Instrumentation Tape Recorders Using DAT Technology

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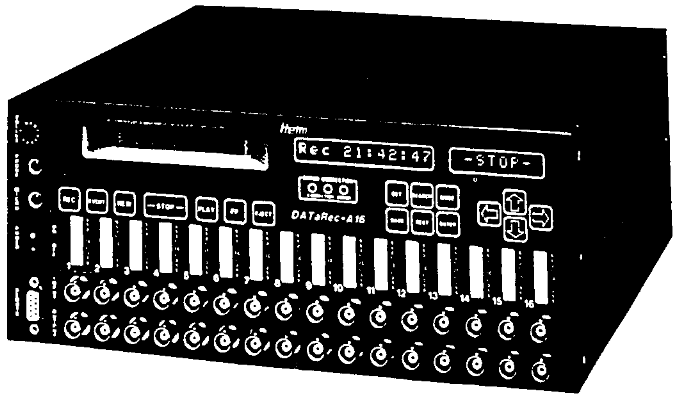
Instrumentation tape recorders have been known since the fifties. However, their requirements have undergone complete changes. More and more, the large “dinosaur type recorders” are superseded by new technologies, but when it comes to recording large data volumes over a long time the magnetic tape cannot be replaced by alternative recording methods. The following presentation will introduce magnetic tape units based on the 4 mm digital audio tape. This family of units has achieved large importance during recent years, since the DAT tape units have very small dimensions and can be used for all purposes. Depending on the application, analog and digital magnetic tapes are used. Thanks to the use of digital signal processors the system specifications could be improved to a considerable extent.

Multi-channel analog recorders operate with digital signal processing. The transmission characteristics concerning amplitude and phase errors were improved such that the residual error can be neglected during daily metrology work. Furthermore, automatic calibration improves system accuracy and simplifies the units’ maintenance.

Instrumentation Tape Recorders sind seit den 50-er Jahren bekannt. Die Anforderungen haben sich im Laufe der Jahrzehnte jedoch grundlegend geändert. Die großen “Dinosaurier Type Recorder” werden mehr und mehr durch neue Technologien verdrängt. Bei der Registrierung von großen Datenmengen Ober über längere Zeit kann das Magnethand durch alternative Registrierverfahren nicht ersetzt werden. In folgendem Vortrag werden Magnethandgercäte, basierend auf das 4 mm Digital Audio Tape, vorgestellt. Diese Gercäte-Familie hat in den letzten Jahren besondere Bedeutung erlangt, da die DAT - Bandgercäte sehr kleine Abmessungen aufweisen und universell eingesetzt werden können. Je nach Anwendung werden Analoge- und Digitale - Magnetbandgercäte benutzt. Durch den Einsatzt von digitalen Signalprozessoren konnten die Systemspezifikationen wesentlich verbessert werden.

Merhkanal Analog - Recorder arbeiten mit digitaler Signalverarbeitung. Die Übertragungseigenschaften im Bezug auf Amplituden- und Phasenfehler haben sich derart verbessert, daß die Restfehler im meßtechnischen Alltag

vernachlcässigt werden können. Automatische Kalibrierung erhöht die Systemgenauigkeit und vereinfacht die Gerätewartung.



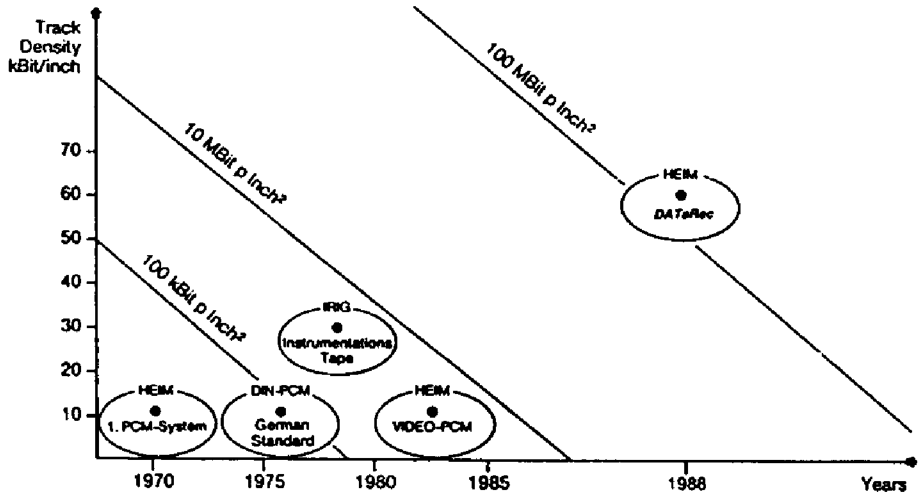
16 channel DAT recorder with full digital signal processing.

1.0 Introduction

For decades longitudinal reel-to-reel tape recorders have been used as data storage devices in telemetric applications. High technical status and high reliability were characteristics of these magnetic tape units. Figure 1 shows the technical development of the magnetic tape technology. At the beginning of the seventies the first instrumentation digital recorders were introduced. For digital recording the well-known analog tape units were used in direct recording mode. The packing densities at that time were 10 kBit/inch and the systems had no error correction facilities. With passing years the packing density was increased to 33 kBit/inch. Substantial improvements in the drive mechanism and head area were no longer possible. The transfer rates could only be improved by improving the tape speed and by distributing the data volumes to several tape tracks. This is how magnetic tape systems were built that had 42 tracks and tape speeds up to 240 inch/s. Due to the constant increase of recording density the error rates became larger and larger which was no longer acceptable for the customer. At the same time the system costs and the tape costs increased.

Many user have eagerly waited for alternative recording methods. A light on the horizon were the optical storage media introduced in the eighties. The end of the magnetic tape units was forecast. In spite of this initial euphoria, the optical disk did not take the place of the magnetic tape. Magnetic tapes are still predominant in mass storage applications. Due to the introduction of new developments, especially the use of the helical scan technology and error correcting systems, even new fields of application could be opened up.

