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General Performance of the SANDUS Digitizers

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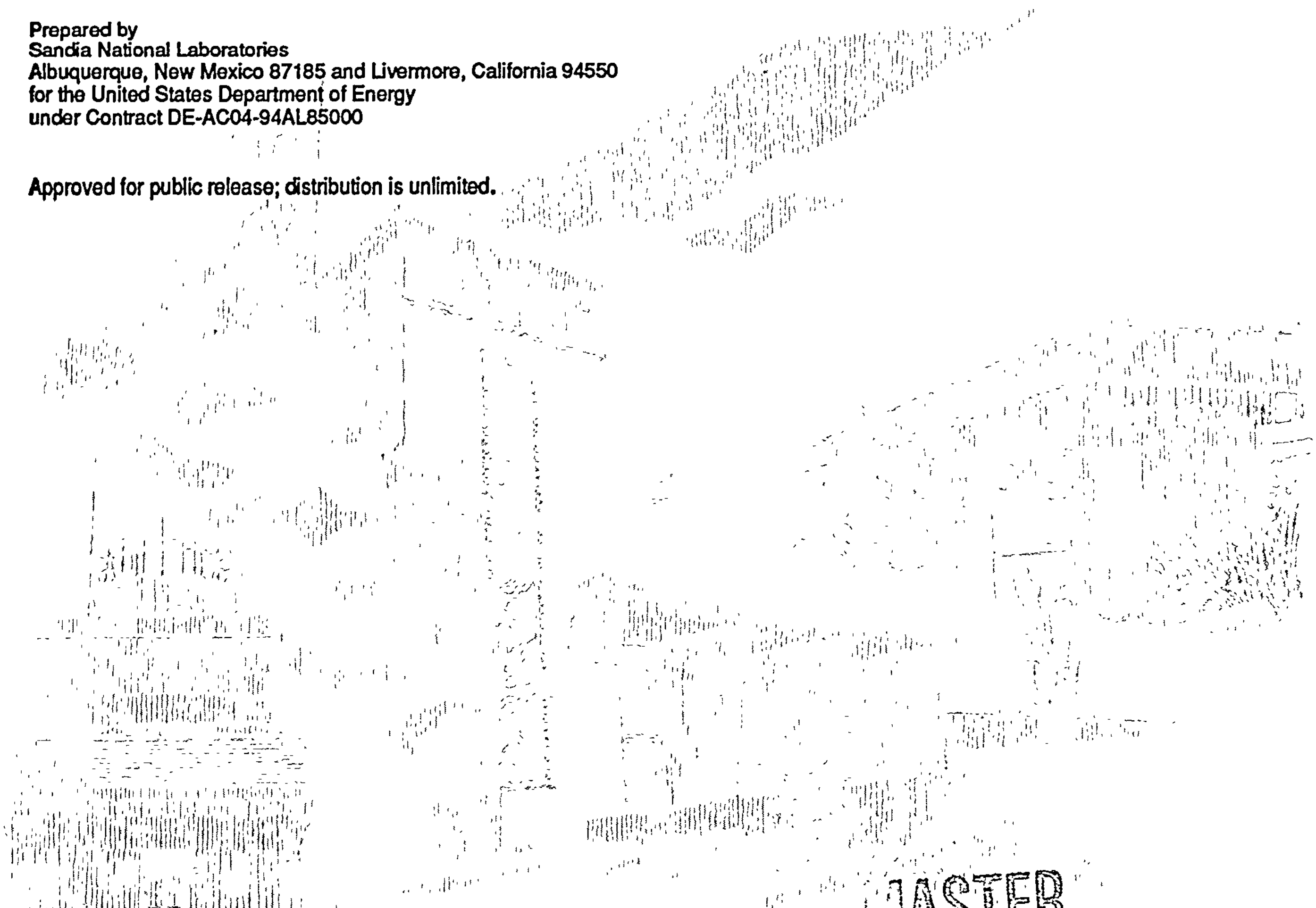

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ABSTRACT

The SANDUS (SANdia Digital Underground System) waveform digitizing system was developed by the instrumentation development division in support of underground nuclear testing and first fielded in the late 70's. This system has been successfully used for over a decade for the digitization of signals from DC to 10 Mhz. This report is intended to be a broad survey of the fundamental performance characteristics of the system. The data included herein were obtained from a small number of channels under a limited number of configurations and should provide the reader with the general range of performance parameters. As a survey, the laboratory and analytical procedures for the tests have not been detailed.

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The SANDUS (SANdia Digital Underground System) waveform digitizing system was developed by the instrumentation development division in support of underground nuclear testing and first fielded in the late 70's. This system has been successfully used for over a decade for the digitization of signals from DC to 10 Mhz. This report is intended to be a broad survey of the fundamental performance characteristics of the system. The data included herein were obtained from a small number of channels under a limited number of configurations and should provide the reader with the general range of performance parameters. As a survey, the laboratory and analytical procedures for the tests have not been detailed.

ACKNOWLEDGMENTS

The author wishes to acknowledge the capable efforts of Mr. Eddie Baker of Division 9321 who extensively helped with the configuration of tests. Mr. Dave Geene was also very helpful in arranging for us to run tests on SANDUS 505, one of the three SANDUS systems used in current UGT. Further acknowledgment is due Mr. James Opalka, one of the designers of the SANDUS system who patiently provided valuable detailed information about the system.

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GENERAL PERFORMANCE OF THE SANDUS DIGITIZERS

Philip J. Green

1. INTRODUCTION

This report discusses the basic performance characteristics of the SANDUS (SANdia Digital Underground System) digitizing channels. Full SANDUS specifications are published in a Sandia Report [1]. The system has the capability of recording digital and analog data. The focus here is on the waveform digitizing channels which record analog data. There are two basic types of channels which may be used. The highest frequency system is a 10 Mhz bandwidth system which can digitize at a maximum rate of 50 megasamples/second. This type of channel consists of a TA590-10 signal conditioner module and a TA592 presample filter and digitizer module which gives 8 bits of resolution or 256 levels over the analog window. This window is 4 volts at the TA592 digitizer module. This system will be referred to here for convenience as the WFD592 system. The lower frequency digitizing channel has a 100 Khz bandwidth and can sample at a maximum rate of 500 kilosamples/second. The data can be selected to be either 8-bit (256 levels) or 12-bit (4096 levels). The lower frequency channel consists of a TA5901 signal conditioner module and a TA591 presample filter and digitizer module. The lower frequency system will be referred to here at WFD591. Tables I and II provide a cursory summary of the results of this investigation.

