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EFFECTIVE WAVEFORM RECORDER EVALUATION PROCEDURES

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ABSTRACT

The evaluation of waveform recorders is a subject attracting considerable attention as waveform recorders continue to increase in capabilities without dramatic increase in costs. However, caution is required when developing evaluation procedures because of the potential of any evaluation procedure to overestimate the performance of a device. Here we describe a system which is controlled by a Microvax II with instrumentation control through the IEEE-488 bus. Evaluation procedures are described with attention given to the "pathological cases" which can lead to significant misestimates of a digitizer's performance. These evaluation procedures are aimed at being consistent with the new Trial Waveform Digitizer Standard [1] generated by the Waveform Measurements and Analysis committee appointed by the Instrumentation and Measurement Society of IEEE. This standard has been recently accepted by the IEEE as a trial use standard through July 1991 and is available from the IEEE Service Center as IEEE Std. 1057.

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. 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 completed work on a Trial Use Standard which was adopted by the IEEE and is available now as a published trial standard. 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. An arbitrary waveform generator capable of outputting 200 megapoints/sec. is also included. The high frequency 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 set of tunable octave bandpass 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 best-fit sinewave to be bracketed by a magnitude of 0.07 LSB (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 allows only valid input commands and reads following parameters, recognizing space or comma delimiters between parameters. 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 an 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 an iterative least-squares minimization 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 ideal measurement resolution, it can be shown that the root-mean-square error is 0.289 [1]. 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 LSB). Here 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 (peak-to-peak value) of the fitted sinewave. This 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]

$$DNL(k) = W(k)/Q - 1$$

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]

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

where P(k) is the probability for code k given that the input is a sinewave. P(k) is given by [1]

$$P(k) = \frac{1}{\pi}\left\{\sin^{-1}\left[\frac{V(k-2^{N-1})}{A2^N}\right] - \sin^{-1}\left[\frac{V(k-1-2^{N-1})}{A2^N}\right]\right\}$$

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

The Trial Use Standard recommends overdriving the digitizer a small amount for determining DNL. It was our intent to minimize the amount of data accumulated to complete the sinewave testing. We chose to avoid overdriving the digitizer so that the same data array can be used for DNL determination and for sinewave fitting. 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. Figure 4 shows 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. 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

The frequencies at which evaluations are to be made are selected. Care must be taken to avoid test frequencies which are harmonically related to the sample frequency. The signal generator output is routed through the set of six octave tunable notch filters. 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 non-linearity are plotted as a function of frequency to complete the basic digitizer evaluation.

DIGITIZER EVALUATION EXAMPLES

The Trial Use 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, cross-talk, 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 waveform recorder evaluation are shown in figures 5 - 7. 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 increases as amplitude decreases. 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.

Evaluations are also valuable at the component level. Figure 8 shows the results of evaluating a 250 megasample/second unit using a high-speed logic analyzer to capture the 250 megabyte/second data stream. The unit shows 4.6 effective bit performance out of 8 bits. Visual examination of the residuals is again very useful in picking out repetitive coding errors in the unit. This particular unit had the very unusual property that it miscoded dramatically on non-successive positive-going edges. This is evident from the spikes in the residuals plot.

The Trial Use Standard for Digitizers also addresses the issue of avoiding "pathological" test conditions. These are conditions which can lead to erroneous evaluation results that can be significantly worse or better than the actual performance. In figures 9 and 10 we show an example of an evaluation which indicates very large differential nonlinearity and many missing codes from the digitizer. However, the sinewave fitting evaluation indicates a very good performance of near 7 effective bits out of 8. This misleading differential nonlinearity occurs because the number of samples per cycle is an exact integer number. The sample rate is 50 megasamples/sec. and the signal frequency is 500 kilohertz which gives exactly 100 points per cycle. Sampling the signal at the same points during a cycle can also lead to extreme effective bits values. However, this effect is significant when the number of points per cycle is small. Here we are sampling the sinewave at 100 points per cycle which gives a good estimate of the RMS error.

Another look at figure 9 reveals a point that requires attention. In order for the effective-bits determination to be accurate, the input sinewave must be very pure. Otherwise, it is incorrect to calculate an RMS error based on the assumption that the input is purely sinusoidal. In figure 9 the plot of residuals reveals a definite periodic pattern. This may be caused by systematic digitizing errors but is more likely to be the result of having an input that contains harmonic distortion so that a significant fraction of the residuals simply reflects the non-pure input. In this particular case, although the digitizer performance was almost 7 bits out of 8, nearly 0.6 effective bits degradation was the result of having an input containing harmonic distortion.

Figure 11 indicates the effect of filtering an array of digital data consistent with the analog bandwidth of the digitizer. Figure 3 was a sinewave fit for a digitizer with a sample rate exceeding 1 gigasample/sec. However, the analog bandwidth for the digitizer is significantly lower than the Nyquist frequency for the digitizer or near 350 MHz. The result of simply applying a lopass filter with 350 MHz cutoff is shown in the effective bits plot of figure 11. It can be seen that a significant improvement in effective bits performance is shown. Filtering consistent with the bandwidth of the digitizer is, in general, legitimate. However, the rolloff of the digitizer may vary significantly from the typical lopass filter rolloff affecting the accuracy of this filtering in determining digitizer performance.