Figure 1 Technical Evolution of Tape Recorders



2.0 Magnetic Tape Recorders - Pros and Cons

Magnetic tape recorders can store large volumes of data over several hours. The magnetic tape is cost effective storage medium. The reel units have been substituted by cassette recorders. Magnetic tape cassettes are very easy to handle and are extremely suitable for archiving purposes. The recording speed is not limited by physical processes. Bit rates of hundreds of Megabit/s can be achieved with helical scan technology. Modern magnetic tape system use efficient error correction procedures and are practically error-free. Ruggedized versions of the tape drives are available for mobile applications. They can easily be used for almost every application.

As a rule, the measuring results are evaluated by means of computers. To achieve this, the registered measurement data must be transferred to the computer. The access time of the magnetic tape systems is large, a random access is not possible. For this reason the tape sections must be copied to the computer hard disk before evaluation takes place. The actual processing can only take place in the second step. The tape recording format must allow joining of individual data areas in start/stop mode. The ambient temperature range is determined by the magnetic tape. The range of -10 ºC to 45 ºC is regarded as a reliable working range. In case of more frequent use the magnetic tapes are subject to physical wear and should be replaced after being used approx. 50 times.

3.0 Optical Disk - Pros and Cons

Computers are capable of processing measurement data directly from the optical disk. Access times are within the range of milliseconds and normally do not affect the evaluation time. The disks can be read any number of times without being subject to mechanical wear.

The recording/writing time is limited to several hundreds of kilobytes. In this field no spectacular improvements can be expected. During the recording/writing process the pads of the disk surface must be heated. To achieve this, time and energy is required from the read-write head. However, this energy cannot be increased to an unlimited extent, since otherwise the magneto-optical layer will be damaged. Disk systems are suitable for stationary applications. Mobile applications can hardly be realized, since the slightest vibrations and shocks will result in write errors. Optical disks are too expensive for being used as archiving media. There are no definite experimental values concerning ambient temperatures variations.

4.0 Digital Audio Tape

During the second half of the eighties approximately 60 Japanese companies developed the “Digital Audio Tape” under strict secrecy. They introduced a new cassette with very high tape quality for the new DAT system. Originally, these magnetic tape units were designed to allow reproduction of music recordings true to life and supersede the compact cassette. However, their excellent system parameters opened absolutely new fields of application.

Almost every magnetic tape unit was developed mainly for audio and music recording. Metrology applications followed later. This also applies to the Digital Audio Tape (DAT). The tape drive and the cassette can still be used for the recording of measurement data. The electronics and interface boards had to undergo special developments. In 1988 a new group of instrumentation tape recorders using DAT technology was created.

Figure 2 shows the typical DAT mechanism. The head drum is 30 mm in diameter and works with a speed of 2000 rpm. The 90 º angle contact is remarkably small. The two rotating heads are offset by 180 º, but because of the 90 º angle of tape contact they only have 50 % tape to head contact. A simple threading mechanism with less tape path elements ensures safe operation without tape knotting up. The tape is moved from the left to the right. A tape tension sensor ensures the correct tension of approximately 10 g. The reel motors are controlled by means of a digital control circuit. Several servo systems with very complicated control algorithms are required for correct tape transport.

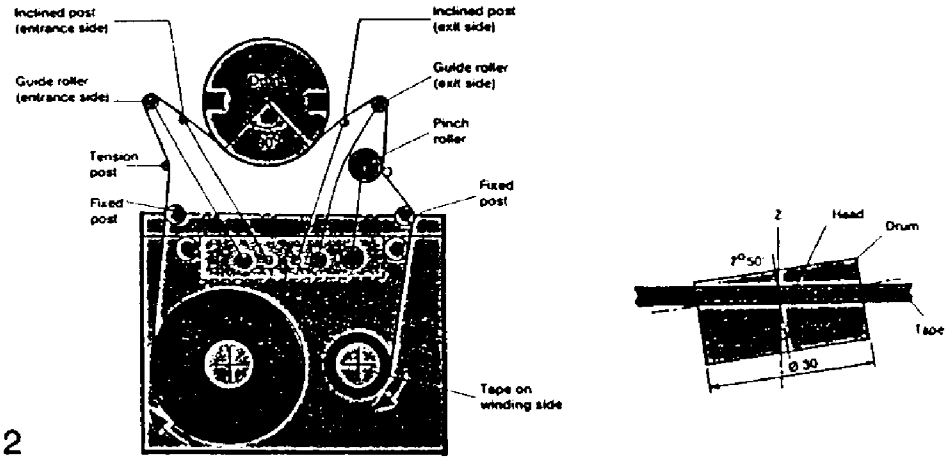
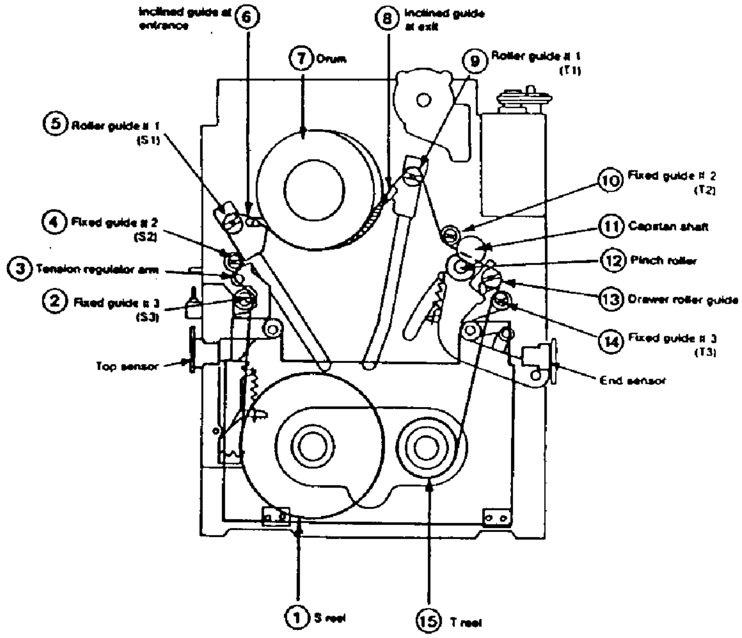


Figure 2

Figure 3 shows the tape path elements. The tape that is pulled out of the cassette by S reel 1 (supply reel) passes fixed guide # 3 2, tension regulator arm 3, fixed guide # 2 4, and roller guide # 1 5. Next the angle for winding around the drum 7 is corrected by entrance side slant guide 6 and the tape is wound around drum 7. Then the angle is corrected to the original angle by exit side slant guide 8, the tape passes roller guide #1 9, fixed guide # 2 10 and passes between capstan shaft 1 1 and the pressed pinch roller 12. Then it passes roller guide 13 and fixed guide # 3 14 and is wound on the T reel 15 (take reel) inside the cassette. Tape linearity is controlled by entrance and exit guides # 1 5 and 9.

