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AUTOMATED TEST AND EVALUATION CENTER FOR WAVEFORM DIGITIZER SYSTEMS AND COMPONENTS

Philip J. Green
Div. 7121, Sandia National Labs
Albuquerque, NM 87185
phone: (505)844-4186

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ABSTRACT

In our instrumentation development efforts we find it necessary to be able to evaluate the performance of waveform digitizing systems with sampling rates from a few kilohertz to more than a gigahertz. Our goal has been to develop an integrated system which can provide quantitative results on the performance of systems and subsystems. Here we describe a system which is controlled by a Microvax II with instrumentation control through the IEEE-488 buss. The evaluation procedure is delineated in reference to a Trial Waveform Digitizer Standard [1] generated by the Waveform Measurements and Analysis committee appointed by the Instrumentation and Measurement Society of IEEE. The standard has been recently accepted by the IEEE and will become a published standard. In this work, special focus is given to the accurate measurement of effective-bit performance and differential nonlinearity of waveform digitizers.

INTRODUCTION

Modern instrumentation is presently advancing in sophistication at a rapid rate paralleling the developments in basic electronic technology. Analog to digital conversion continues to be provided with higher precision and faster processing rates. These conversion modules are at the heart of the new generation of waveform recorders. Single point measurements of analog values correlated with precision times are being replaced by the waveform recording of analog values over long time windows. Time verniers provide subsample-period time resolution. Digital signal processing techniques are incorporated within the instrument to provide smooth output data to the user. Analog oscilloscopes are being replaced by digital scopes which use waveform recording techniques to measure a waveform digitally and then process the digital array to provide a smooth trace on the scope screen. The precision of analog to digital conversion at high frequencies is now sufficient to allow digital scope trace generation indistinguishable from their analog counterparts. Evaluation methods for these waveform recording devices need to be precise and

quantitative. A recognition of this need resulted in the appointment, by the IEEE Instrumentation and Measurement Society, of the Waveform Measurements and Analysis Committee [1]. This committee recently submitted a working draft of a Trial Use Standard which was adopted by the IEEE and will be available as a published standard within the next year. This Trial Standard addresses the definition and measurement of the performance parameters of digitizing waveform recorders. The results reported in this paper have been determined using methods consistent with this Trial Use Standard. Methods are discussed for measuring the effective-bits performance of a waveform digitizer and determining differential nonlinearity.

WAVEFORM DIGITIZER EVALUATION PROCEDURES

HARDWARE ENVIRONMENT: A high frequency test and evaluation station has been assembled and is represented in figure 1. Programmable sources available include a precision dc source, a pulse generator, and a sinewave signal generator. The signal generator provides high purity sinewave output at up to 1 gigahertz. A high bandpass (>10 gigahertz) sampling oscilloscope is a key instrument for accurately defining the sources that are injected into waveform digitizers. This scope can provide between 9 and 10 bit(near 0.1 percent) definition of waveforms if they are stable and assuming extensive averaging can be used. Sinewaves are routed through a 6-element set of octave tunable notch filters providing tuning from 31 megahertz to 2 gigahertz. To avoid frequent cable interconnecting, the various sources are routed through the set of filters with a programmable matrix of coaxial switches. The switch array is shown in figure 2. We have carefully examined the purity of the high frequency sinewave signals with and without the switches to insure insignificant introduction of signal distortions. We found the RMS value of the error between data and bestfit sinewave to be bracketed by a magnitude of 0.07 least-significant-bits which corresponds to an effective bits variation of about 0.3 bits. This measurement was made over a range of 3 to 300 megahertz. We did not consider this error fluctuation significant since the average effective-bits change introduced when bypassing the switch matrix was -0.1 corresponding to an improvement in RMS-error of 0.023.

A programmable spectrum analyzer is also included in the station for examining the purity of input signals. A high frequency digital data capture unit is included for testing of subsystems or A/D converters on evaluation boards. This data capture unit presently can capture 8-bit data streams at up to 330 megabytes/sec.

SOFTWARE ENVIRONMENT: All instrumentation units of the test and evaluation station are IEEE-488 programmable and controlled with a Microvax. The basic software package used is labeled IDR [2] or Interactive Data Reduction program. This code was developed at Sandia laboratories over the last ten years for application in screenroom situations. IDR is VMS based and is command driven. It presently includes some 126 commands for hardware control, data recovery, array manipulation and data analysis. It includes a command parser that reads commands and following parameters, recognizing space or comma delimiters between parameters, and allowing only valid commands. The hardware control commands allow one to send setup information to an instrument, query an instrument and recover present settings, arm and trigger an instrument, and recover data arrays from the instrument. There are six working arrays into which instrument data or data files can be read. Extensive graphics capability allows plotting of single or multiple arrays in various formats. Simple operations such as addition, subtraction, multiplication, and division can be done to full arrays or point-by-point between arrays. Other array operations include differentiation, integration, comparison, and exponentiation. Calculations for arrays include Fast Fourier Transform, filtering, rms determination, maximum and minimum of array, and convolving of arrays.

