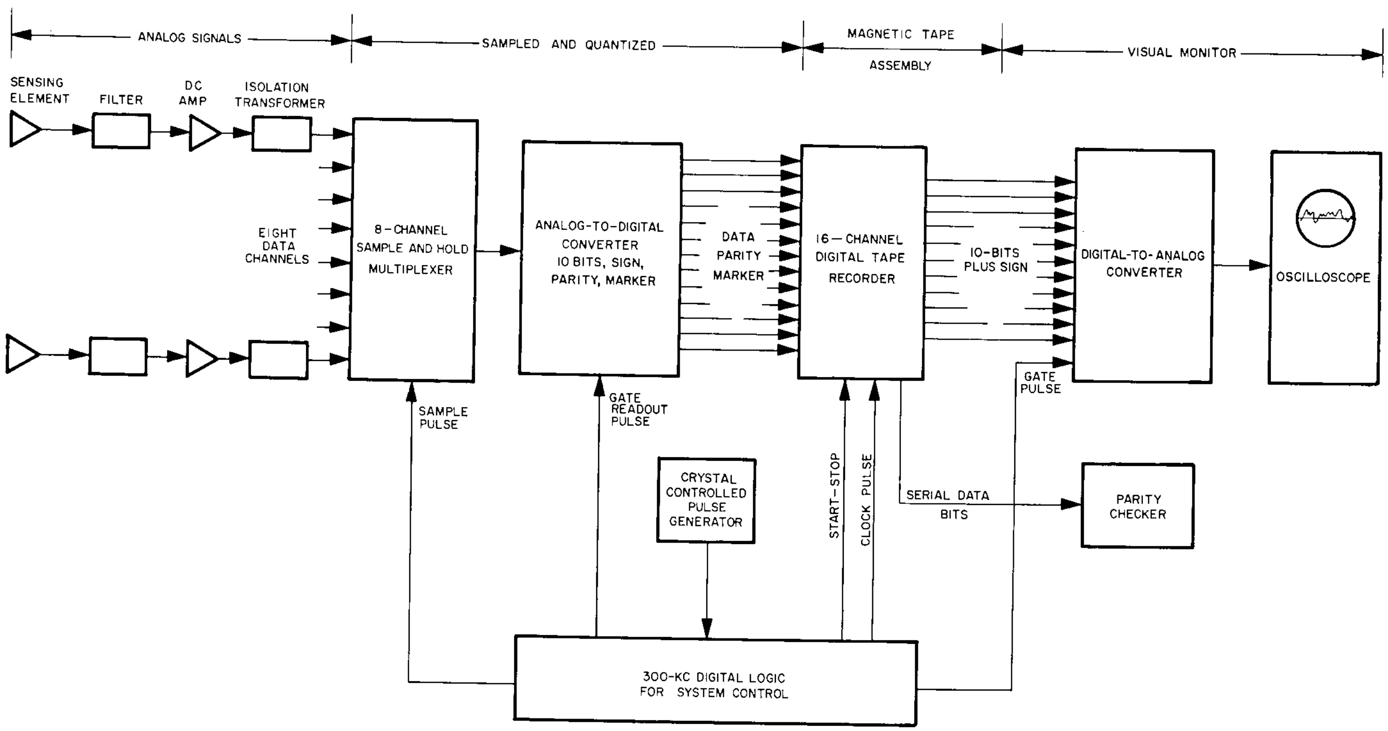

Fig. 1 - The digital recording system in which eight data channels are sampled, digitally quantized, and multiplexed onto one-inch magnetic tape