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 5 - 7 were selected to show their effectiveness in revealing problems with a digitizer. For this particular 50 megasample/second unit the general performance was unsatisfactory. The effective bits curve of figure 5 showed anomalous behavior near 1 MHz and also appeared to increase with frequency. The frequency response curve of figure 6 (in arbitrary units) shows a very broad-band rolloff which confuses the issue of effective bits for this digitizer. Uniform valued inputs into the waveform recorder did not lead to uniform inputs to the digitizer portion of the recorder. The result was that smaller amplitude signals were being digitized at the higher frequencies. In general the effective bits measure of a digitizer increases as the amplitude is reduced. Clearly the DNL plot of figure 7 shows some problems with differential nonlinearity at frequencies near 1 MHz, 7 MHz, and above 8 MHz. The effective bits curve showed unusual problems at low input frequencies which were associated with poor matching characteristics of interleaved 25 megasample/second ADCs.

Figure 9 - 10 emphasized the care necessary to avoid "pathological" conditions (sometimes referred to as "sweetspots") in the evaluation of digitizers. In this example we showed a condition that led to the determination of an evaluation parameter much inferior to its actual value. An example of the "sweetspot" condition is the possibility

that one can measure an effective bits performance of over 11 bits for an 8-bit digitizer if the ratio of the sample frequency to the input sinewave frequency is a small integer value.

REFERENCES

[1] Trial Use Standard for Digitizing Waveform Recorders, prepared by the Waveform Measurements and Analysis Committee of the IEEE Instrumentation and Measurement Society, published by IEEE as Trial Use Standard 1057.

[2] Interactive Data Reduction Program, Bill Boyer, Div. 9321, Sandia National Labs.