WAVEFORM DIGITIZER EVALUATION SOFTWARE

Commands which specifically apply to waveform digitizer evaluations are the sinefit command and the code-bin-histogram command. The Trial Use Standard for digitizers, referenced in the introduction, includes both 3-parameter and 4-parameter fitting algorithms for fitting sine functions to data arrays. The 3-parameter algorithm gives a closed form solution for the amplitude, DC offset, and phase of a sinewave for a known frequency. The 4-parameter algorithm uses a least-squares minimization iterative method to find the best values of all four sinewave parameters by minimizing the sum of squares of differences between the data array and the fitted sinewave function. The 4-parameter algorithm will converge quickly only if the initial estimates are very good. We have incorporated this fitting algorithm in the following manner. For a given array, we use standard techniques to initially estimate the sinewave parameters. A general nonlinear least squares fitting algorithm which uses a gradient search method is then used to refine these estimates. Finally, the 4-parameter algorithm is used to precisely determine the best-fit values of the amplitude, DC offset, phase, and frequency of the fitted sinewave. This procedure has been found to work very well even with few points per cycle (near Nyquist) and with data arrays having noise levels near ten percent. The RMS value of the difference between the data array and the fitted sinewave is calculated to determine the degradation of the digitizer performance. For a given digitizer with 0.5 LSB (Least Significant Bit) ideal measurement resolution, it can be shown that the root-mean-square error is 0.289. The effective bit performance of a digitizer is calculated using the equation

$$\text{EFF-BITS} = N - \log_2(\text{RMS-actual}/\text{RMS-ideal})$$

where RMS-actual is the RMS value of the actual error between the data array and the fitted sinewave, and RMS-ideal is this same error for the ideal digitizer (RMS-ideal = 0.289). The value of N is the number of bits of the digitizer. This value is determined in this software by selecting the smallest integer value of N that will allow digitization of twice the amplitude of the fitted sinewave. The peak-to-peak voltage is calculated for generation of the response curve of the digitizer as a function of frequency. The software module which does the sinewave fitting plots the best-fit sinewave overlaid with the fitted data array. Parameters output to the screen are the sinefit parameters and the effective-bit performance parameters along with the number of iterations required to fit the sinewave to the data. An example of this output is given in figure 3. The same parameters are output with a plot of the fitting residuals. The graphics output allows visual confirmation of satisfactory sinewave fitting.

Differential nonlinearity of a waveform digitizer leads to errors in code values that are a function of the code value itself. For a linear digitizer, each code value should correspond to a constant range of input voltage. This range is referred to as the code-bin-width. For an N-bit digitizer the code-bin-width should be the fullscale range of the digitizer divided by 2**N. Differential nonlinearity as a function of code value [DNL(k)] is given by [1]

$$\text{DNL}(k) = W(k)/Q - 1$$

where W(k) is the actual code-bin width and Q is the ideal code-bin-width. When DNL is given as a single number not dependent on code value, that number is the maximum absolute value of the array of DNL values. DNL is most directly determined by driving a digitizer with a linear ramp input that triggers randomly and covers the entire range of the digitizer. If a large number of data points are accumulated and the trigger point has been truly random, then each code value ideally would have been registered an equal number of times. The statistically significant deviations from uniformity lead to non-zero values of DNL for different code values. Since the basic performance characteristics of the digitizer are determined with pure sinewave inputs, it becomes convenient to determine DNL(k) from the same arrays that are used for effective bits determinations. This can be done by correctly accounting for the nonconstant derivatives of a sinewave. The result for DNL(k) becomes [1]

$$DNL(k) = \frac{n(k)/N}{P(k)} - 1$$

where P(k) is the probability for code k given that the input is a sinewave. P(k) is given by [3]

$$P(k) = \frac{1}{\pi}\left[\sin^{-1}\left(\frac{V*(k-2^{N-1})}{A*2^{N}}\right) - \sin^{-1}\left(\frac{V*(k-1-2^{N-1})}{A*2^{N}}\right)\right]$$

where V = Full scale voltage of digitizer
A = Maximum amplitude of input sinewave
N = Number of bits of the digitizer

In application there are some difficulties that must be accommodated. A non-ideal digitizer will output some code values outside the range of maximum amplitude of the input sinewave. These are code values for which the ideal probability of occurrence is zero. Likewise, if one were to choose the maximum and minimum values of the digitizer array to define the amplitude, the values of DNL(k) near these extremum values will be inaccurate as a result of using ideal P(k) values that maximize at these array extrema. We chose here to make the determination of DNL(k) independent of the sinewave fitting procedures and thus used simplifications to determine the maximum amplitude of the input sinewave. We assume that the number of points in the code-bin histogram is very large compared to 2**N. This is a necessary requirement if statistically significant measures of DNL are to be made. Under this assumption, the amplitude (in code values) was calculated using weighted averages from the codebin histogram. Figures 4 and 5 show plots of the code-bin histogram and the differential nonlinearity, DNL(k), derived from this histogram. The accompanying parameters are the maximum and minimum code values in the digitizer array, the RMS value of the DNL(k) array, DNL-MAX, and the number of codes that did not appear in the array. Visual examination of the DNL plot is very valuable in locating sources of large DNL (such as missing codes). The total number of points in the array is also included. The difference between the maximum and minimum code values gives the number of code values used in the array. For the DNL(k) values to be significant, the ratio of total number of points in the array to the number of code values used should exceed 20. The DNL parameters are included on the output plot of the code-bin histogram and the DNL(k) curve derived from this histogram.