A new cassette with small dimensions has been developed for the DAT drive mechanism. This development has been influenced by many years of experience with the video and the compact cassette. The DAT cassette is completely closed when not in use. Not only the front with the magnetic tape, but also the tape reels are covered and thus protected against dirt. The tape reels are fixed mechanically. This means the tape cannot loosen and form loops during transporting. Only when being inserted into the drive mechanism is the cassette opened on the front for the magnetic tape and on the bottom for the reel motors. Identification holes in the cassette that are mechanical sensors in the DAT drive mechanism give information on the tape material, track width and recording lock. DAT cassettes are commercially available with a recording time of 60 and 120 minutes. For two hours recording 60 m of magnetic tape are necessary. A new cassette with 180 m tape and 3 hours recording time is also available on the computer market for streamer applications. The maximum recording time for the DAT cassette is restricted to three hours.



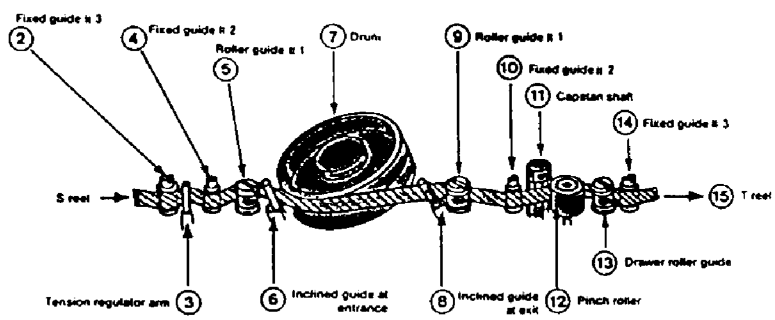


Figure 3

Why is the DAT drive especially suitable for mobile applications? An answer to this question if found easily, when looking at the tape guide and the tape drive. The smaller the weights, the more insensitive a magnetic tape drive will be against vibration and acceleration effects.

The DAT cassette only weighs 23 grams, and the moving parts of the cassette are also of lightweight construction. Special attention should be paid to the tape tension regulator arm. Small dimensions and light weight of this part not only mean insensitivity towards vibrational influences, but also a large dynamic range for tape tension regulation.

The small drum diameter, only 90 ° tape head contact and exact tape tension regulation provide the DAT system with excellent features. The DAT drives operate trouble-free under vibrations of up to 5 g. With suitable vibration isolators the tape units can be subjected to 15 g shock (operating). These values are even above the airborne instrumentation recorder. According to experiences made up to now, the DAT tape drives show extreme reliable operating characteristics and can be used in a wide range for data recording in instrumentation engineering without hesitation.

5.0 Multi-Channel Analog Tape Recorders

Through multi-channel signal electronics Digital Audio Tape Drives become analog instrumentation recorders. The bit rate is fixed to 1.536 MBit/s, which determines the signal band width of the analog channels. As in all PCM systems the input and output filters take influence on the channel band widths. The multipole analog filters used up to now no longer meet the requirements to measurement accuracy and do not allow the full utilization of the available signal band widths. Only digital signal processing can improve the specifications of an analog recording system. The example of the DATaRec family shows that in 16-channel mode a fully usable signal band width of 2.5 kHz can be achieved for every channel with 90 dB dynamics and less than 0.1 º phase error.

The block diagram, Figure 4, shows the individual subassemblies of the DATaRec tape recording system.

5.1 Digital Filters

In PCM systems the analog signal is transferred in a time sequence of equidistant sampling values, and then digitized. The relationship between the signal frequency and the minimum required sampling frequency is given by the SHANNON sampling theorem. To retain the signal frequencies in the origonal signal, it says that the sampling frequency must be chosen such that it is twice the highest signal frequency contained in the origonal signal. In order to meet the requirements of the sampling theorem input and output filters are used in PCM systems.

The existing channel capacity could only be fully utilized with an ideal low-pass filter (see Figure 6). In this case it would be possible to simply double the signal frequency to select the sampling frequency. Figure 7 shows the requirements of an input filter for a 16-bit system. The filter attenuation should be larger than -96 dB at the point f_s -f_b, since the so-called aliasing errors can occur. The reason for this failure is undersampling which is produced by violation of the sampling theorem. As it is known that each filter is always a compromise, depending on the application, different filter types must be chosen.

The DATaRec magnetic tape system do not use analog filters. The Delta Sigma analog-to-digital converter operates with 64-times oversampling and thus a simple RC section is sufficient as analog filter. Due to this fact it is possible to achieve