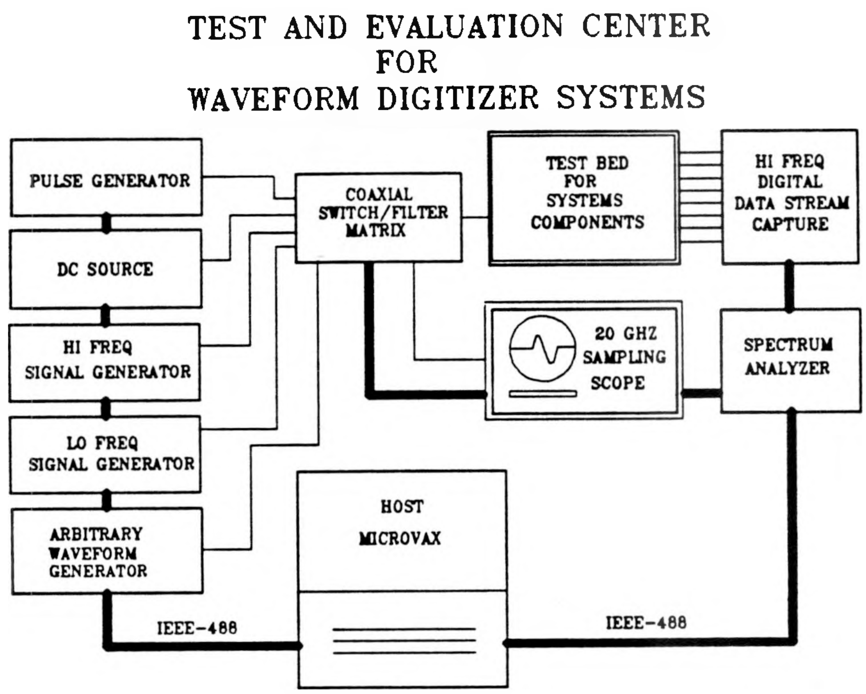


FIGURE 1. BLOCK DIAGRAM OF THE HIGH FREQUENCY EVALUATION CENTER

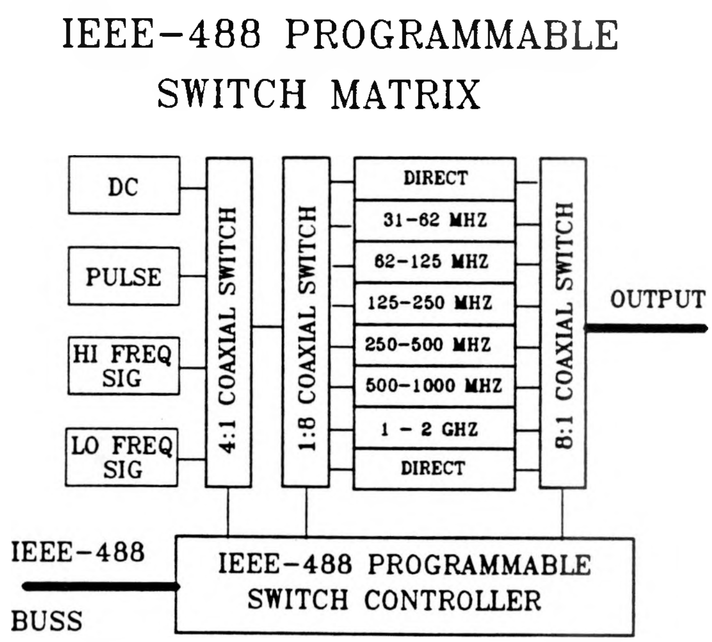


FIGURE 2. BLOCK DIAGRAM OF THE COAXIAL SWITCHING MATRIX

TEST AND EVALUATION CENTER
FOR
WAVEFORM DIGITIZER SYSTEMS