DIGITIZER EVALUATION PROCEDURES

An initial parameter setup program is run which queries the operator for the sampling rate, number of bits of the digitizer, and the number of frequencies at which evaluations are to be made. The program then selects signal generator frequencies from one percent of the sampling rate up to the sampling rate specifically including a frequency near the Nyquist value. The program checks to avoid frequencies near integral divisors of the sampling frequency. The signal generator output is routed through the set of six octave tunable notch filters. The number of measurements routinely exceeds six and the program outputs a settings table for multiple passes. A command file is generated for each pass. The software package, IDR, has the capability to run command files which set the signal generator, set the selected coaxial switch, arm and trigger the digitizer, and acquire data arrays. These data arrays are saved in a file. Once these data files are accumulated, they are available indefinitely for analysis. Using the new data file, each individual array is examined by doing the sinewave fit(with residuals), the code-bin histogram, and the Differential Non-Linearity plot. The values of effective bits, peak-to-peak voltage, and differential nonlinearity are plotted as a function of frequency to complete the basic digitizer evaluation.

DIGITIZER EVALUATION EXAMPLE

The Trial Standard for Waveform Digitizers addresses the examination of a number of other performance factors besides those directly associated with the digitizing process such as step response, gain, crosstalk, etc. Those parameters are not discussed here. The focus is on effective bits testing and determination of differential nonlinearity. The accuracy of the effective bits testing is directly coupled with the accuracy of the sinewave fitting procedures used. Our sinewave fitting procedure normally converges in less than 5 iterations. The maximum number of points used for sinewave fits is 4000. In the case of 4000 points with 5 iterations, convergence requires less than 10 seconds. The fitting is coded in Fortran 77 and no significant attempts have been made to improve the fitting time as of this date.

The results of a digitizer evaluation are shown in figures 6 - 8. We show the plots of effective bits, response, and differential nonlinearity. These plots show the basic performance characteristics of a digitizer. The availability of the plots for each sine-fit and each code-bin-histogram is valuable in assessing the precise sources of errors in the digitizing process. The sine-fit residuals plot is a good indicator of the "goodness-of-fit" for a given set of sinefit parameters. The code-bin-histogram and the DNL plot reveal problems with code generation. The first priority in evaluating effective-bits performance of a digitizer is to have amplitudes of input signals that exercise the full code range of the digitizer. Typically a 90 percent amplitude is used to avoid saturation of the digitizer. The near-full-scale effective bits value is conservative since the effective bits determination decreases with amplitude. If the small-signal performance of a digitizer was of particular interest, it would be useful to generate an "effective-bits surface" where the third plot axis is amplitude.

SUMMARY

We have shown here a High Frequency Evaluation Center which can be used to evaluate the performance of digitizers over a wide range of frequencies. The evaluation curves of figures 6 - 8 were selected to show their effectiveness in revealing problems with a digitizer. For this particular 50 megasample/second unit the response curve was not satisfactory. In fact the low amplitude response at medium frequencies caused the effective bits curve to increase with frequency which, in this case, was an amplitude effect and not a performance characteristic. The effective bits curve showed unusual problems at low input frequencies which were associated with poor matching characteristics of interleaved 25 megasample/second ADCs.

This station is being expanded to include attention to other performance parameters of waveform digitizers as addressed in the Trial Standard for Waveform Digitizers.

REFERENCES

[1] Trial Use Standard for Digitizing Waveform Recorders, prepared by the Waveform Measurements and Analysis Committee of the IEEE Instrumentation and Measurement Society, to be published by IEEE.

[2] Interactive Data Reduction Program, Bill Boyer, Div. 9133, Sandia National Laboratories.

[3] Dynamic Performance Testing of A to D Converters, Hewlett Packard, Product Note 5180A-2.