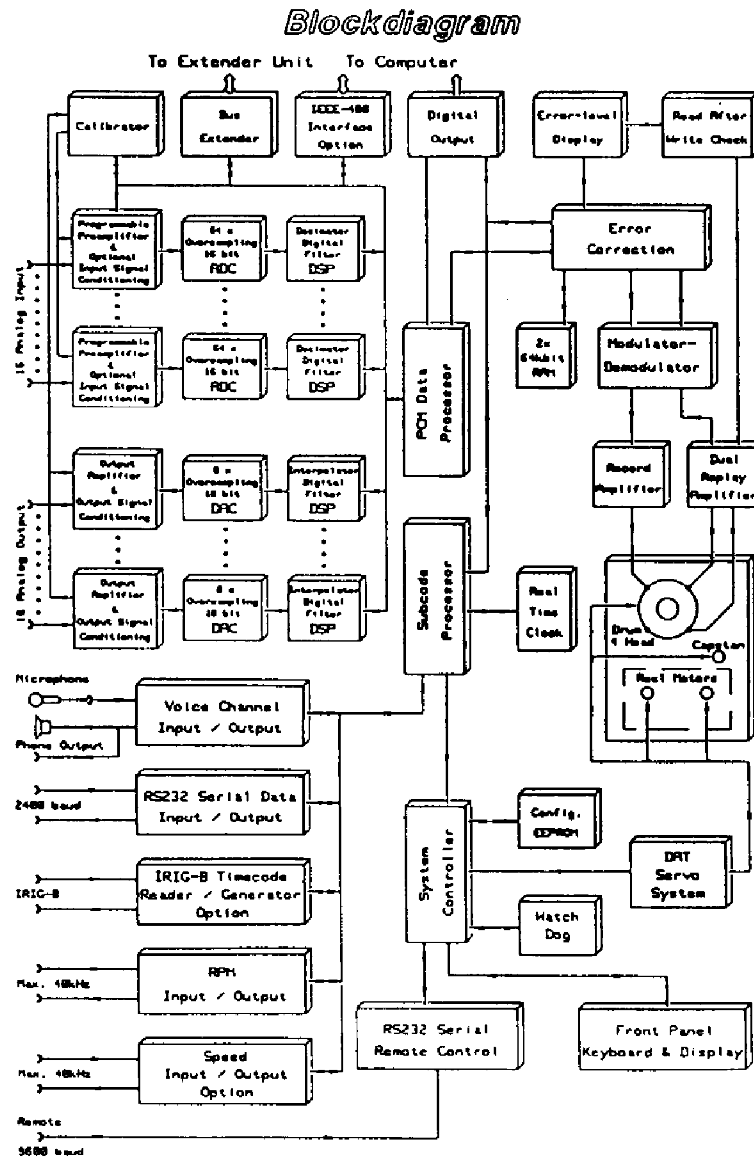


Figure 4

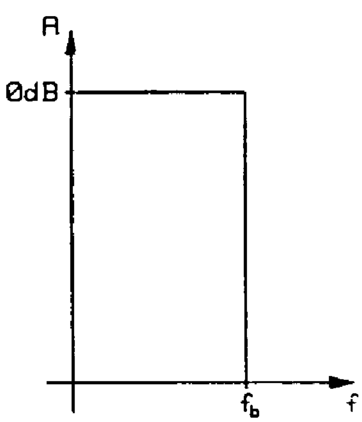


Figure 6

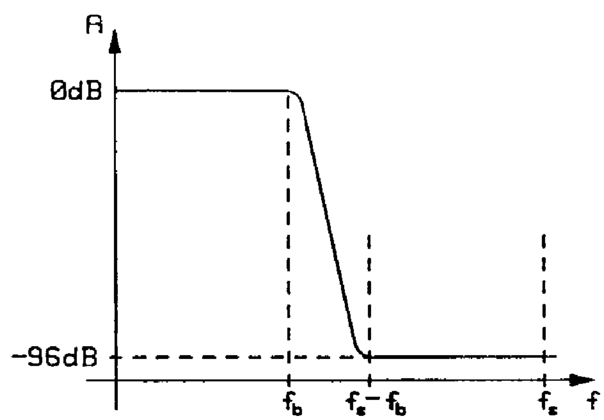


Figure 7

excellent transmission characteristics. The digital filters implemented in the ADC is a very good approach to an ideal low-pass filter. In the transmission area the ripple is smaller than 0.005 dB. In the stop band an attenuation of better than -90 dB is achieved. The phase error is almost zero. Unfortunately, these filters can only be used in 2-channel operation with a limit frequency of 20 kHz. For the lower signal band widths in multi-channel operation digital filtering is effected by means of the signal processors.

Non-recursive digital filters were implemented into the unit. In the literature these filters are often called FIR filters (finite impulse response). Two channels each are served by one DSP. The calculation performance of the processor is limited. Thus, we have to accept a restriction of the Tep figure of the digital filters. The magnetic tape system is equipped with digital filters having 100 to 120 Tep. This results in a full utilization of the MOTOROLA 56001 DSP calculation capacity. However, it must be taken into consideration that the signal processor does not only act as an input filter, but at the same time as an output filter. The input and output filters are absolutely identical. Consequently, one processor must carry out 4 x 100 filter operations within two data words.

In the DATaRec magnetic tape systems the output filters are also constructed as digital filters. The digital-to-analog converter (DAC) operates with 8-times oversampling. Oversampling to us means the fact that the output word rate to the digital-to-analog converter is higher than the word rate contained on the magnetic tape. Seven calculated sampling points were inserted between two original sampling points. For the calculation of the missing sampling points special algorithms are used to achieve possibly the best sin(x)/x response of the original signal. Due to oversampling no analog filters and/or only one single RC circuit is required as analog filter.

5.2 Calibration

In multi-channel PCM systems the calibration of the analog channels is quite complex. All components such as input amplifier, ADC, DAC and output amplifier must be adjusted for offset and gain errors. This adjustment requires at least four potentiometers per channel. If the input voltage ranges can be switched over, these measuring ranges must also be adjusted and/or equipped with high-accuracy resistors. It is known that analog components have short and long-term drift values. In most cases, temperature changes result in short-term offset voltage changes. Long-term variations of the zero and gain stabilities are caused by component ageing. A measured-value resolution of 12 bits stability can be ensured by using high-quality components. Offset and gain adjustments should be carried out every three months, if the system accuracy is to be maintained. With higher-resolution PCM systems there will be large stability problems. Even the best analog components cannot guarantee a long-term stability of more than 3 months for a 16-bit system. Not to mention the cumbersome adjustment procedure. For this reason, completely new solutions had to be found for the DATaRec magnetic tape system.

After extensive stability inspections it was found that most analog components have excellent short-term stability figures. The maximum registration time of the magnetic tape system is 2 - 3 hours. This is sufficient, if the signal electronics stability is ensured during recording or replay. An automatic calibration system was developed for the DATa-Rec magnetic tape system family. In the meantime, the calibration described here has been patent-protected for Josef Heim KG.