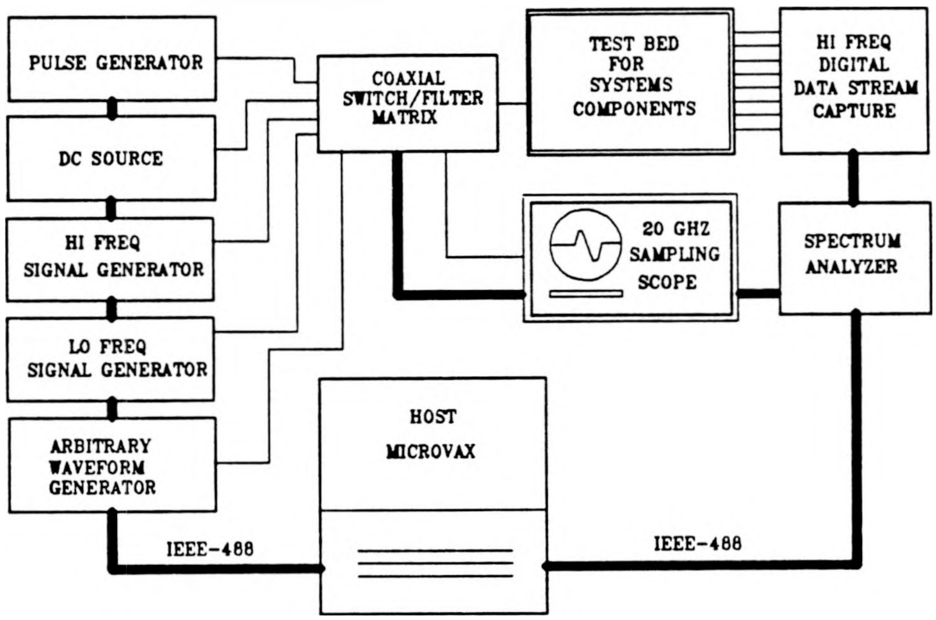


FIGURE 1. BLOCK DIAGRAM OF THE HIGH FREQUENCY EVALUATION CENTER

IEEE-488 PROGRAMMABLE SWITCH MATRIX

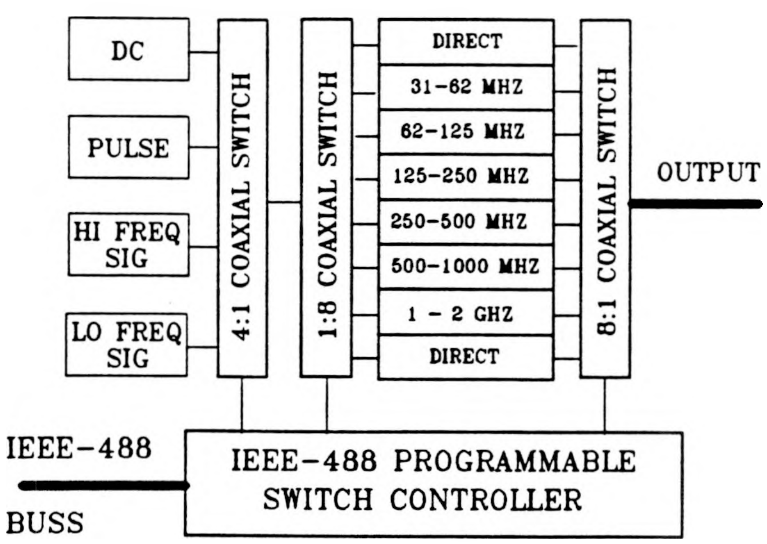
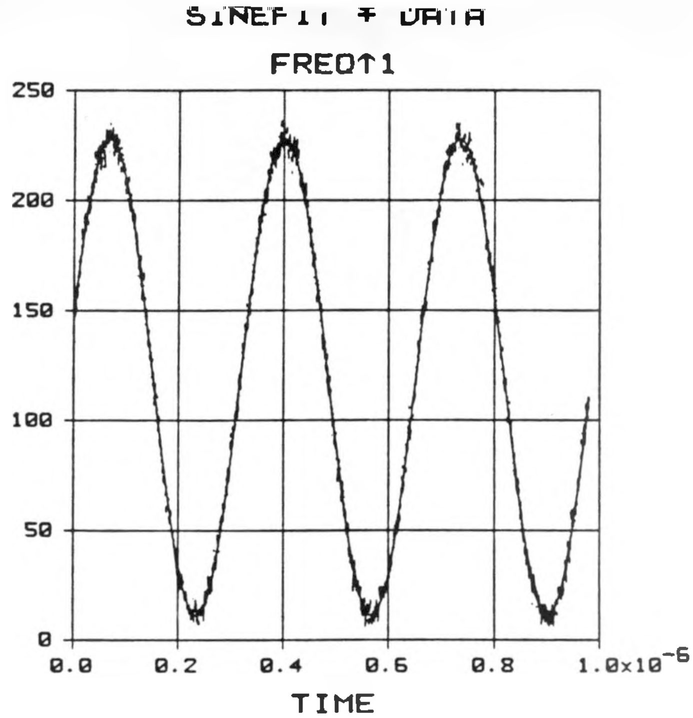
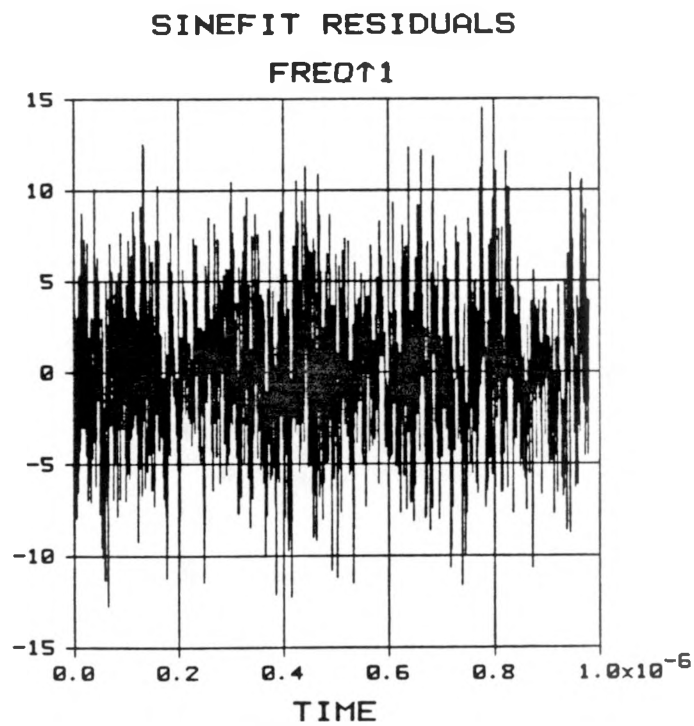