TEST AND EVALUATION CENTER FOR WAVEFORM DIGITIZER SYSTEMS

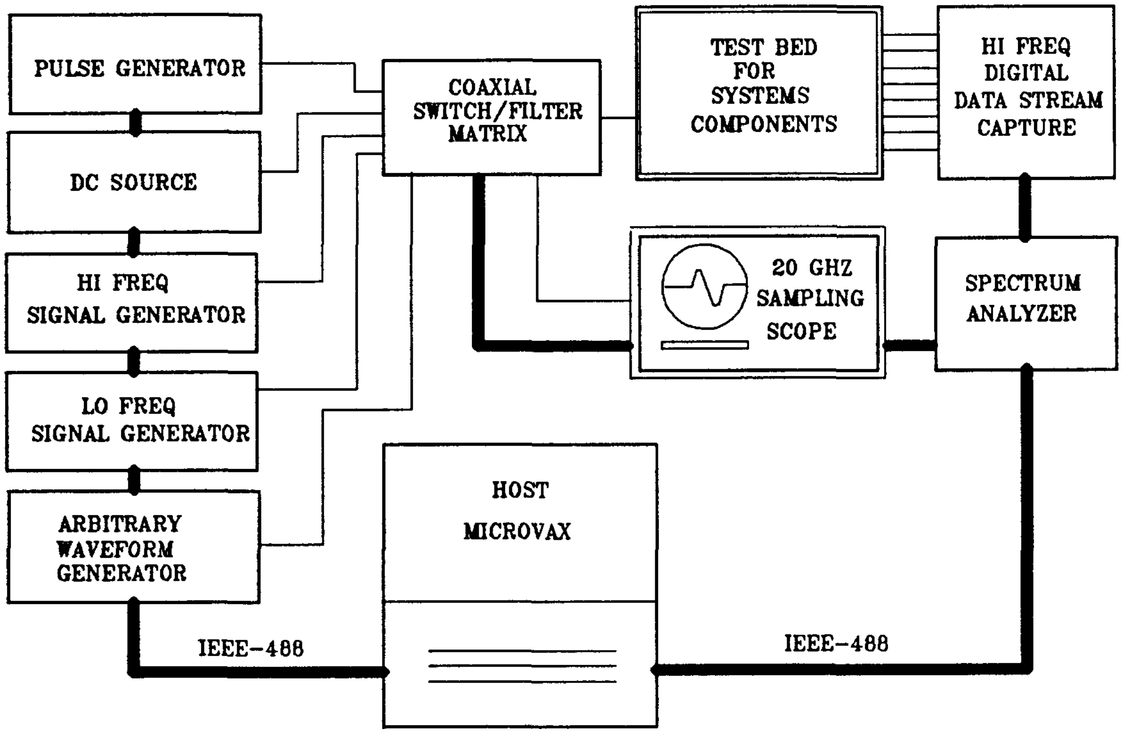


FIGURE 1. BLOCK DIAGRAM OF THE HIGH FREQUENCY EVALUATION CENTER