Both the WFD591 and the WFD592 digitizers have a range of selection for gain, input offset, sample interval, and presample filter. Table III shows the possible selections for the WFD591. Selections include 8 offsets, 13 gains, 8 sample intervals, and 9 presample filter values. Similarly, Table IV indicates the range of selections for the WFD592 channels. There are 8 offsets, 9 gains, 8 sample intervals, and 6 presample filter settings.

The overall system performance is checked with an extensive test program called DHTEST. This test program examines all parts of the system as well as the basic analog performance of the channels. Table V lists the tests performed. A calibrator unit (TA489) is integrated into the system and is used for the tests that relate to data integrity. These are OFFSET CHECKS, FILTER AND SAMPLE INTERVAL CHECKS, SIGNAL GAIN CHECKS, and CALIBRATION FUNCTION CHECKS. These analog performance characteristics are compared with a predetermined set of limits to determine if the channel is performing adequately. When a unit passes DHTEST, the user can be assured that the unit is functioning in the system correctly, that the settings of the actual channel match the setup table, and that the static or DC performance is satisfactory. The remainder of this report focuses on a quantitative evaluation of the full transient response of the SANDUS waveform digitizing channels.

TABLE I: SANDUS 100 KILOHERTZ CHANNEL PERFORMANCE SUMMARY

FREQUENCY RESPONSE

FILTER	-3dB	-6dB
200 KHZ	160 KHZ	210 KHZ
100 KHZ	80 KHZ	105 KHZ

DIGITIZATION ACCURACY - EFFECTIVE BITS

FILTER	AMPLITUDE	20 KHZ	100 KHZ
200 KHZ	80% FULL SCALE	7.8	6.8
	10% FULL SCALE	8.3	7.3
100 KHZ	80% FULL SCALE	7.8	7.8
	10% FULL SCALE	8.3	8.3.

OVERVOLTAGE RECOVERY

GAIN	OVERDRIVE FACTOR	RANGE OF RECOVERY TIMES
2	1.6X	negligible
20	1.6X	negligible
200	1.6X	negligible
2	16X	1 - 8 microseconds
20	16X	1 - 20 microseconds
200	16X	7 - 15 microseconds
2000	16X	8 - 15 microseconds

CROSSTALK: INSIDE SANDUS CRATES: <80 dB
AT TRANSLATOR COUPLER: <80 dB

TABLE II: SANDUS 10 MEGAHERTZ CHANNEL PERFORMANCE SUMMARY

FREQUENCY RESPONSE

FILTER	-3dB	-6dB
10 MHZ	6 MHZ	8 MHZ

DIGITIZATION ACCURACY - EFFECTIVE BITS

FILTER	AMPLITUDE	1 MHZ	4 MHZ	8 MHZ
10 MHZ	80%	6.9	5.7	4.4
10 MHZ	20%	7.0	7.3	6.4

OVERVOLTAGE RECOVERY

GAIN	OVERDRIVE FACTOR	RANGE OF RECOVERY TIMES
1	1.75X	<50 nanoseconds
10	1.75X	<50 nanoseconds
100	1.75X	<50 nanoseconds
1	17.5X	900 - 1150 nanoseconds
10	17.5X	1000 - 2300 nanoseconds
100	17.5X	1000 - 2300 nanoseconds

CROSSTALK: INSIDE SANDUS CRATES: <80 dB
AT TRANSLATOR COUPLER: <80 dB

TABLE III: Possible WFD591 settings of OFFSET, AMPLIFIER GAIN, SAMPLE INTERVAL, and FILTER

7	6	5	4	3	2	1	0
ARM	INPUT OFFSET			AMPLIFIER GAIN			

ARM	INPUT OFFSET		AMPLIFIER GAIN	
0 - Trig	000 - -FS	100 - 0	0000 - NA	1000 - 200
1 - Arm	001 - -3/4	101 - +1/4	0001 - 1	1001 - 500
	010 - -1/2	110 - +1/2	0010 - 2	1010 - 1000
	011 - -1/4	111 - +3/4	0011 - 5	1100 - 5000
			0101 - 20	1101 - 10000
			0110 - 50	1110 - NA
			0111 - 100	1111 - NA

7	6	5	4	3	2	1	0
PRE TRIG	SAMPLE INTERVAL			FILTER IDENTIFICATION			

PRE TRIG	SAMPLE INTERVAL		FILTER IDENTIFICATION	
0 - 0	000 - 400μS	100 - 20μS	0000 - 500HZ	1000 - 50KHZ
1 - 512	001 - 200μS	101 - 10μS	0001 - 500HZ	1001 - 100KHZ
	010 - 100μS	110 - 4μS	0010 500HZ	1010 - 200KHZ
	011 - 40μS	111 - 2μS	0011 - 1KHZ	1011 - 200KHZ
			0100 - 2KHZ	1100 - 200KHZ
			0101 - 5KHZ	1101 - 200KHZ
			0110 - 10KHZ	1110 - 200KHZ
			0111 - 20KHZ	1111 - 200KHZ

TABLE IV: Possible WFD591 settings of OFFSET, AMPLIFIER GAIN, SAMPLE INTERVAL, and FILTER

7	6	5	4	3	2	1	0
ARM	INPUT OFFSET			AMPLIFIER GAIN			
0 - Trig	000 - -FS		100 - 0	0000 - NA		1000 - 200	
1 - Arm	001 - -3/4		101 - +1/4	0001 - 1		1001 - 500	
	010 - -1/2		110 - +1/2	0010 - 2		1010 - NA	
	011 - -1/4		111 - +3/4	0011 - 5		1011 - NA	
				0100 - 10		1100 - NA	
				0101 - 20		1101 - NA	
				0110 - 50		1110 - NA	
				0111 - 100		1111 - NA	

7	6	5	4	3	2	1	0
PRE TRIG	SAMPLE INTERVAL			FILTER IDENTIFICATION			
0 - 0	000 - 4μS		100 - 200NS	000 - 200KHZ		100 - 1MHZ	
1 - 512	001 - 2μS		101 - 100NS	001 - 200KHZ		101 - 2MHZ	
	010 - 1μS		110 - 40NS	010 - 200KHZ		110 - 5MHZ	
	011 - 400NS		111 - 20NS	011 - 500KHZ		111 - 10MHZ	