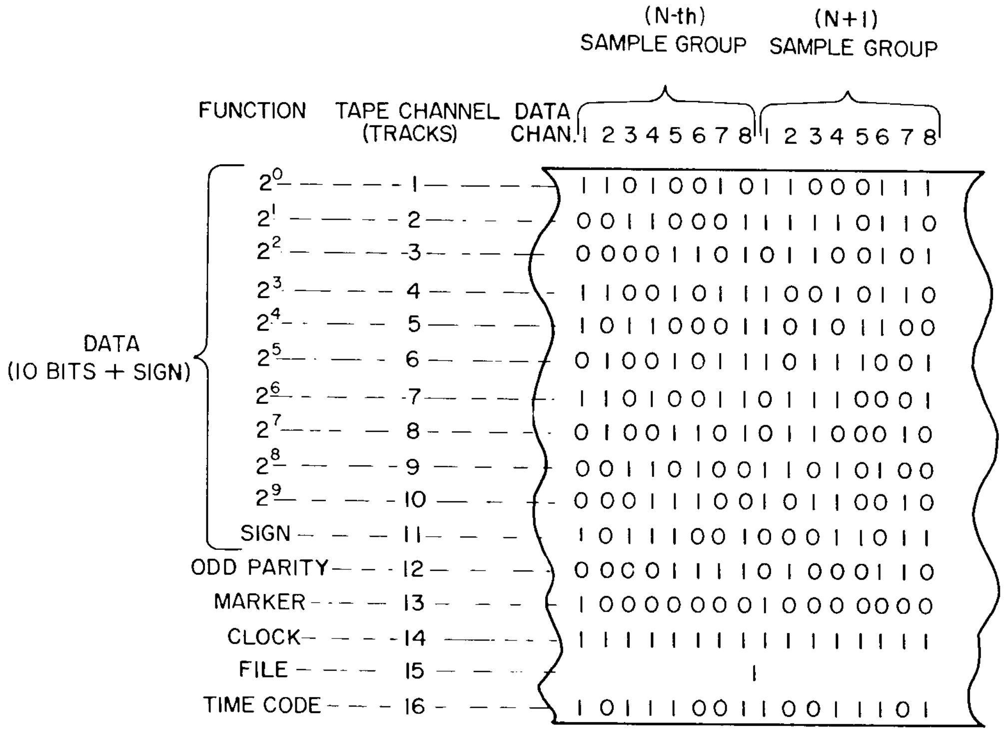

Fig. 2 - Magnetic tape format showing how each data channel is digitalized into 10 bits plus sign. The tape recorder used is a 16-channel dual-head recorder.

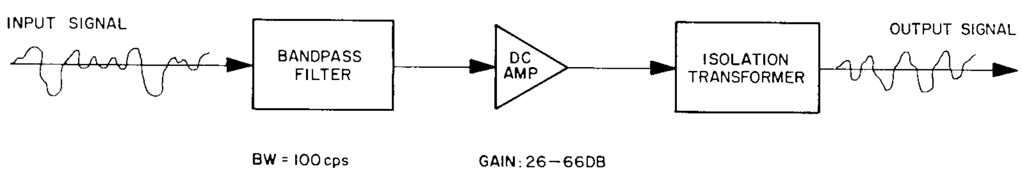

Fig. 3 - One of eight identical analog sections in the digital recording system

100-cycle bandpass between half-power points and a sharp drop off of response outside of the bandpass range. The filters feed eight Kintel dc amplifiers, models 111 BF and 112 A (both types have identical characteristics). These amplifiers are chopper stabilized to minimize any dc drift. The internal wideband noise is approximately 12 microvolts peak to peak, as referred to a shorted input, at maximum amplification. The input and output cables for the amplifiers are shielded two-wire cables with the shields floating at the inputs to the amplifiers. This prevents any noise pickup on the shields from being fed into the sensitive amplifiers. Each amplifier feeds a UTC-A21 isolation transformer that is inserted into the system to prevent any dc from biasing the sample-and-hold networks of the multiplexer since the signals that are of interest are strictly ac; any dc getting through the system only biases the encoding process.