FIGURE 2. BLOCK DIAGRAM OF THE COAXIAL SWITCHING MATRIX



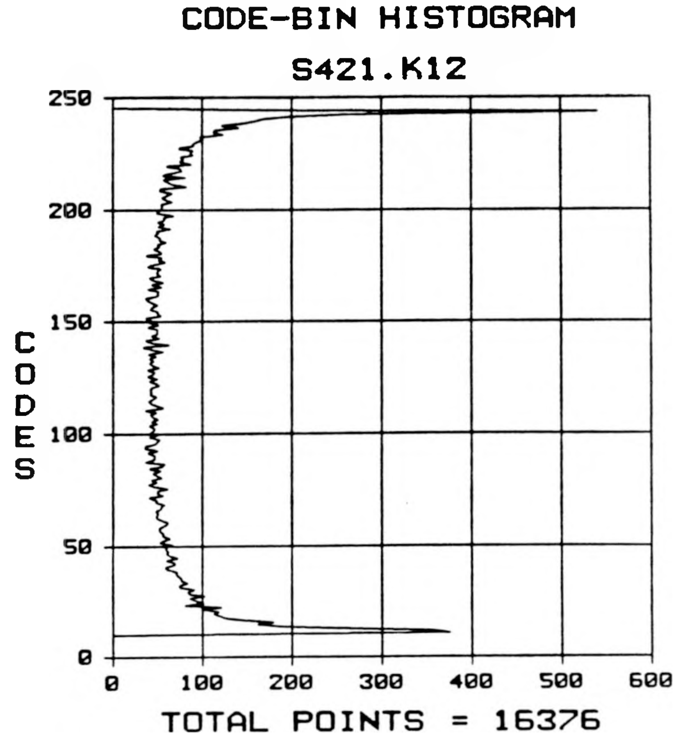


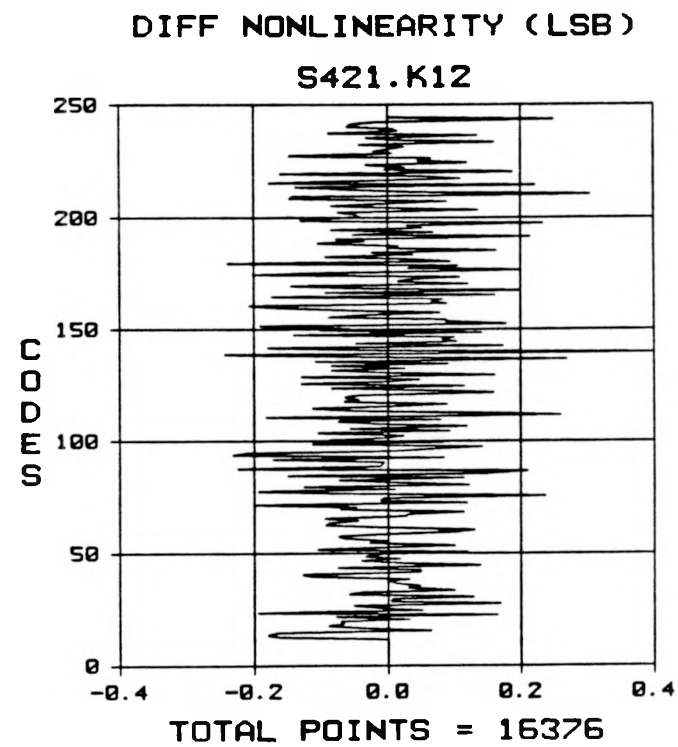
SINE FIT RESULTS:

OFFST: 119.5
AMPLI: 108.5
FREQY: 3.002 mhz
PHASE: 15.970 deg

RMS ERR = 4.449
IDL ERR = 0.289
EFF BITS = 4.054
OUT OF 8.0
RANGE = 217.0
# ITER. = 5

FIGURE 3. SINEWAVE FIT WITH RESIDUALS AND FIT PARAMETERS





DIF NOLNRTY PARMS:

CODE-MAX:	243.0
CODE-MIN:	9.0
# ZERO CDES:	0
DNL (RMS):	0.11
DNL (MAX):	0.40

FIGURE 4. CODE-BIN HISTOGRAM AND DIFFERENTIAL NONLINEARITY PLOT: DNL(k)