The initial idea of automatic calibration was that all analog assemblies be inserted into the unit without having any adjustment. By the use of high-quality components the short-term stability is garanteed for some hours. There is no provision for adjustment of the signal electronics within the magnetic tape unit. Obviously the analog circuits have offset and gain errors, these errors are corrected as follows:

Figure 8 shows the block diagram of the automatic calibration. Two assemblies must be calibrated independently of each other,. the input amplifier with the ADC and the DAC with the output amplifier. The core of the calibrating system is a 20-bit slow ADC. This ADC is factory-adjusted with a high-precision DC voltage. The adjustment can also be performed later by the user, in order to maintain the system accuracy for several years. Besides the 20-bit ADC there is a 14-bit DAC on the calibrating board. This DAC serves as voltage source for adjusting the input amplifier.

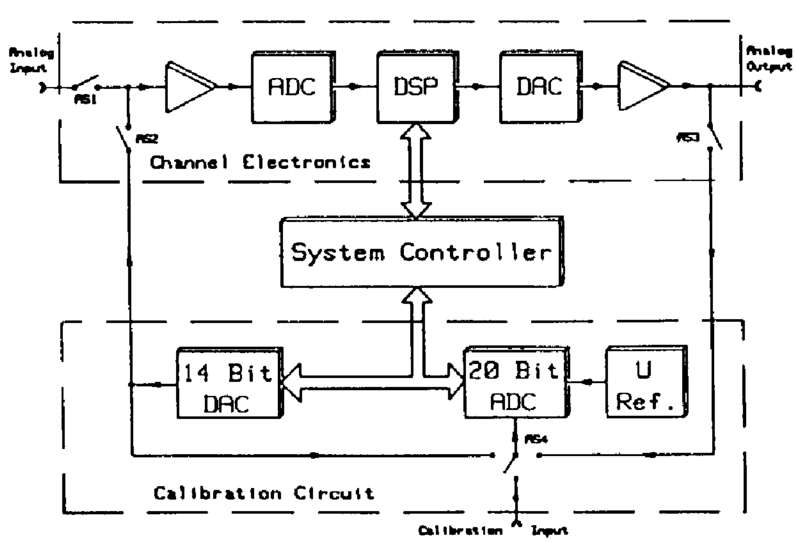


Figure 8

Provided the 20-bit ADC has been adjusted, the calibration is performed as follows:

The input signal is separated from the input jack using the AS1 analog switch. The AS2 analog switch is closed and the system controller switches a DC voltage corresponding to 75 % of the measuring range to the amplifier input via the 14-bit DAC. The analog-to-digital converter converts the DC voltage, the system controller can read the actual value via the DSP. The measurement is repeated at -75 % of the maximum recording capacity. Figure 6 shows the calibrating curve. After the +75 % and -75 % points are determined, the system controller calculates the zero and gain errors. During this measurement procedure it is not important that precicely 75 % precise of the maximum recording capacity is used or not. The output voltage of the digital-to-analog converter, i.e. the actual calibrating voltage, is determined very precisely during the calibration procedure using the 20-bit ADC. The deviations from the system controller are calculated with this value.

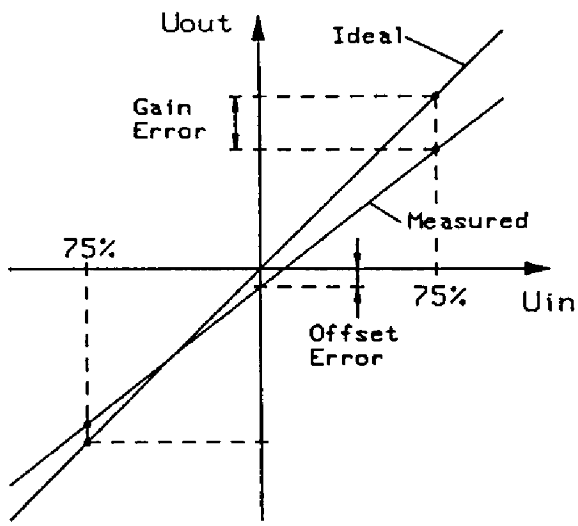


Figure 9

This is the procedure to determine the offset and gain errors for each channel. During digital filtering the signal processor performs approx. 10 million additions and multiplications per second. Before a data word is output to the system controller for tape recording, offset and gain errors are checked. An offset correction is nothing but an addition including a + or - sign. A gain error means multiplication. The current deviations were determined by the system controller during the calibrating process and the last step before the data words are output is an addition for the zero corrector and a multiplication for the gain corrector.

In a second step the errors of the digital-to-analog converter and the output amplifier are determined. The system controller transmits a data word corresponding to +75 % and -75 % of the maximum recording via the DSP to the DAC. Via the AS3 and AS4 analog switches the output voltage is measured by the 20-bit ADC and the zero and gain deviations are calculated for the output part, just as for the input part. Correction is performed again by means of an addition and a multiplication for the zero and gain errors.

6.0 Discussion of Specifications

The DATaRec is the first magnetic tape system with complete digital signal processing. Due to the features of this system the specification has considerably improved, and a new level in PCM magnetic tape systems achieved. The improved technical specifications over other magnetic tape systems requires further explanation.

Every magnetic tape unit, in the ideal world, should replay an analog signal that is identical to the origonal input signal. The record/replay process should not introduce any errors or distortion. Unfortunatly the ideal case cannot be achieved, however the main causes for errors occuring in PCM systems and how they are reduced to a minimum in the DATaRec will be discussed in the following chapters.

6.1 Accuracy and Resolution

It is generally known that a higher measured-value resolution ensures higher system accuracy. However, this thesis can only be accepted with certain restrictions. A higher measured-value resolution is only meaningful, if all system characteristics can be improved by its implementation.

In PCM systems the dynamic transmission characteristics are determined by the input and output filters. However, the analog filters avaliable currently only have up to a measured-value resolution of 12 bits. In other words: the transmission characteristics of the filters used determine the system accuracy, no matter what the measured-value resolution is. The DATaRec magnetic tape system uses 16-bit ADCs and 18-bit DACs. With these modules and other measures the specified system accuracy was achieved.