Sampling-and-Quantizing Section

This stage of the system has two major components, a multiplexer and an analog-to-digital converter; both units are commercially built by Adage, Inc. The first unit of this stage is the multiplexer to which all eight analog channels are fed for sampling and holding. The multiplexer has two function switches, one for the number of channels to be fed into it (either 1, 2, 4, or 8), and a mode switch for either parallel or sequential operation. Basically, this unit is a high-speed switch preceded by RC holding networks, and it provides analog outputs compatible with the input requirements of the analog-to-digital converter.

The multiplexer continuously follows the voltage variations of the inputs. When a sample pulse is fed to the multiplexer, it will disconnect and hold the instantaneous voltage values of all eight inputs on its sample-and-hold modules, assuming that it is in the parallel eight-input mode. It will then switch these sampled values to the converter, at a rate compatible with the conversion time of the converter, until all eight channels have been evaluated. The multiplexer will then follow the inputs again until the next sample pulse causes it to hold the input voltage values. In the sequential mode, the multiplexer will hold one channel at a time and feed it to the converter for evaluation; it will continue to step along each channel at the time of each sample pulse until the required number of channels have been sampled and encoded, after which it will repeat the cycle with the next sample pulse. In no case of operation, either parallel or sequential, can the multiplexer be sampled at a rate faster than the time it takes the converter to complete its evaluation of ten bits plus sign.

A multiplexer makes it possible to encode a number of inputs with the use of a single converter. The sample-and-hold modules enable the converter to operate at a greater accuracy and over a greater frequency range for a given conversion time than it could otherwise achieve without this holding technique.

Analog-to-Digital Converter

Before getting into the operation of the analog-to-digital converter, some background on the selection of a converter might be instructive. When selecting conversion equipment, one has to consider the conversion accuracy desired, the frequency range of the data, the voltage levels of the data, and the number of channels to be sampled.

The first consideration is the frequency range of the data, for this determines the converter speed that is needed. If the data has a frequency range of f_1 to f_2, then the required periodic sampling rate must be at least twice the rate of the highest frequency component, as required by present-day information theory. This means that the converter must be able to complete its evaluation at some time less than $1/2f_2$ seconds. Once the speed of the converter has been determined, the next consideration is the conversion accuracy.

Some converter manufacturers state that their converters have an accuracy that is equal to $1/2^N$, where N is the number of bits that can be encoded excluding the sign bit. This would lead one to believe that if a converter is capable of 10 bits plus sign, the accuracy is $1/2^{10}$ or 0.1 percent. It would be more explicit to specify the accuracy in two parts, *e.g.*, 0.1 percent $\pm 1/2$ bit. The second part indicates the "fineness" of quantization, the number of steps in the transfer characteristics, while the first part indicates the linearity or uniformity of placement of the quantization steps based on full-scale value. The first part is suggestive of the analog accuracy, the second of converter resolution. A converter that has a resolution of 0.1 percent means that given an analog signal with 1 volt full scale, the converter can resolve a change of 1 millivolt over the entire voltage range with a code resolution of plus or minus 1/2 least-significant bit. Resolution can therefore be stated as

$$R = \frac{V_{FS}}{2^N} \times 100, \qquad (1)$$

where R = percent resolution, V_{FS} = full-scale voltage of converter, and N = number of bits (excluding sign).

The accuracy of the converter without sample-and-hold can be approximated by

$$A = \pi f t \times 100, \qquad (2)$$

where A = percent accuracy, f = frequency of data, in cps, and t = conversion time of converter, in seconds.