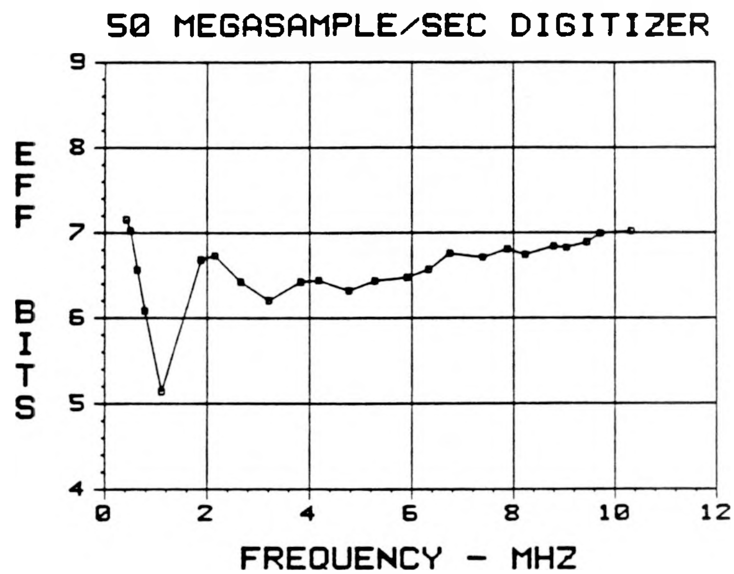


FIGURE 5. EFFECTIVE BITS:
50 MEGASAMPLE/SECOND DIGITIZER

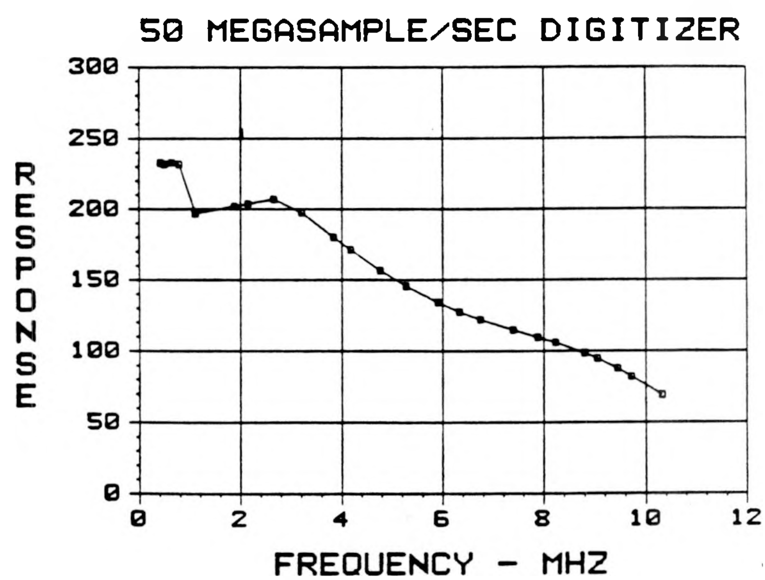


FIGURE 6. RESPONSE CURVE:
50 MEGASAMPLE/SECOND DIGITIZER

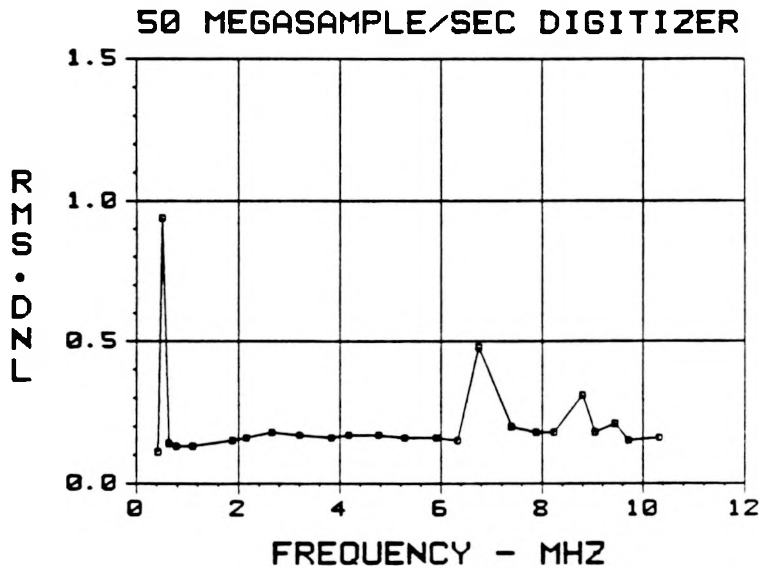
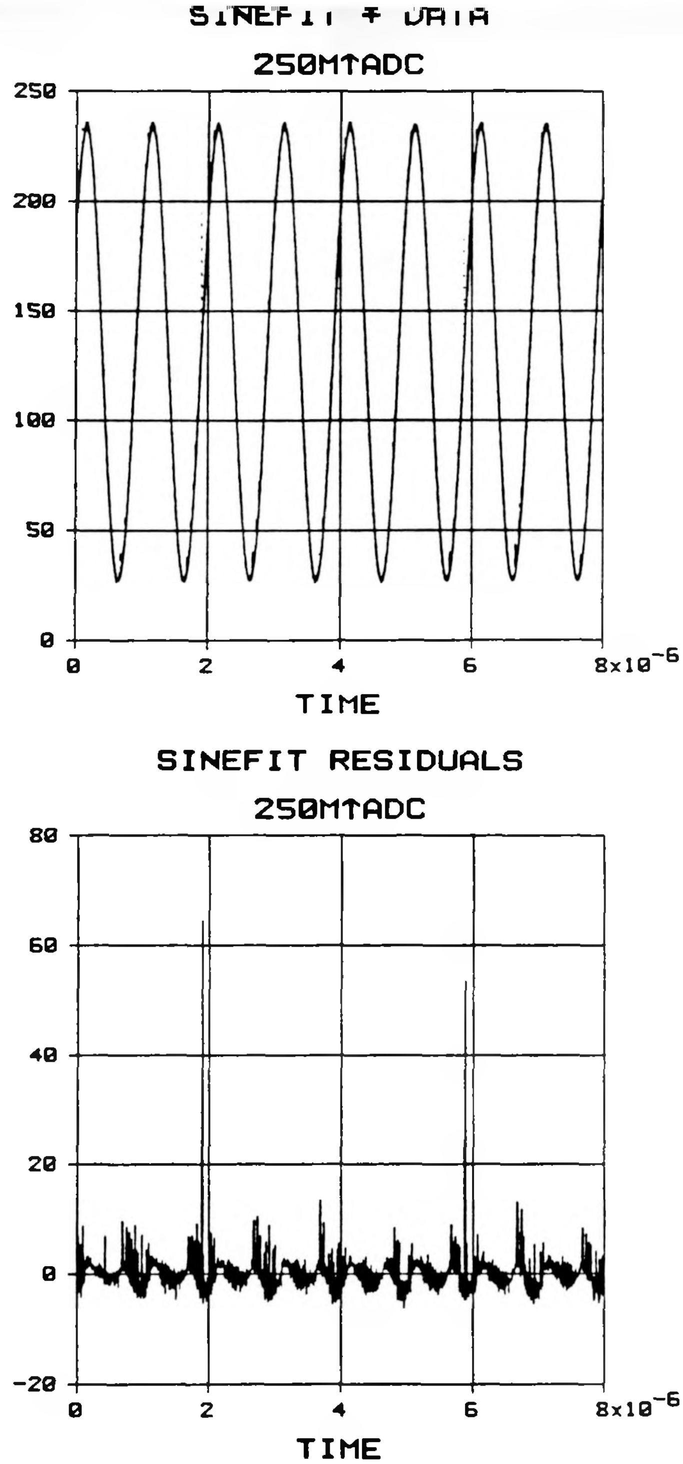