The DC voltage stability is ensured by the automatic calibration system. The DC voltage stability is approx. 15 bits resolution. For a wideband magnetic tape system this value is excellent. The dynamic characteristics are determined by the input and output filters. It must be noted that the overall error limits stated apply to both, record and replay.

6.2 Dynamic Range

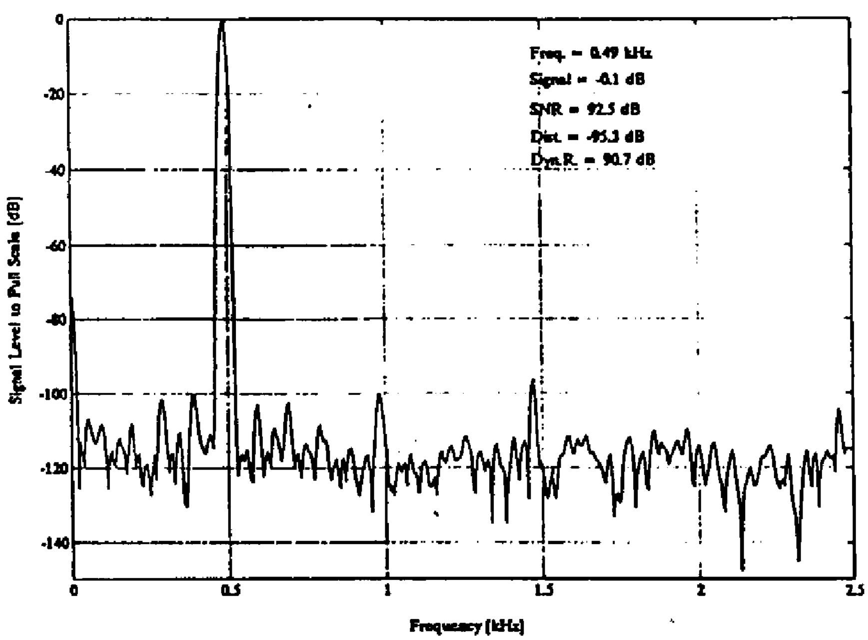
The dynamic range is the ratio between the fully modulated channel and the smallest measuring signal, expressed in decibels. The theoretical dynamic range of a PCM system is as follows:

$$\text{Dynamic Range} = 6.02 \times N + 1.76\ \text{dB} \quad (N = \text{number of bits})$$

Consequently, a 16-bit system, as is with the DATaRec magnetic tape system, would achieve a dynamic range of 98 dB. These theoretical values are limited by linearity errors, noise and other influencing factors. When quantifying error not only the ADC but also the DAC should be considered, in fact when the entire system is quoted preamplifiers and output amplifiers need to be included.

All in all the DATaRec magnetic tape system achieves a dynamic range of 90 dB. Figure 10 shows the result of a measurement. A measurement signal of 490 Hz was registered in 16-channel mode slightly below the maximum recording limit (-0.1 dB). When calculating the useful dynamic measuring range the harmonics produced are considered as well. Figure 9 shows that the distortion (second and third harmonic) occurs at -95.3 dB. The signal-to-noise ratio is 92.5 dB. Consequently, this results in a useful dynamic range of 90.7 dB.

Figure 10



7.0 Test Method of High Dynamic Range

The provision of reliable test results for high-resolution PCM systems becomes more and more complicated, since currently used test equipment do not have the required dynamic range. What requirements will have to be met by the test devices?

Signal Sources

High spectral purity of the measured signal. More than -100 dB is demanded. The Brüel & Kjaer sinus generator, type 1051, meets these requirements. With its spectral purity of -106 dB this generator is suitable for measurements with a dynamic range of up to 100 dB.

Analyzers

Spectrum analyzers have almost no chance. There is no commercially available spectrum analyzer in the world market which might achieve a dynamic range of more than 100 dB. The market offers units with a measuring range of 100 dB, such as Hewlett & Packard's Model 3585B. However, due to inherent distortion, these units are only useful up to a dynamic range of max. 90 dB.

In order to test the dynamic range of the DATaRec magnetic tape system on a reliable basis, we had to find new methods. The only possibility is to take the measured data over from a computer and to calculate the dynamic range using well-known analyzing methods such as Fast Fourier Transform (FFT).

The Brüel & Kjaer type 1051 was used as signal generator. The measured data was taken over from a PC and processed with a special calculating software. In many cases the signal-to-noise ratio, also called dynamic range, was determined as follows:

The measuring channel is fully modulated with a sinus signal and measured as effective value. The second step is to short-out the measurement input and the effective value of the noise voltage determined at the output. The ratio is then stated as signal-to-noise ratio. This measuring method leads to completely useless measuring results, since the distortions in the transmission channel are not considered.

The result shown on figure 10 was measured according to the following method:

A 1024 point FFT is effected with the MIN7 window. This window function is described later in detail. The maximum in the spectrum is searched and the sum of the right and left “K” points is calculated. When during this calculation window coefficients normalized to E = 1 are used, then the accuracy of the signal performance is very high. In this case FFT is raised to the second power.

The noise performance is determined by adding up the squared spectrum and divided by the window energy. During adding the range around ±K does not have to be considered, since this section represents the signal component.

When using FFT the window effects are generally known. The FFT result of a pure sinus signal is nothing but the window function used, displaced by the measured signal frequency. For this reason, the dynamic range of the measurement can never be above the dynamic of the windowDue to measurement inaccuracies even certain reserves are required. The following formula ensures reliable measuring results:

Window Dynamic SNR + 40 dB

The well-known window functions such as Rectangular, Hanning, Hamming, Kaiser-Bessel etc. do not meet these requirements. The best of these probably is the so-called “Kaiser-Bessel” window, the highest sidelobes (SNR) of which are at -69 dB. The bandwidth is 1.8 times the line spacing (compared with 1.0 for Rectangular, and 1.5 for Hanning). Theoretically, a Gaussian function (e^{-x}) transforms into another Gaussian function with no sidelobes at all, but the Gaussian function is infinitely long and must be truncated in practice. Truncation results in a highest sidelobe of -69 dB gives a bandwidth of 1.9 times the spacing and is thus slightly inferior to the Kaiser-BesseL

Several new window functions have been developed for the performance measurements at the DATaRec magnetic tape system. The FT7 (flat-top) is designed especially for minimizing the picket fence effect and provides very positive amplitude results. The highest sidelobe is -147.7 dB and the noise bandwidth is 4.4. The FT7 window is perfectly suitable for high-precision amplitude measurements up to a dynamic range of 110 to 120 dB. The price paid for the amplitude accuracy was a larger noise band width. Figures 11 and 12 show the FT7 window functions.