TABLE V: List of Tests Performed by DHTEST

SR = STATUS REGISTER CHECK
DS = DATA STREAM STATUS REGISTER CHECK
OS = OFFSET CHECKS
DC = DATA CONVERSION CHECKS
TF = TRIGGER FUNCTION CHECKS
PS = PRESAMPLE TESTS
SI = FILTER AND SAMPLE INTERVAL CHECKS
DM = CHECK THE DATA MODULE ONLY
SG = SIGNAL GAIN CHECKS
CF = CALIBRATION FUNCTION CHECKS
SC = CHECK THE SIGNAL CONDITIONER ONLY
TA = TEST ALL FUNCTIONS
TS = TEST AS SET UP

2. TRANSIENT RESPONSE EVALUATION APPROACH

All Digitizer performance tests were consistent with the IEEE Trial-Use Standard for Digitizing Waveform Recorders [2]. Fundamentally we wish to inject a series of dynamic signals that include frequency components from DC to beyond the bandwidth limits of the waveform digitizer channel design. We digitize these signals, reconstruct the waveform from the digital array data, and compare the reconstructed result with the input. We examine, in particular, the frequency response of a channel, the effective-bits measure (or digitizing accuracy) of the waveform digitizer, and the recovery characteristics of the signal conditioning amplifiers from various inputs which overdrive the input window limit of the channel. Further significant tests include a measure of crosstalk between channels in crates and timing relationship between channel trigger and first recorded data. Each of these measurements will be briefly discussed and representative results presented.

The overall goal of this study is to develop a production test procedure that will allow quantification of all the critical performance parameters for a channel. Detailed attention to the data procurement procedure and document generation are required since we have three SANDUS units, each handling 128 waveform digitizer channels (total = 384 channels), and we have board level inventory to field nearly 500 more channels in other configurations. A four-hour bench process with 1 hour of computer analysis and graph generation is not reasonable for such a large number of channels.

3. WFD591 PERFORMANCE CHARACTERISTICS (100 KILOHERTZ CHANNELS)

The WFD591 digitizer has sample interval settings from 2 microseconds (or 500 kilosamples/second) to 400 microseconds (or 2.5 kilosamples/second). The presample filter settings are designed to effect appropriate antialiasing filtering. The dynamic performance of a waveform recorder channel is normally the most degraded at its highest signal frequencies and maximum sample rates. The WFD591 was examined at its highest sample rate (500 ksps) and two highest filter settings (100 Khz and 200 Khz). The 200 Khz filter setting is actually a bypass of all filtering with the signal conditioning amplifiers providing the only filtering. At present, the setup software for the UGT shots does not allow this "filter-bypass" setting.

3.1 GAIN ERRORS - WFD591

In DHTEST offsets at seven levels are input and the digitally recorded output is required to be within ±7 counts (out of 4096) of a nominal value at the highest and lowest offsets. This acceptance window reduces to ±4 counts at the center of the analog window. To be considered acceptable, the gain results must be satisfied at all seven levels. Statistically this implies that deviations from linearity will be significantly smaller than the allowed window at any single level. Furthermore, the full calibration procedures followed in system operation remove any gain-error concerns.

3.2 STEP RESPONSE AND FREQUENCY RESPONSE - WFD591

A waveform digitizer samples the input signal at fixed intervals. In this test, the sampling was every 2 microseconds. The frequency response of an analog system can be derived from the response of the system to a step input. The ideal step input makes the transition from the baseline level to some fixed level in a time very short compared to the risetime of the analog system being tested. In this case a series of input steps were programmed into an arbitrary waveform generator. The expected risetime of a WFD591 channel at the 200 Khz filter setting is near 2 microseconds. The step time of the input AWG was about 6 nanoseconds. Since the expected risetime is on the order of the sample interval, we cannot expect to obtain more than 2 or 3 samples of the actual step transition. We need a detailed record of the step response in order to get an accurate indication of the frequency response. We accomplish this by precisely staggering the input step pulses in time so that we can overlay them to obtain more sample points on the transition edge. Figure 1 shows an average of the recorded pulse for the filter setting of 200 Khz. For the WFD591 we were able to do interleaving by a factor of 8. The subsequent detail provided for the step response is shown in figure 2. With this interleaving process we were able to get some 10 or 12 points on the fastest part of the transition (10% to 90% part). With single sampling we would have gotten 1 or 2 points only. Figure 3 shows the resultant frequency response of the system. From the figure it can be seen that the output is down by nearly a factor of 2 or by 6 dB at 200 Khz. The rolloff is rather broad, the 3 dB point being near 160 Khz. Figures 4, 5, and 6 give similar information for the WFD591 with a 100 Khz filter setting. We see that the output is near the 6 dB point at the 100 Khz characteristic frequency of the filter. The 3 dB point is near 76 Khz. Again the rolloff is quite broad. It should be mentioned that these characteristics are consistent with the original design specs. The filters were specified to be high quality monotonic filters whose output would be down by 6 dB (0.5) at their characteristic frequency. This is mentioned because the characteristic frequency of an analog system is typically expected to be the 3 dB point or the frequency at which the output is down by 0.707.

Figure 7 simply gives a comparison plot for the 100 Khz and 200 Khz filter settings. We should note here that the 200 Khz "filter" setting is actually a bypass of the presample filter system so that the 200 Khz filtering is actually done by the amplifier. Figure 8 overlays the response curves for comparison.