Using Eq. (2), one can see that if a conversion accuracy of 0.1 percent is required of a 10-kc

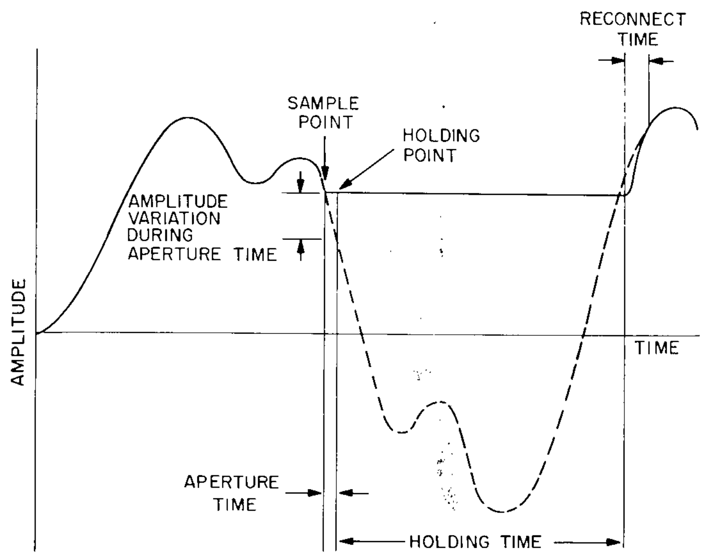

Fig. 4 - Effect of sampling and holding on a time-varying function

converter, then the converter could only process data that had a frequency no higher than 3 cps. In order to handle 5-kc data at the Nyquist sampling rate of 10 kc, a converter would have to have a conversion rate of at least 30 nanoseconds to obtain the required accuracy of 0.1 percent. One way to get around using a faster converter would be to insert a sample-and-hold circuit, which would have the effect of giving the converter more time to complete its decisions and then the accuracy of the converter would be dependent on the aperture time and holding capability of the sample-and-hold circuit.

In Fig. 4 the aperture is an indication of the time response of the sample-and-hold circuit in acquiring the value of the analog input, and the amount of amplitude variation during aperture time becomes apparent in the diagram. This amplitude variation of the analog signal necessitates the use of a sample-and-hold circuit for a converter that is relatively slow, since it is somewhat easier to implement a sample-and-hold circuit with a 0.1 microsecond aperture than to build a converter that will give ten bits plus sign in 0.1 microsecond.

Another consideration of the sample and hold is its holding and reconnect time. When holding a number of channels in a parallel mode, the holding value of the signal will decay before the converter is able to quantize the last few channels. This, of course, depends on the holding time, the number of channels to be held, and the conversion time of the analog-to-digital converter. The reconnect time gives an indication of how fast the sample and hold can acquire a new signal after disconnect from a holding mode.

The analog-to-digital (A/D) converter that is used in the field recording system is a bipolar device taking about 88 microseconds to convert ten bits plus sign and a parity bit, and it is used with a sample-and-hold circuit. It also functions as a bipolar digital-to-analog (D/A) converter, with the analog output being amplified by an operational amplifier.

The operation of the A/D converter is a serial approximation of adding resistors to the circuit until the sum of the currents balance at the summation point feeding the comparator.

The time between decisions is approximately 8 microseconds, which corresponds to the internal clock period. The total digital equivalent value of the balancing current is stored in a series of flip-flops giving the quantized value, in straight binary, of absolute value and sign. Each conversion is completely independent of the preceding one, and the time between conversions is 20 microseconds. The converter in this system can make 10,000 complete conversions per second; because of the present state of the art, this would be considered medium speed.

The output from the converter is gated in parallel onto magnetic tape, in time-division multiplexing when used with a multiplexer, and the tape format is as shown in Fig. 2, with one exception that will be explained later in the section on tape formating.

Digital Magnetic Tape Recorder Section

The digital tape recorder used in this system is a Potter M906 II variable-speed, 16-channel, dual-head recorder with manual and remote control. This recorder is run with a packing density of 267 bits per inch, or 8 kc at a speed of 30 ips (inches per second). To achieve a higher input, a speed of 60 ips can be used, but in this system the speed of the A/D converter is limited to 10 kc, and therefore the packing density of the tape unit is not pushed beyond its limitation.