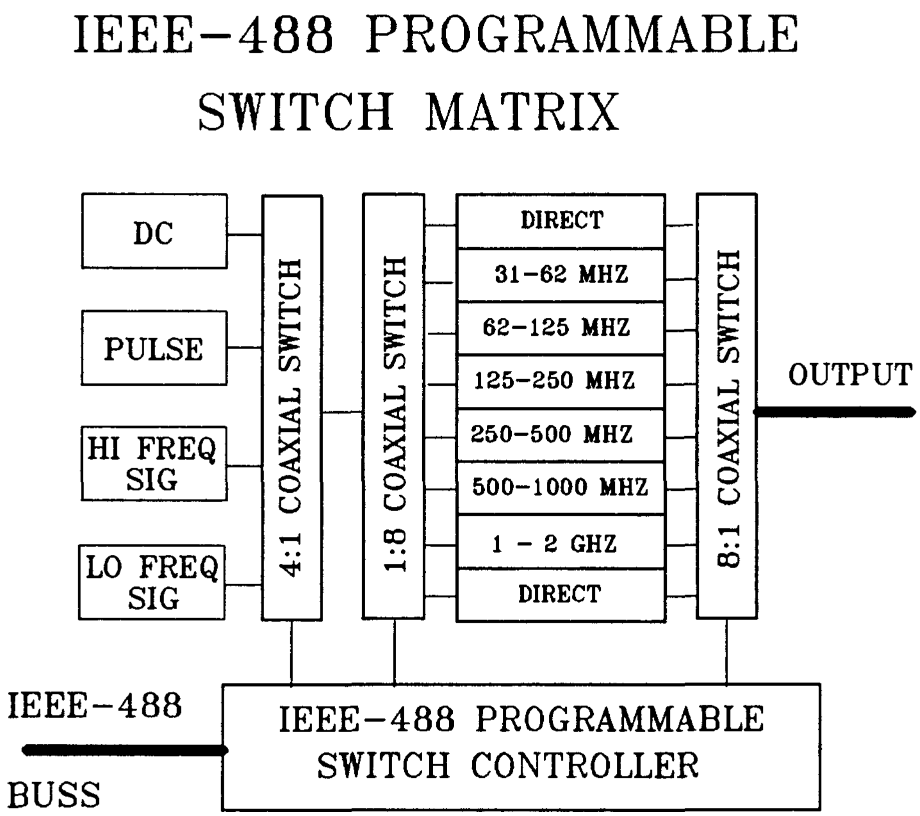
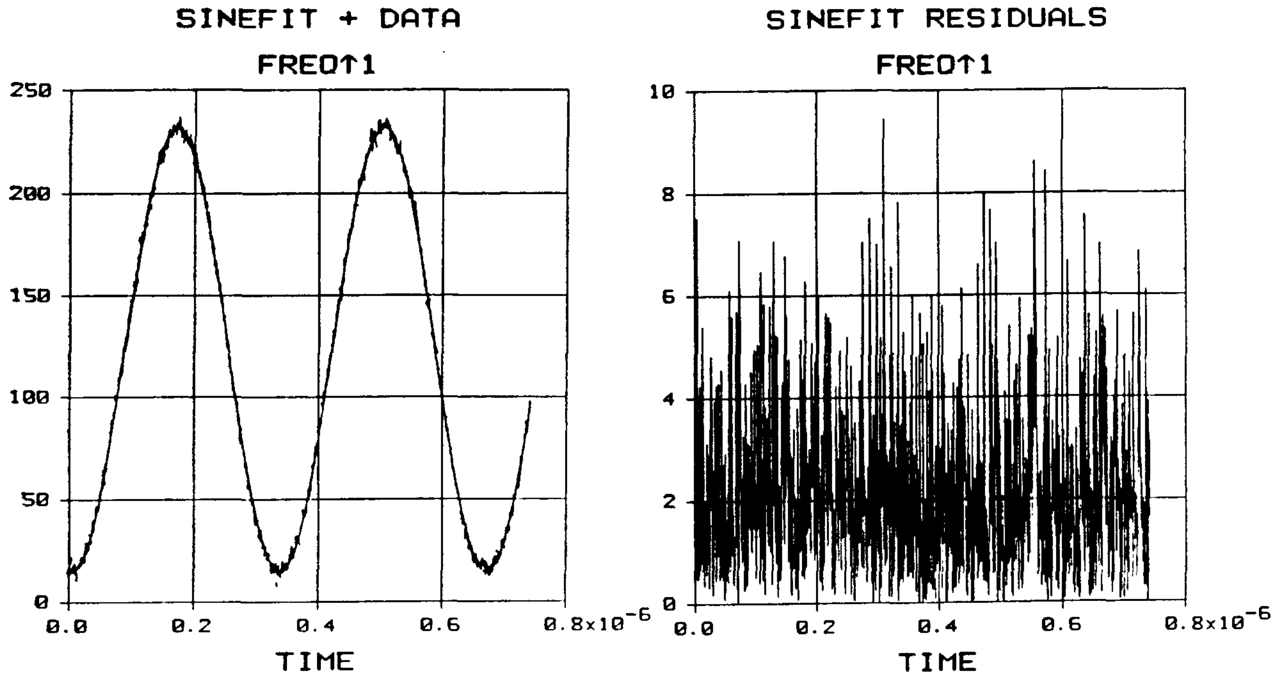


FIGURE 2. BLOCK DIAGRAM OF THE COAXIAL SWITCHING MATRIX



SINE FIT RESULTS:

OFFST: 123.2
AMPLI: 108.8
FREQY: 2.999 mhz
PHASE: -95.214 deg

RMS ERR = 2.769
IDL ERR = 0.289
EFF BITS = 4.738
OUT OF 8.0
RANGE = 217.5
# ITER. = 4

FIGURE 3. SINEWAVE FIT WITH RESIDUALS AND FIT PARAMETERS

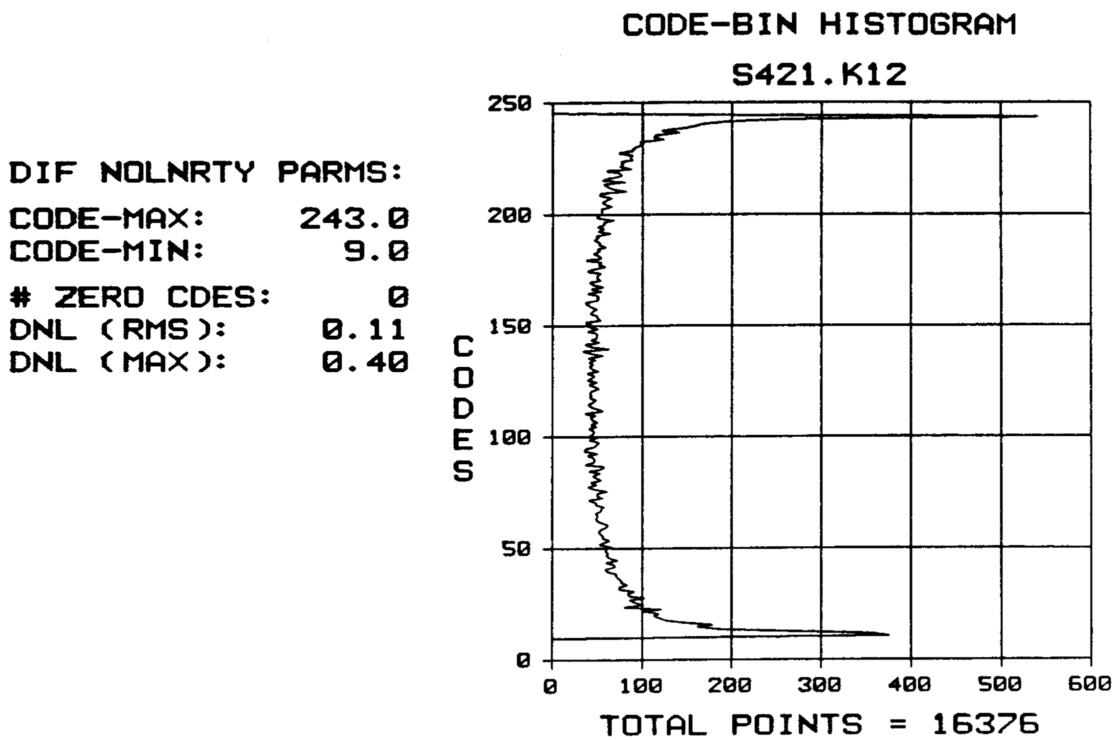


FIGURE 4. CODE-BIN HISTOGRAM

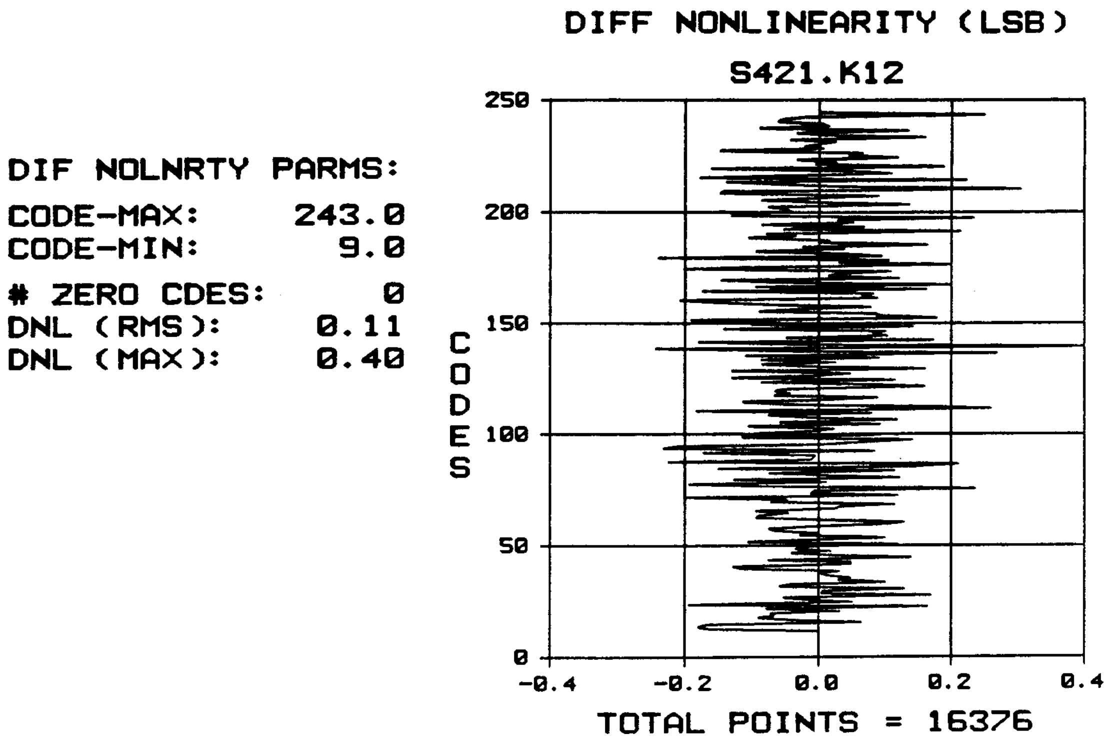


FIGURE 5. DIFFERENTIAL NONLINEARITY PLOT: DNL(k)