3.3 EFFECTIVE BITS (DIGITIZATION ACCURACY) - WFD591

A series of 12 sinewaves ranging in frequency from 2.67 Khz to 111 Khz were generated by the AWG and input to the WFD591. The channel has a 12-bit digitizer and gives codes outputs from 0 to 4095. The measure of effective bits reflects the basic precision of the digitizing process. The effective bits plot of figure 9 shows values near 8.0 with a dropoff to 6.5 bits at the highest frequency of 111 Khz. This plot is for the WFD591 with a filter setting of 200 Khz. If the internal filter setting is 100 Khz, the result of figure 10 is obtained. A 7.8 effective bit figure means that the accuracy of digitization is about 1/(2**7.8) or ±0.22%. This precision result, called effective-bits, is amplitude dependent. Typically measurements are made at 80-90% full-scale and at 10-20% scale. The effective bits results at the lower amplitudes are better. For

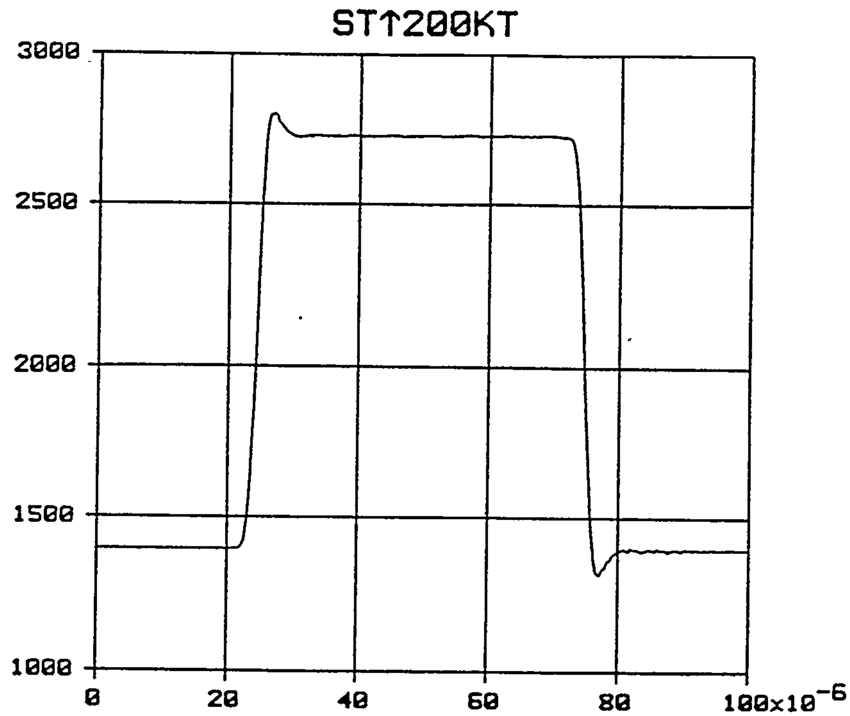

Figure 1: Recorded pulse to WFD591, equivalent-time sampled with filter setting of 200 Khz

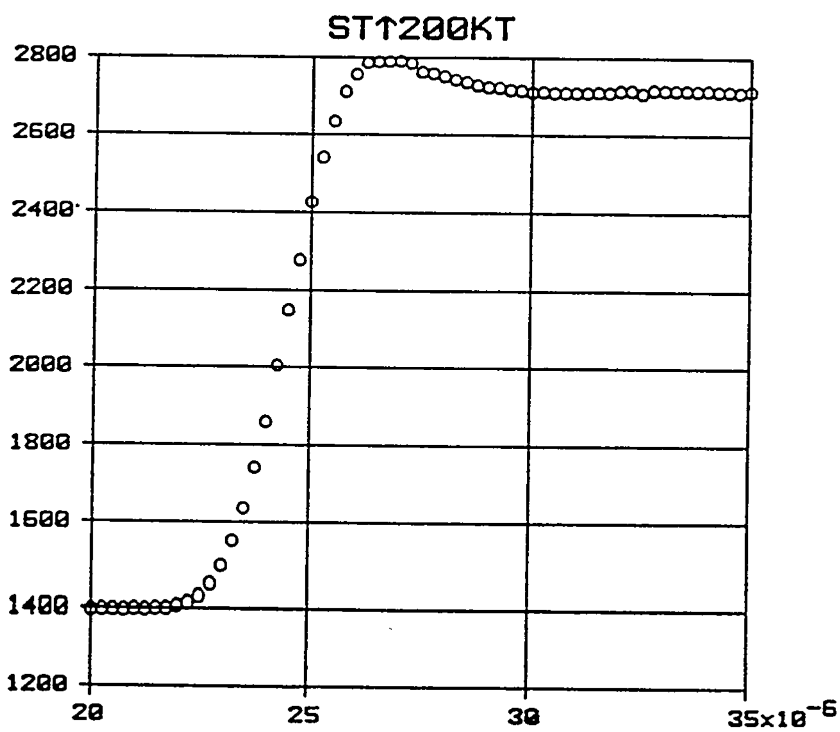

Figure 2: Recorded pulse to WFD591, detail of the leading-edge samples for 200 Khz filter setting