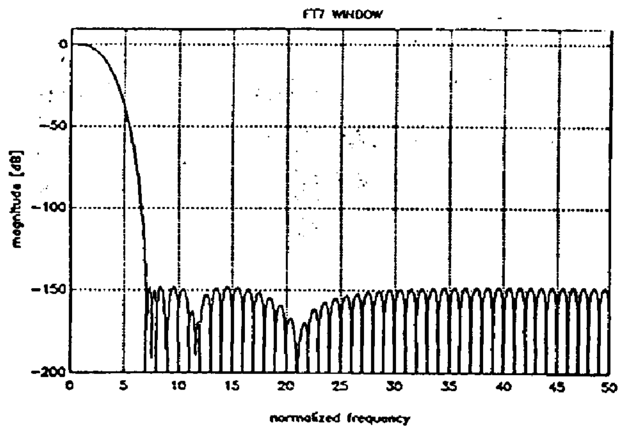


Figure 11

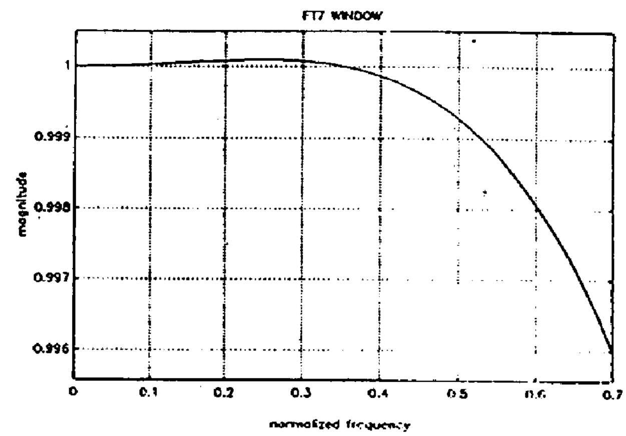


Figure 12

For highest-dynamic measurements the MIN7 window was created. When this window function was developed, we considered the future. The MIN7 window allows measurements with a dynamic range of up to 140 dB, since the highest sidelobe is -180.5 dB. Using the MIN7 window PCM systems of up to 23-bit resolution can be checked. The picket fence error is higher than in case of the FT7 window, but the noise bandwidth is reduced to 2.6. Figures 13 and 14 show the MIN7 window function.

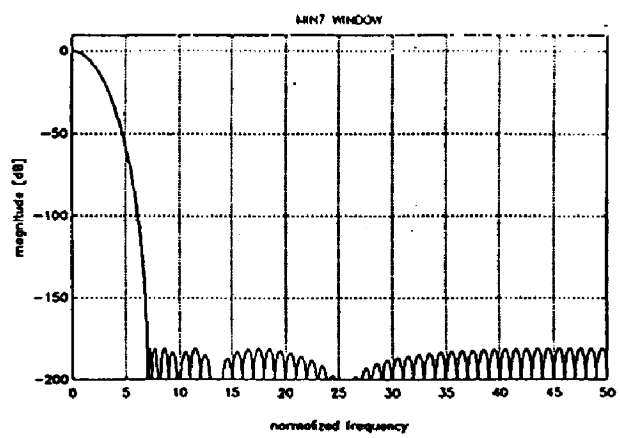


Figure 13

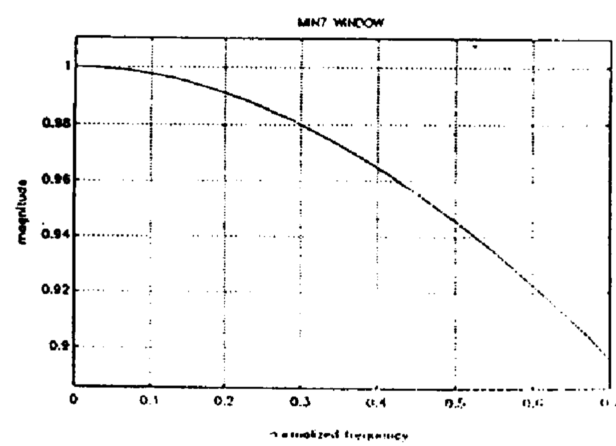


Figure 14

The following table compares the known window functions with the new-developed ones.

The window parameters of the FT7 and MIN7 windows will be published by us soon. However, we are always in a position to provide our customers the standardized window coefficients free of charge on demand. By this we want to support measurements with larger dynamic ranges.

Window Type	Highest Sidelobe (dB)	Sidelobe Falloff (dB/decade)	Noise Bandwidth	Maximum Amplitude Error (dB)
Rectangular	-13	-20	1.00	3.9
Hanning	-32	-60	1.50	1.4
Hamming	-43	-20	1.36	1.8
Kaiser-Bessel	-69	-20	1.80	1.0
Truncated Gaussian	-69	-20	1.90	0.9
FT7 (HEIM)	-147.7	0	4.48	0.0062
MIN7 (HEIM)	-180.5	0	2.63	0.4591

7.1 Filter Parameters

The digital filters were described in section 5.1. The present section shall describe the filter parameters in detail. Besides the required attenuation in the stop band the filters shall have amplitude and phase response in the transmission area. Very good results were achieved with the digital filters implemented in the DATaRec magnetic tape system. The following plots show the filter characteristics. All figures include input and output filters, and the measurements were made during recording and replay. The measurements were made with the following devices:

Spectrum Analyser, Hewlett & Packard	Model 3585B
Network Analyser, Hewlett & Packard	Model 3577A
Digital Oscilloscope, Tektronix	Model 2430

Figure 15 shows the amplitude response of a 2.5 kHz filter. The transmission characteristics are independent from the limit frequency. This example applies to all filter frequencies with corresponding scaling.