When using a tape unit of 16 channels, it has been found to be more effective if the clock channel is located in the middle, in this case channel 8. This will help to alleviate some of the problems of interchannel time displacement, jitter and skew. Figure 2 shows the tape format as used in this system, with the exception that the clock channel in actual practice is located in channel 8, for reasons mentioned before, and the figure depicts it in channel 14 for illustrative purposes only.

To minimize rf noise from the reel drive and capstan motors, it has been found advantageous to isolate the tape transport electrically from the line voltage with a rf transformer. The read-write amplifiers and all associated control electronics are fed from an isolation power supply to further reduce the effects of rf noise pick-up. Cooling fans help to reduce the effects of servo-jitter when the tape unit is to be run for a long time period. When shipping a tape unit of this size and weight, it is best to ship it horizontally and mounted on a shock pad. Most of the bolts are supporting a sizeable shear stress, so shipping in a vertical position may cause motors to become dismounted and the very heavy tape transport could shear the bolts that mount it to the rack. After a few years of shipping, there have been no problems of shearing bolts when the tape unit is shipped horizontally and when a reinforced rack cabinet, capable of withstanding 500 pounds of almost concentrated weight, is used.

Visual Monitor Section

The fourth stage of the system has a visual monitor and a parity checker for inspection of the data. The visual monitor is a D/A converter and is identical with the A/D converter, but it works in reverse. With the aid of the read-after-write feature of the recorder, data is read from the magnetic tape in parallel to the D/A converter, and the output becomes serially quantized steps of the binary code. The D/A output can be fed directly to an oscilloscope where the step voltages can be displayed, or it can be fed through an appropriate filter to give an appropriate reconstruction of the original analog signal. This visual representation enables one to see if there has been any clipping in the encoding process due to high excursions of the input signal. It also assures the operator that everything is functioning satisfactorily and the information has been read onto tape correctly. The code selector enables one to monitor any of the eight channels that have been encoded.

The parity checker takes each word that has been encoded and checks for an odd number of bits after the data has been written on tape. The parity bit is generated by the A/D converter, and the use of the channel selector enables checking of any or all eight channels simultaneously. There would be no parity error if the input signals overloaded the A/D converter. The overload would result in a loss of information, and this discrepancy can be readily seen on the visual monitor or by lights on the converters. The parity errors are tallied on a binary counter, and the numbei of errors to be expected on a given reel of tape is recorded. There are usually no errors on the tapes, and most errors have been found to be transient rather than permanent errors.

The term "channel" has been used quite frequently throughout this report and a little clarification might be instructive. When applied to the tape unit, there are 16 channels or tracks (see Fig. 2); when applied to the data, there are eight different analog input channels. Each data channel is sampled, encoded, and the code placed laterally onto the 16 tape channels with all the additional information as shown in the diagram in Fig. 2. When all eight data channels have been encoded and written on tape, they comprise a sample group, and a group marker bit is written on tape to identify them.