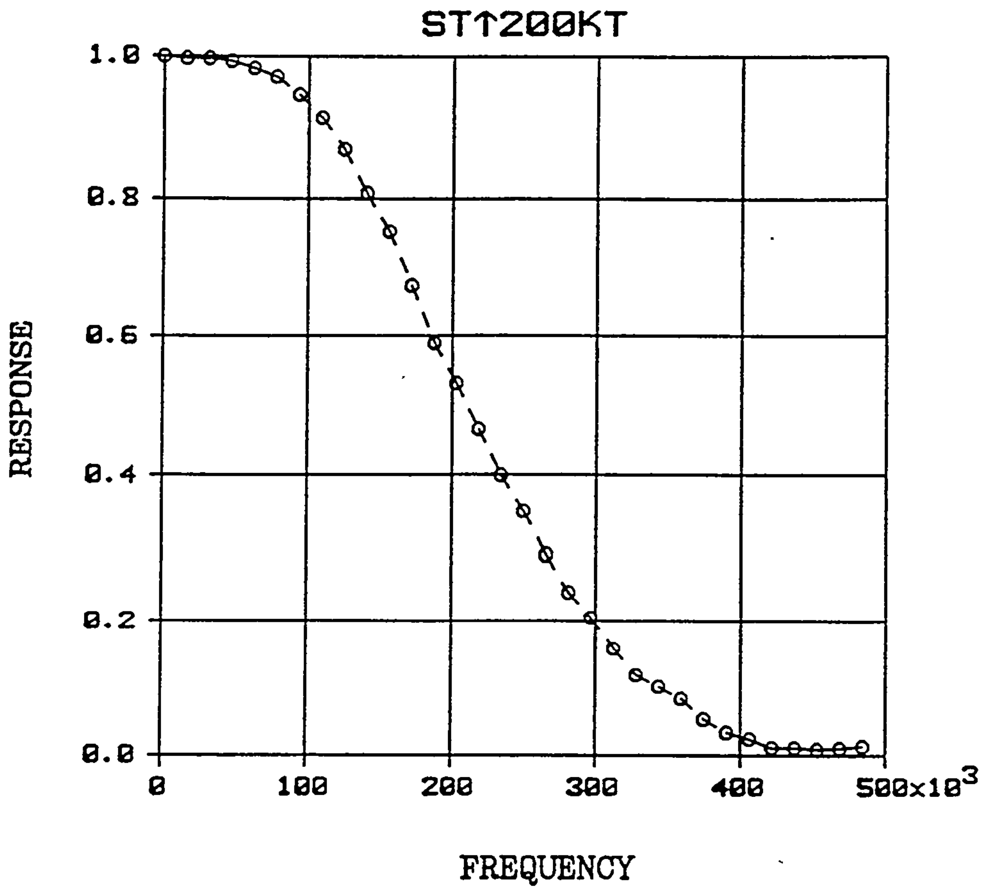

Figure 3: Frequency response curve for the WFD591, 200 Khz filter setting

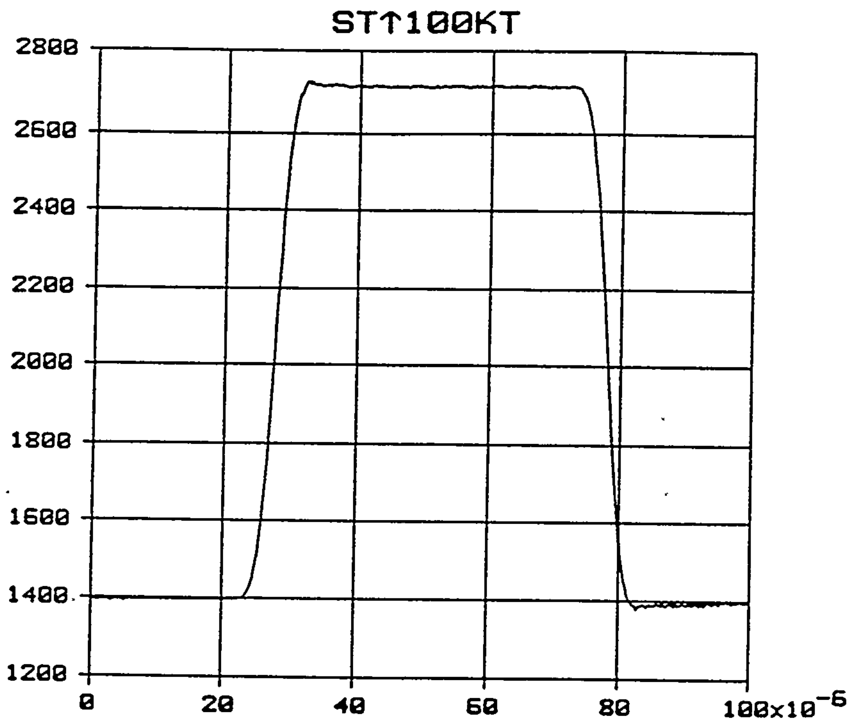

Figure 4: Recorded pulse to WFD591, equivalent-time sampled with filter setting of 100 Khz

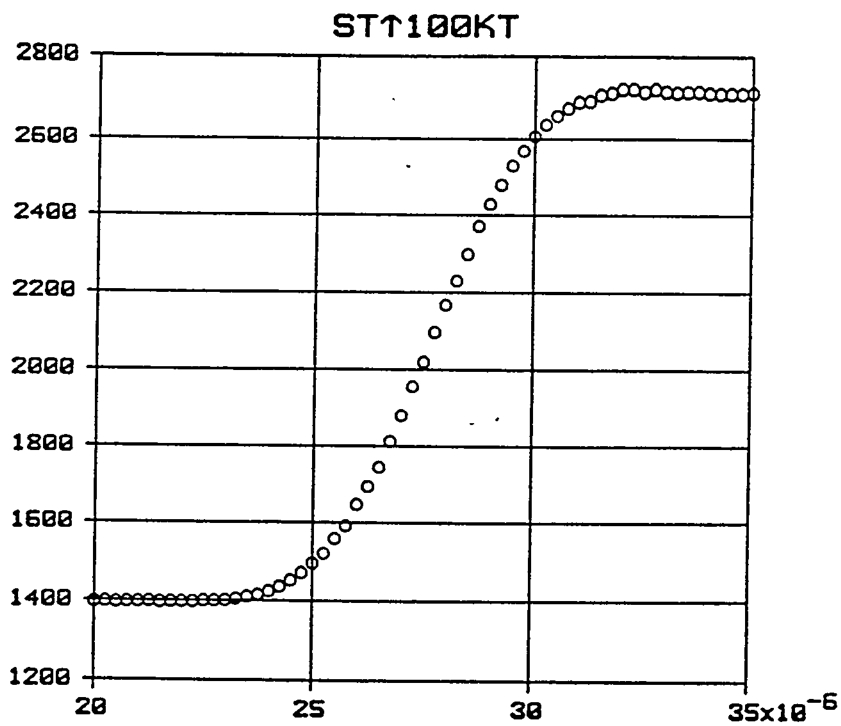

Figure 5: Recorded pulse to WFD591, detail of the leading-edge samples for 100 Khz filter setting