The Cursor was set to zero at 2.5 kHz. At a frequency of 2500 + 890 = 3390 Hz the filter achieves an attenuation of -93.7 dB. The ripple in the transmission area is shown on figure 15. Before reaching the limit frequency the filter operates with no attenuation. This ensure the specified signal band widths to be full utilized.

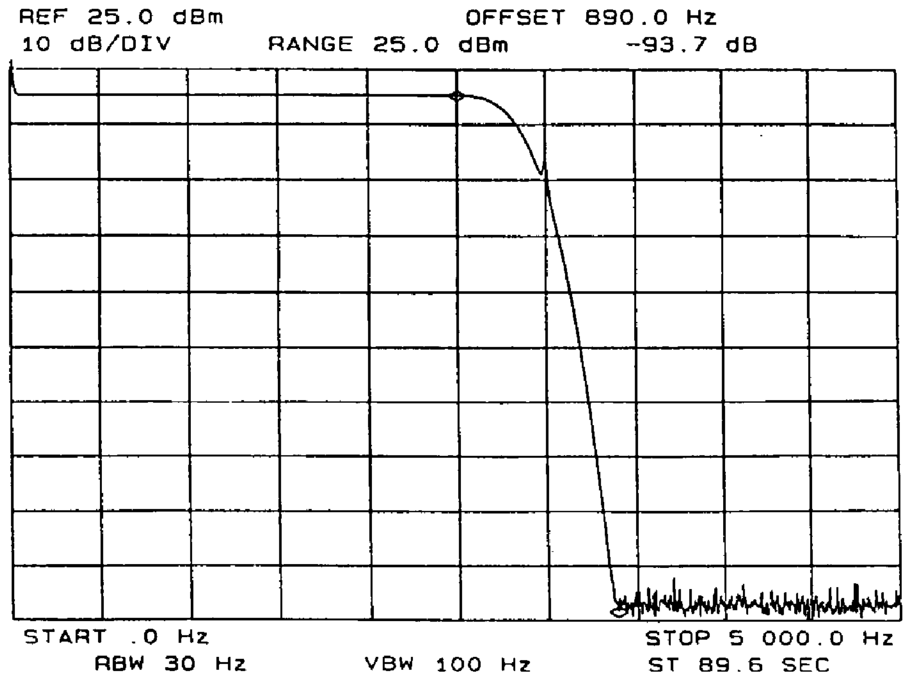


Figure 15

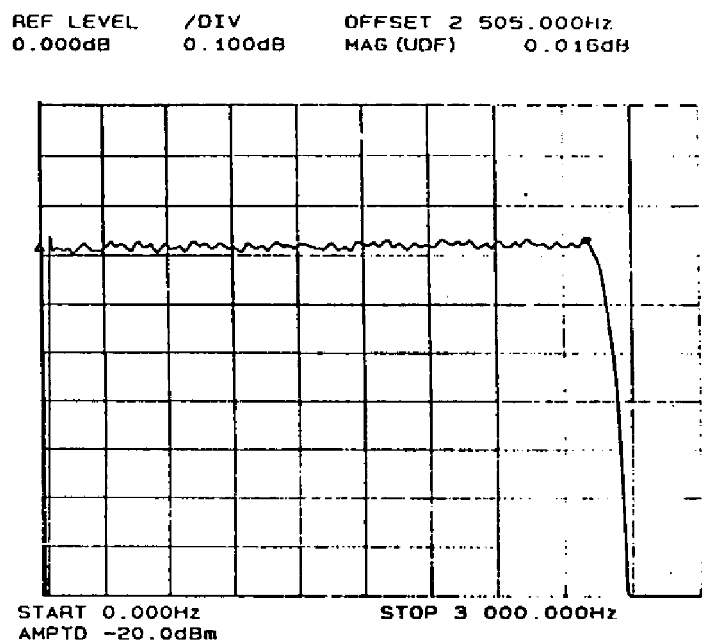


Figure 16

Especially worth mentioning are the small phase errors of the digital filters. Figure 17 shows the phase response. The visible ripple is not the phase error of the system, but the measurement inaccuracy of the network analyser. The digital filters have no phase error from the mathematical point of view. In the technical data the phase error was specified with 0.1 °, since in our opinion this value is the measurable limit. When considering the phase error care shall be taken that the specified error applies as absolute error (to input and output) and does not only represent the phase difference between the measuring channels.

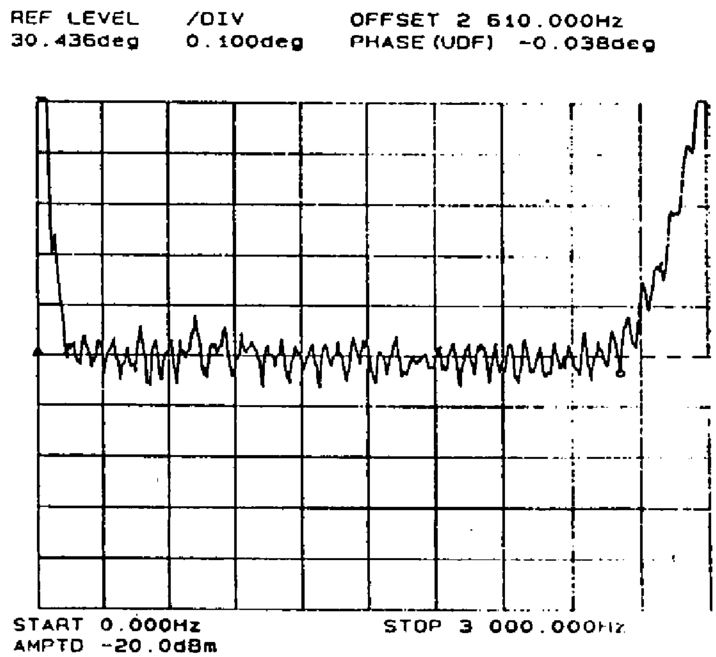

REF LEVEL /DIV OFFSET 2 610.000Hz
30.436deg 0.100deg PHASE (UDF) -0.038deg
START 0.000Hz STOP 3 000.000Hz
AMPTD -20.0dBm

Figure 17