FIGURE 7. RMS DIFF-NONLINEARITY:
50 MEGASAMPLE/SECOND DIGITIZER



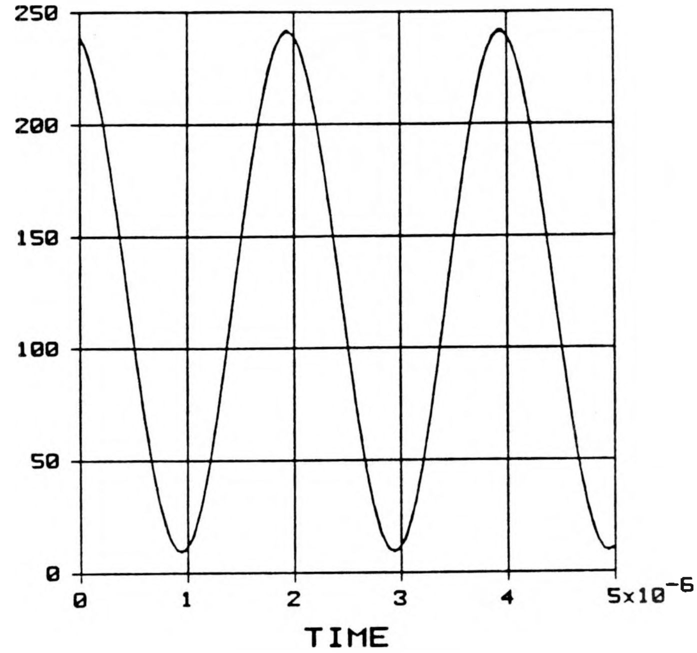
SINE FIT RESULTS:

OFFST:	130.1
AMPLI:	103.0
FREQY:	1.004 mhz
PHASE:	34.172 deg
RMS ERR =	3.060
IDL ERR =	0.289
EFF BITS =	4.594
OUT OF	8.0
RANGE =	206.0
# ITER. =	4