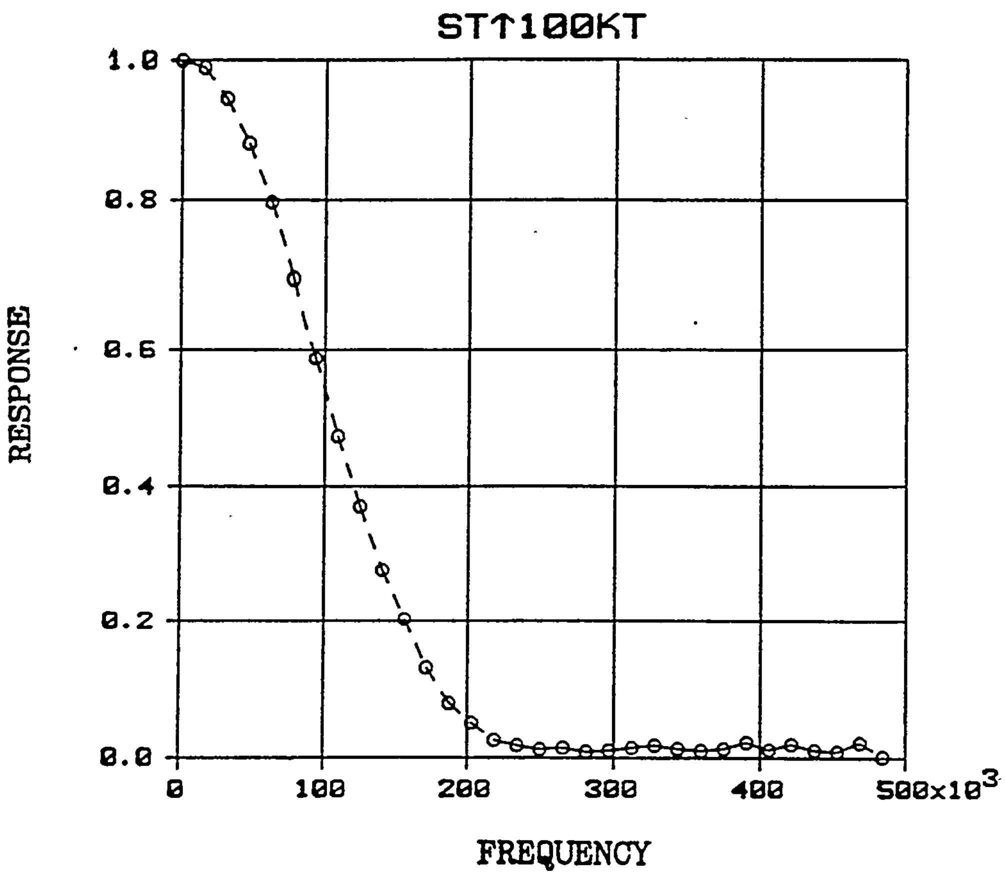

Figure 6: Frequency response curve for the WFD591, 100 Khz filter setting

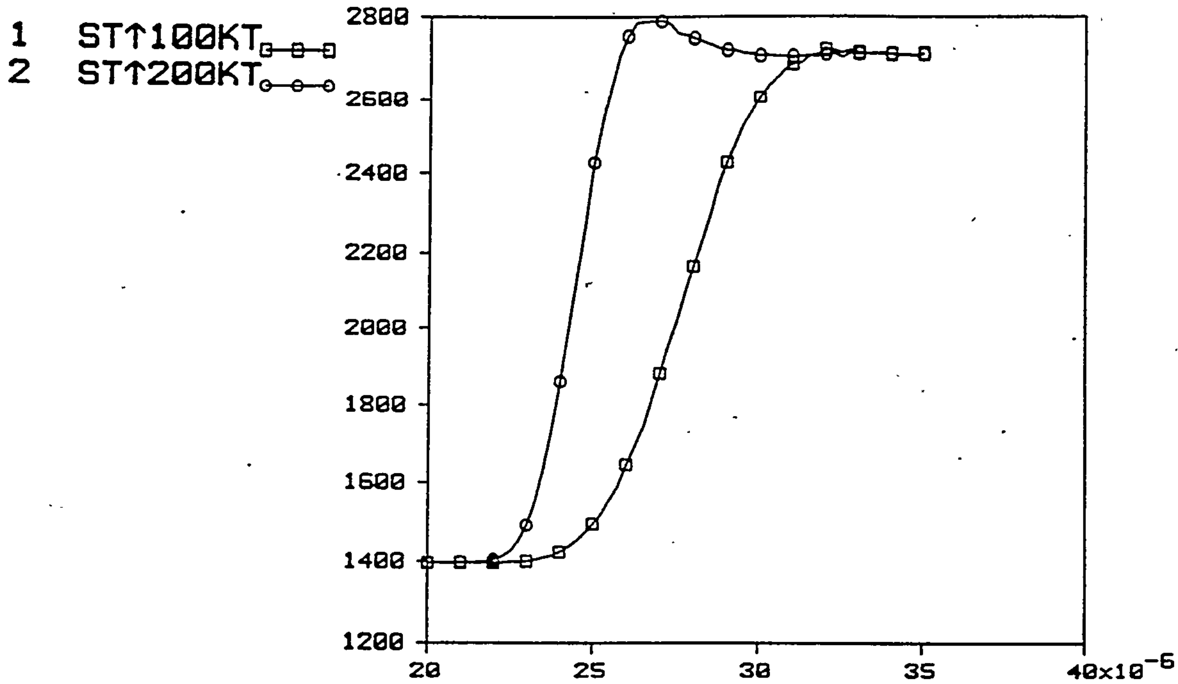

Figure 7: Comparison of step responses for 200 Khz and 100 Khz filter settings

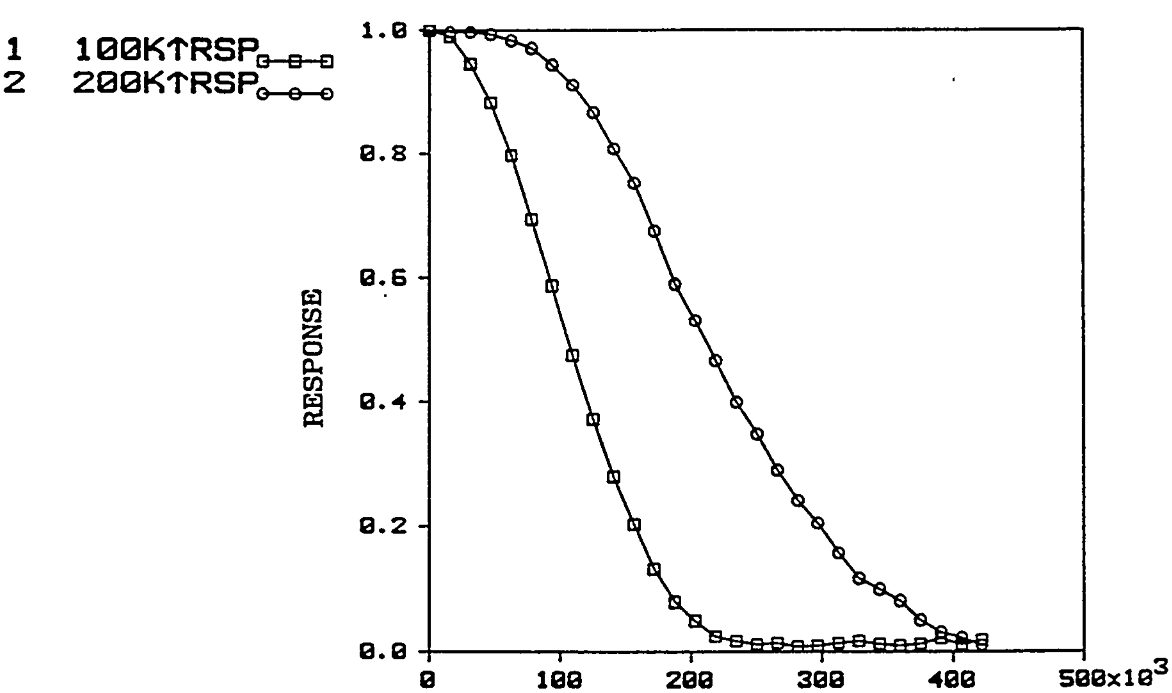

Figure 8: Comparison of frequency responses for 200 Khz and 100 Khz filter settings

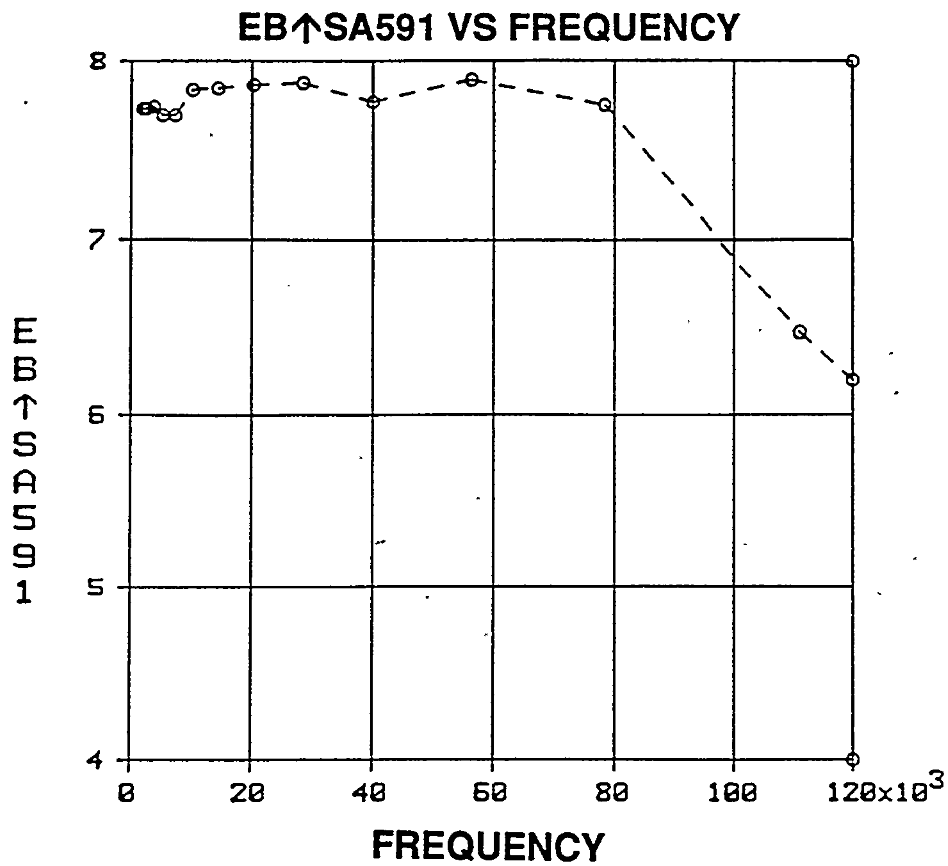