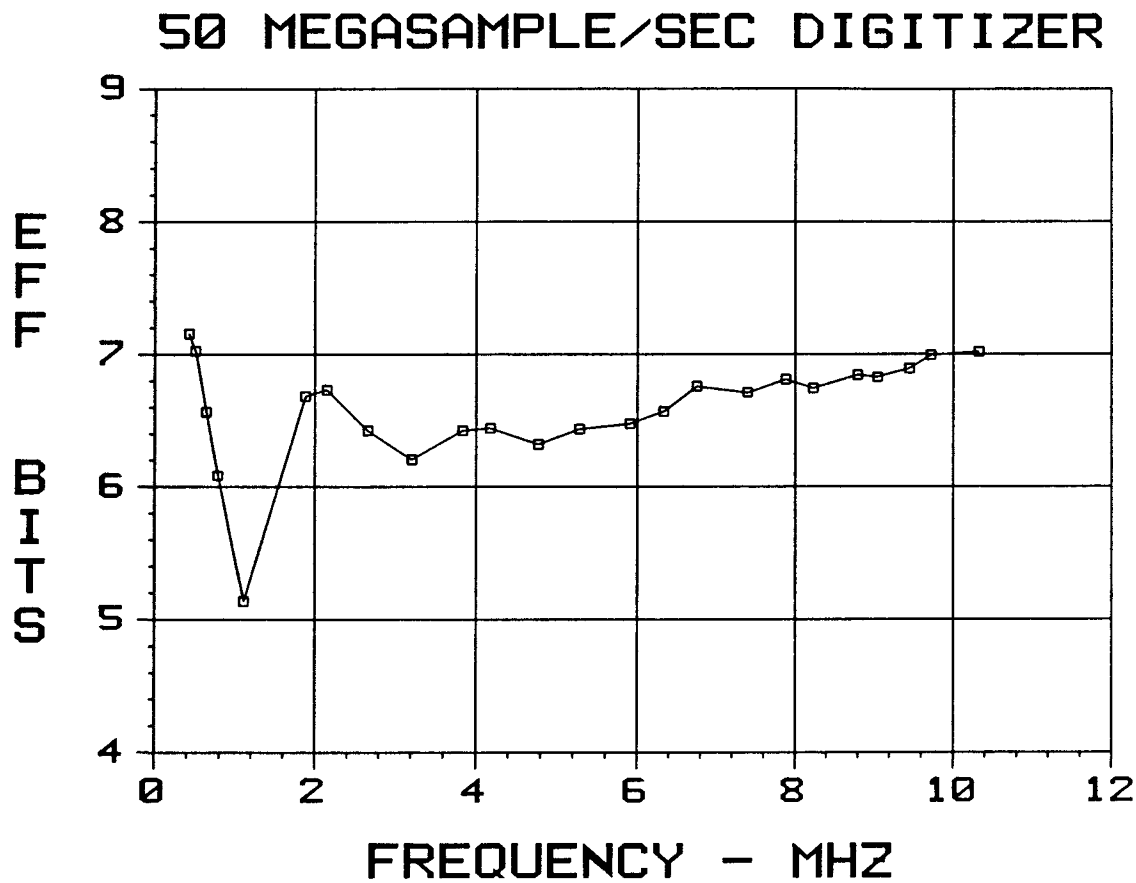


FIGURE 6. EFFECTIVE BITS: 50 MEGASAMPLE/SECOND DIGITIZER

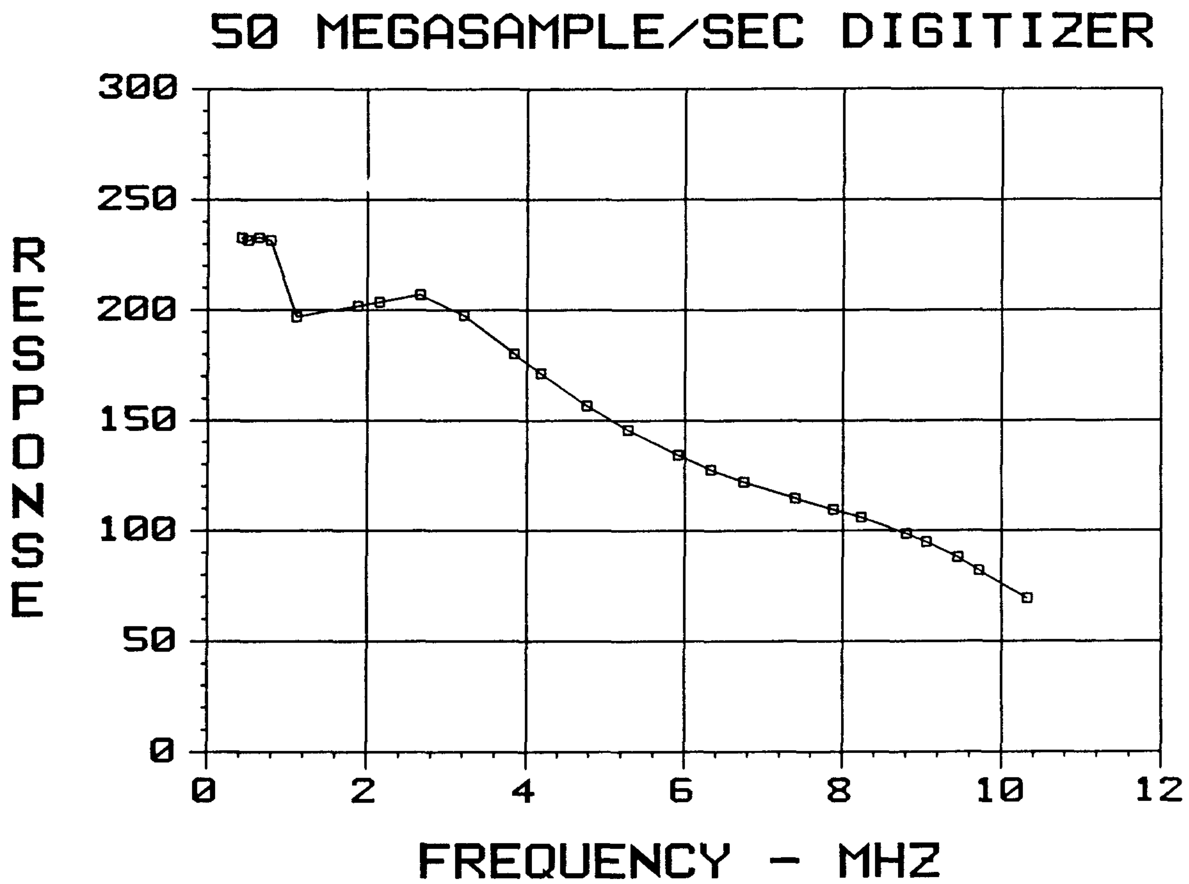