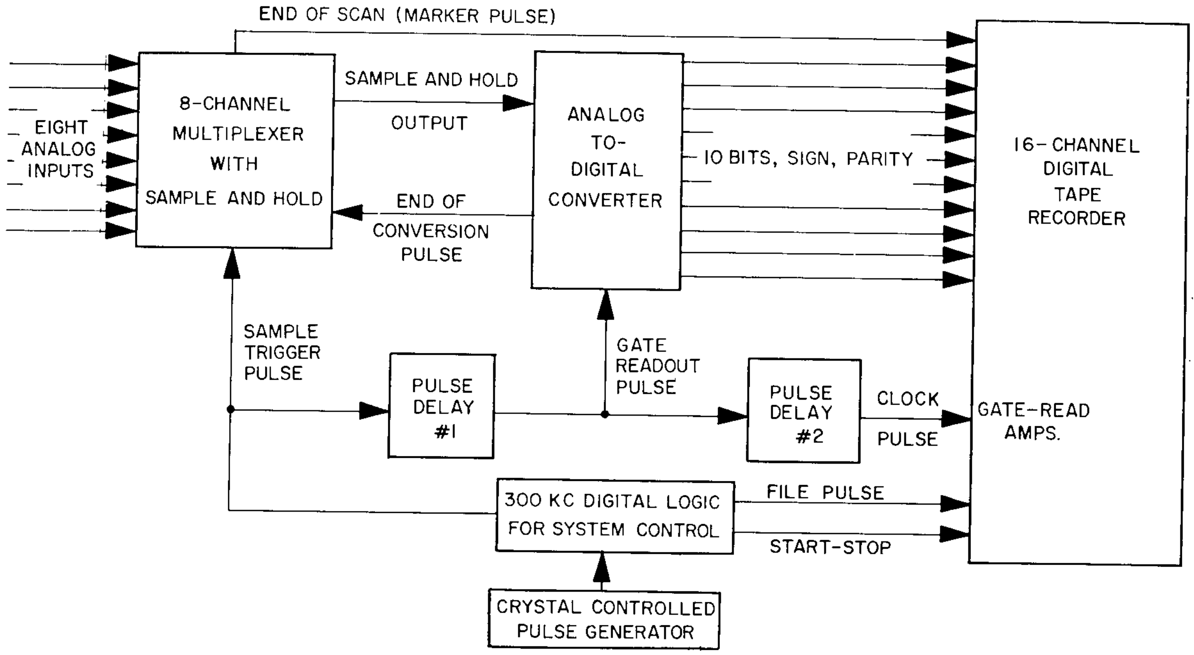

Fig. 5 - Control system for the recording cycle

Control Unit Section

The final stage of the recording system is the control unit which has been implemented from commercial modules of the Navigation Computer Corp. (Navcor "300" Series) capable of 300-kc operation. The system is controlled by a crystal generator that runs at the sampling rate desired and initiates the sequence of events (see Fig. 5). The recording cycle begins by a start pulse which comes from the controller and starts the recorder moving at a selected speed. A pulse is then sent to the multiplexer (sample trigger) and causes it to hold the instantaneous values of the input signals at the sample time. A one-shot multivibrator within the multiplexer initiates a start-conversion pulse for the A/D converter, and the converter begins encoding the first sample-and-hold circuit of the multiplexer. The same pulse that triggered the multiplexer is delayed for the length of the conversion time and becomes the gate readout pulse of the A/D converter; this same pulse is delayed again and becomes the clock pulse which triggers the gate-read amplifiers of the recorder at the time all information lines have settled to their respective values. For every pulse sent from the controller, the multiplexer, through its own internal programming, continues to feed one of its channels to the converter until it reaches the last channel, at which time an end-of-scan pulse is initiated, and becomes the group-marker pulse as shown in Fig. 2. After a predetermined number of clock pulses have been counted, a file pulse is initiated and recorded. This complete cycle is repeated for as long as the system controller is programmed, and at the appropriate time it will send a stop-record pulse to the recorder.

The controller initiates the monitoring and parity checking as shown in Fig. 6. The clock and marker pulses are sent to the controller for decoding, the data channel to be monitored is fed to a digital-to-analog converter for visual representation, and the same data bits are inspected for odd parity. The resulting errors, if any, are tallied.

RESULTS

In 1959 a prototype two-channel system with a 16-track digital tape recorder had been successfully used for field recordings.* In the beginning of 1961 a second improved system was

*W.J. Finney, and H.L. Peterson, p. 54, Report of NRL Progress, April 1959.