FIGURE 8. SINEWAVE FIT:
250 MEGASAMPLE/SECOND COMPONENT

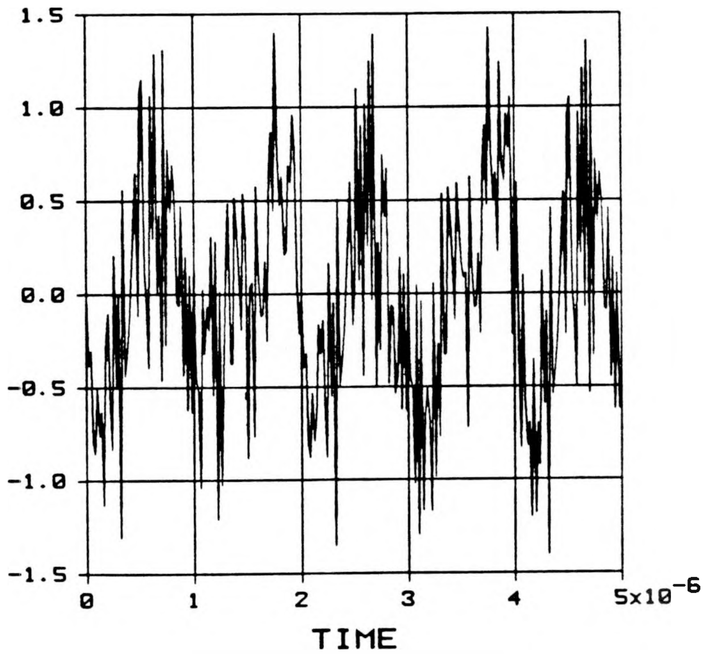
SINEFIT + DATA

S500.K52



SINEFIT RESIDUALS

S500.K52

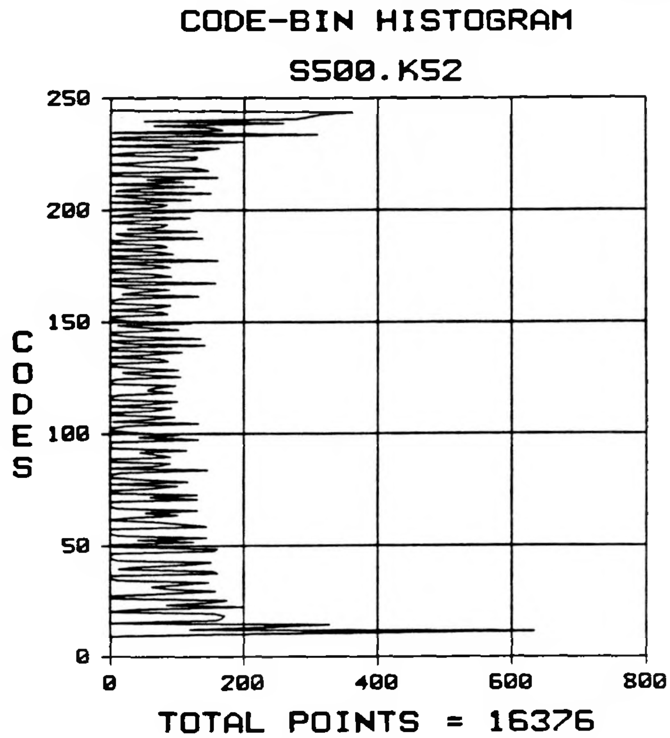


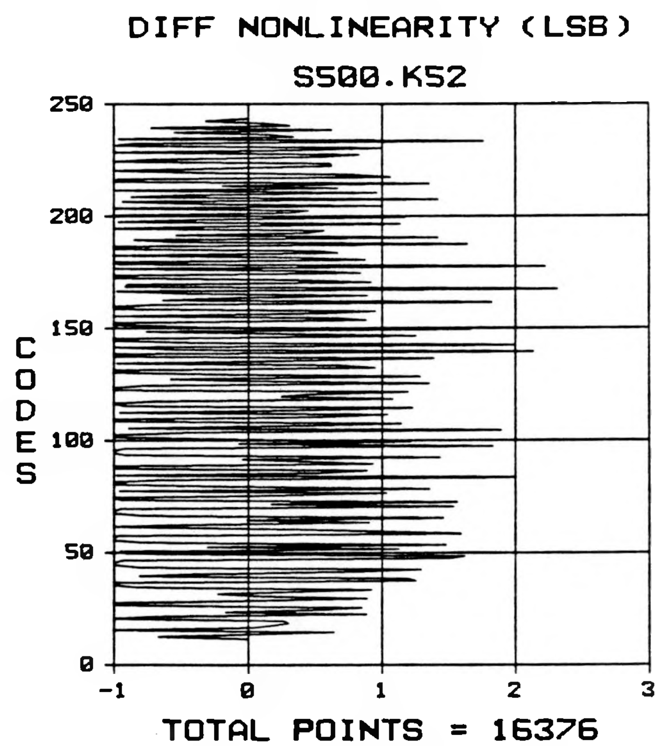
SINE FIT RESULTS:

OFFST: 125.4
AMPLI: 115.8
FREQY: 0.500 mhz
PHASE: 101.201 deg

RMS ERR = 0.614
IDL ERR = 0.289
EFF BITS = 6.911
OUT OF 8.0
RANGE = 231.6
# ITER. = 4

FIGURE 9. SINEWAVE FIT:500 KHZ INPUT SIGNAL





DIF NOLNRTY PARMS:

CODE-MAX:	242.0
CODE-MIN:	9.0
# ZERO CDES:	48
DNL (RMS):	0.94
DNL (MAX):	2.31

FIGURE 10. CODE-BIN HISTOGRAM FOR THE 500 KHZ SIGNAL ALONG WITH THE DIFFERENTIAL NONLINEARITY PLOT: DNL(k)

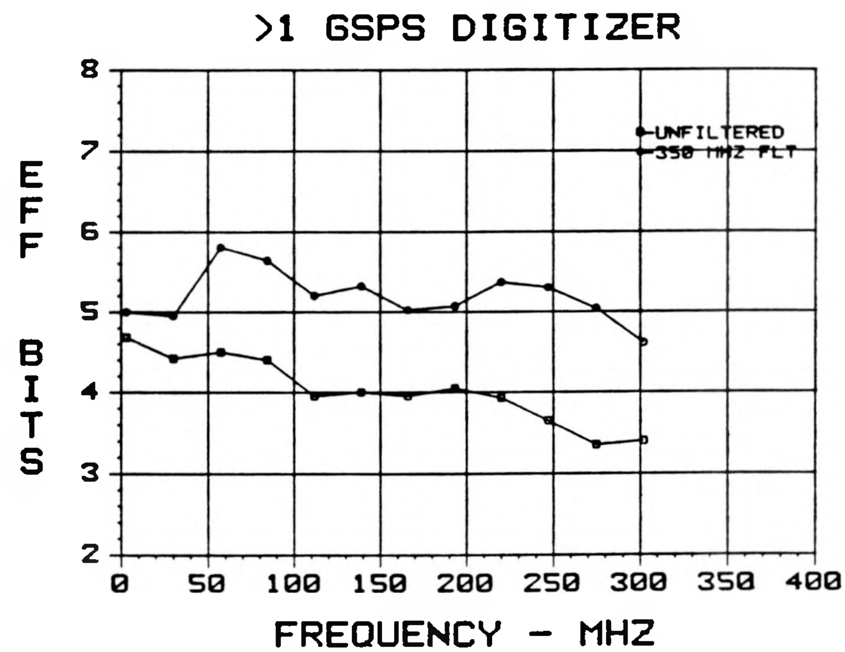


FIGURE 11. EFFECTIVE BITS FOR
>1 GIGASAMPLE/SECOND DIGITIZER:
UNFILTERED AND FILTERED DATA