FIGURE 7. RESPONSE CURVE: 50 MEGASAMPLE/SECOND DIGITIZER

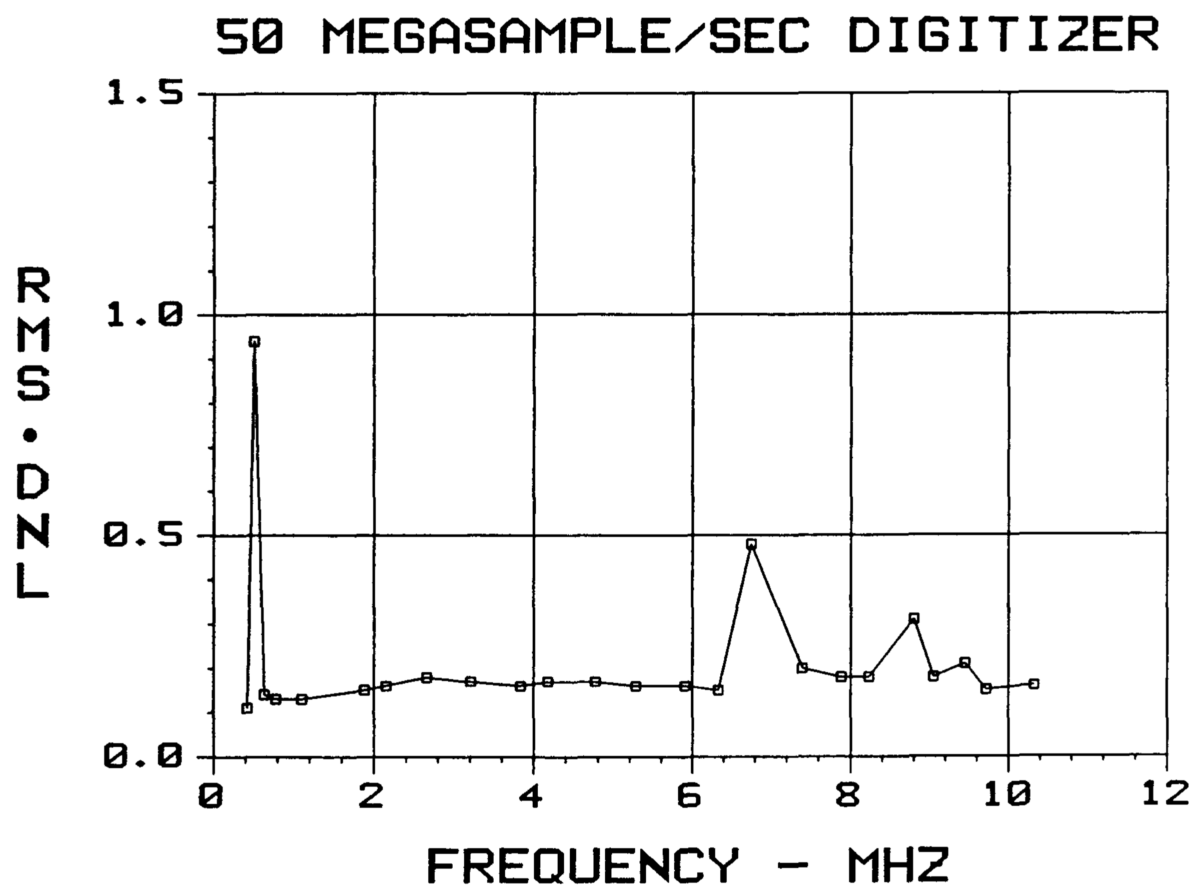


FIGURE 8. RMS DIFF-NONLINEARITY: 50 MEGASAMPLE/SECOND DIGITIZER