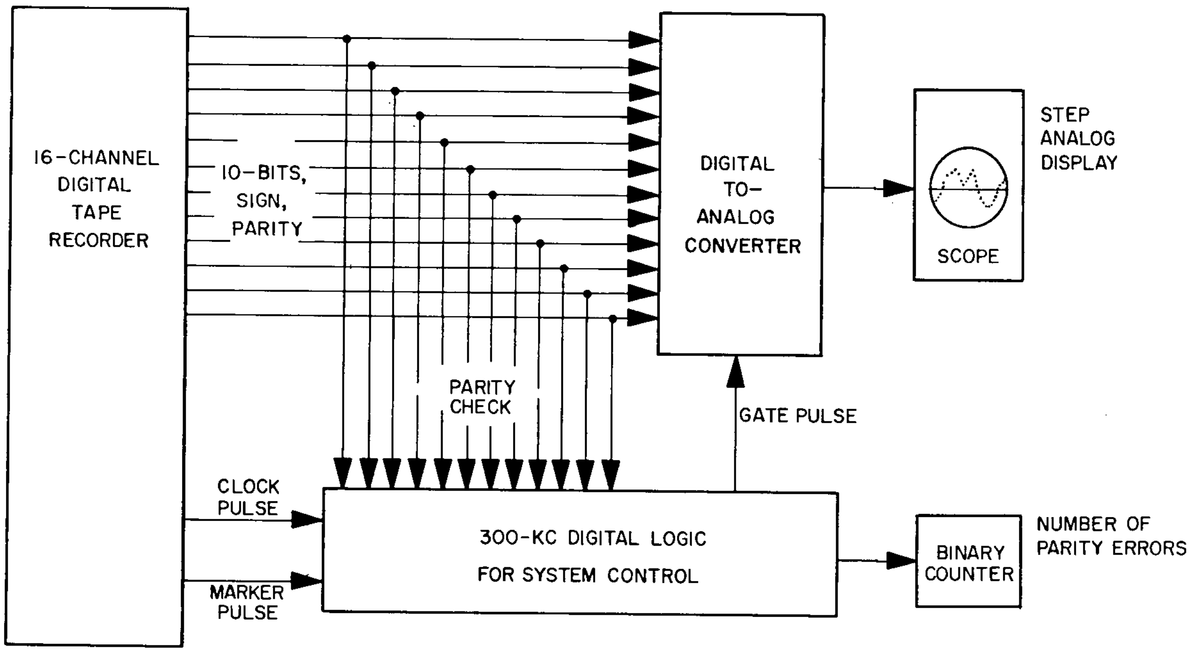

Fig. 6 - Control system for visual monitoring and parity checking

built with multiplexing features and has been used to date without any apparent failures.

FUTURE PLANS

Using the same basic principles, an improved system can be built with the use of ultra-high-speed converters, enabling more inputs to be recorded. This will necessitate the use of high-density recorders and higher speed modules. The limitation of the amount of multiplexing will then be on the packing density capabilities of the recorder. In the present system, it is the analog-to-digital converter that limits the amount of multiplexing.

CONCLUSIONS

In a digital Recording System for field use, one of the more prevalent problem areas is the electrical noise pickup brought about by spurious voltages, transients, and rf feedback from the tape transport drive electronics. This noise pickup gives an erroneous indication of parity errors and implies that there are dropouts on the recorded data tapes. To alleviate these apparent errors, it was found to be very effective to drive all electronics, including the recorder read-and-write amplifiers, from an isolated power supply (*i.e.,* isolated from the tape-drive electronics), and in addition, to insert an rf isolation transformer between the tape-drive electronics and line voltage. This technique has reduced our parity errors from a high of 30 to 40 per reel of tape to one or zero per reel, which shows somewhat conclusively that the apparent dropouts were due almost entirely to spurious and transient voltages and were not permanent errors.

A set of calibration tapes that help to facilitate checking out system integrity is advantageous. One tape should be made at a faster tape speed and greater packing density, but still within the range of the recorder, than that required for normal operation. The timing for the control pulses should be set for these upper boundaries. Another tape made for normal operation should also be included for final checkout. If the system checks out 100 percent at these ranges of operation, it can be safely assumed that it will operate trouble free, barring some unforeseen electrical or mechanical failure.