Figure 9: Effective bits as a function of frequency for the WFD591 at 80% full-scale and 200 Khz filter setting

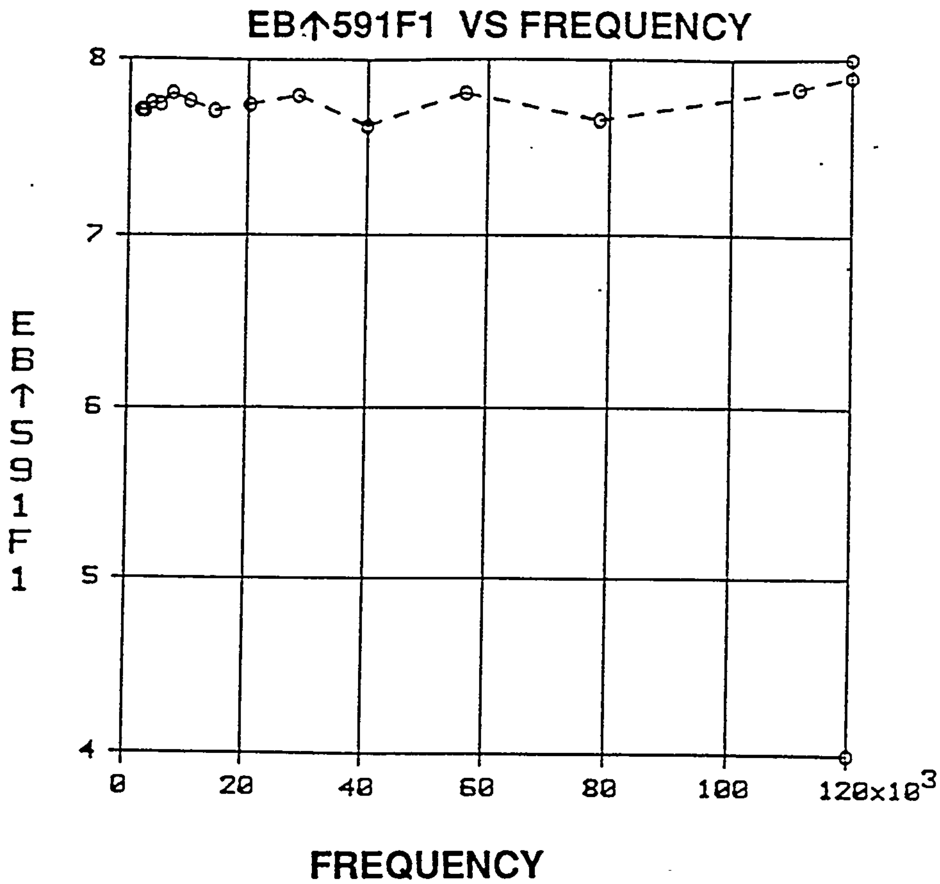

Figure 10: Effective bits as a function of frequency for the WFD591 at 80% full-scale and 100 Khz filter setting

this WFD591 the 10% amplitude effective bits measure is approximately 0.5 bits better at each frequency for an accuracy of ± 0.15%.

These effective-bit results for the WFD591 are "worst-case". The AWG is a 12-bit generator and the output specifications indicate long-term 10-bit accuracy of output. However, because of the configuration requirements for this test, we were not able to verify that the purity of the sinewaves was any better than 8.5 bits. Our results are "worst-case" because they are what we get assuming the input sinewaves are ideally pure. If, in fact, the input sinewaves are only accurate to 8.5 bits, we could not get a digitized output any more accurate than 8.5 bits. Further tests are required to clarify this issue.

3.4 OVERVOLTAGE RECOVERY - WFD591

Another factor which is significant when trying to analyze high frequency transient signals is the overvoltage recovery of the signal conditioners. This recovery is extremely important for underground nuclear testing because of the large zero-time noise spikes generated by the device. After an amplifier is driven into saturation, there is a recovery time before the amplifier output is again an amplified replica of the input signal. However, there are two types of saturation that must be considered separately. The signal conditioning systems have overvoltage protection to prevent damage to the amplifiers caused by short duration input pulses that exceed the linear input range of the amplifier. The WFD591 system has protection circuitry that is enabled when the input pulse amplitude exceeds ±8.2 volts.

For any gain setting, and especially for gain settings above 1, it is easy to overdrive the amplifier without overdriving the input protection circuitry. Figure 11 shows the result of a 1.6X overdrive of a WFD591 channel. The signal window of the WFD591 is 10 volts. The half-window for positive polarity pulses is 5 volts. An 8 volt input is an overdrive of 8.0/5.0 or 1.6. In figure 11 the top curve is for a gain of 2X and an input amplitude of 4.0 volts. The successive curves are for a gain of 20X and input of 0.4 volts, and gain of 200X and input of .04 volts respectively. The input signal width is shown in the very bottom curve to give an indication of the recovery time. Note that the 1.6 overdrive does not overdrive the input protection circuitry for any gain setting. Figure 12 gives a similar comparison of configurations with one notable exception. In this case the overdrive is 16X (or 80.0/5.0). Again, the bottom curve is the shape of the input pulse. The top curve shows a gain 2X amp with input of 40 volts. This top curve shows a baseline recovery distortion which is associated with overdriving the input protection circuitry. This baseline recovery distortion is more clearly seen in figuree 13. Here 4 different channels are compared with each being overdriven with a 40 volt input. The extent of the pulse widening and the baseline distortion vary significantly. Parameters such as these are somewhat component dependent and, consequently, vary among channels. Figure 14 shows a comparison of overdrive characteristics for 5 different channels all set with gain of 2000 and an input of 40/1000 or .04 volts. The net overdrive is 16X but the input protection circuitry is not enabled.

It is clear that the overdrive characteristics vary significantly from channel to channel but over a wide range of conditions these recovery times appear to not exceed 20 microseconds or 10 sample intervals at the maximum sample rate for the WFD591 channels.

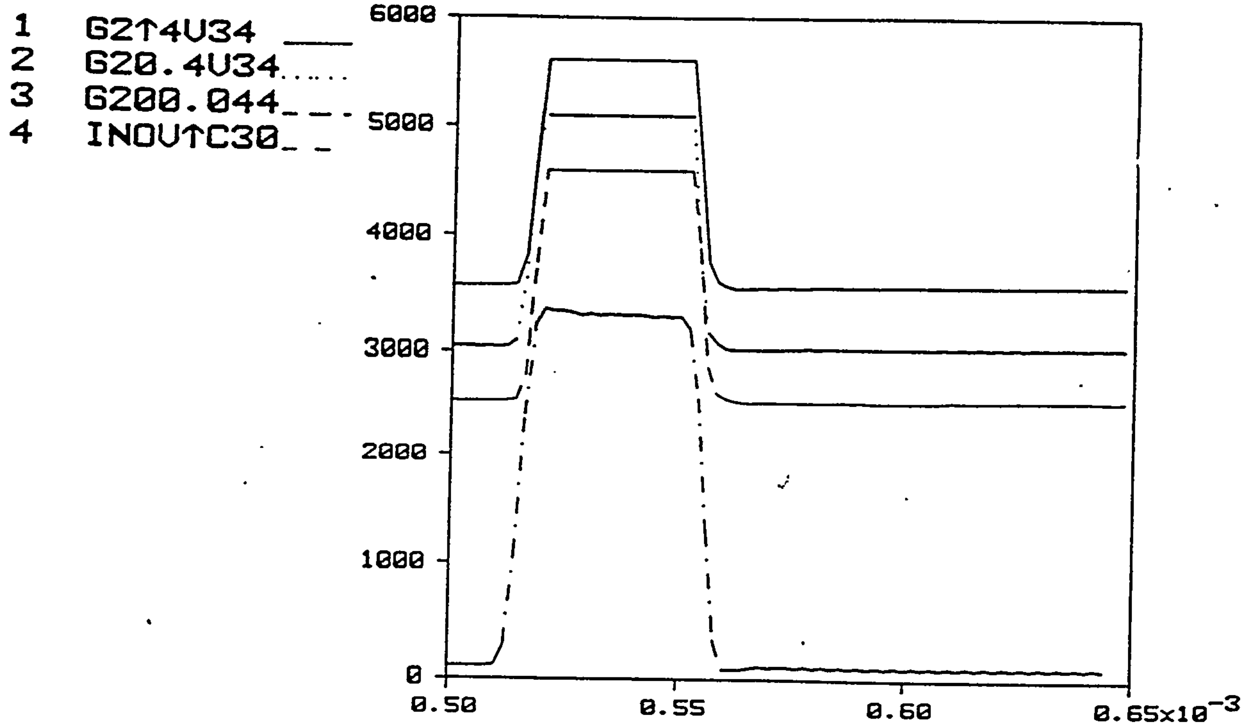

Figure 11: WFD591 Overvoltage recovery for 1.6X overdrive; Gain 2X, 20X, and 200X

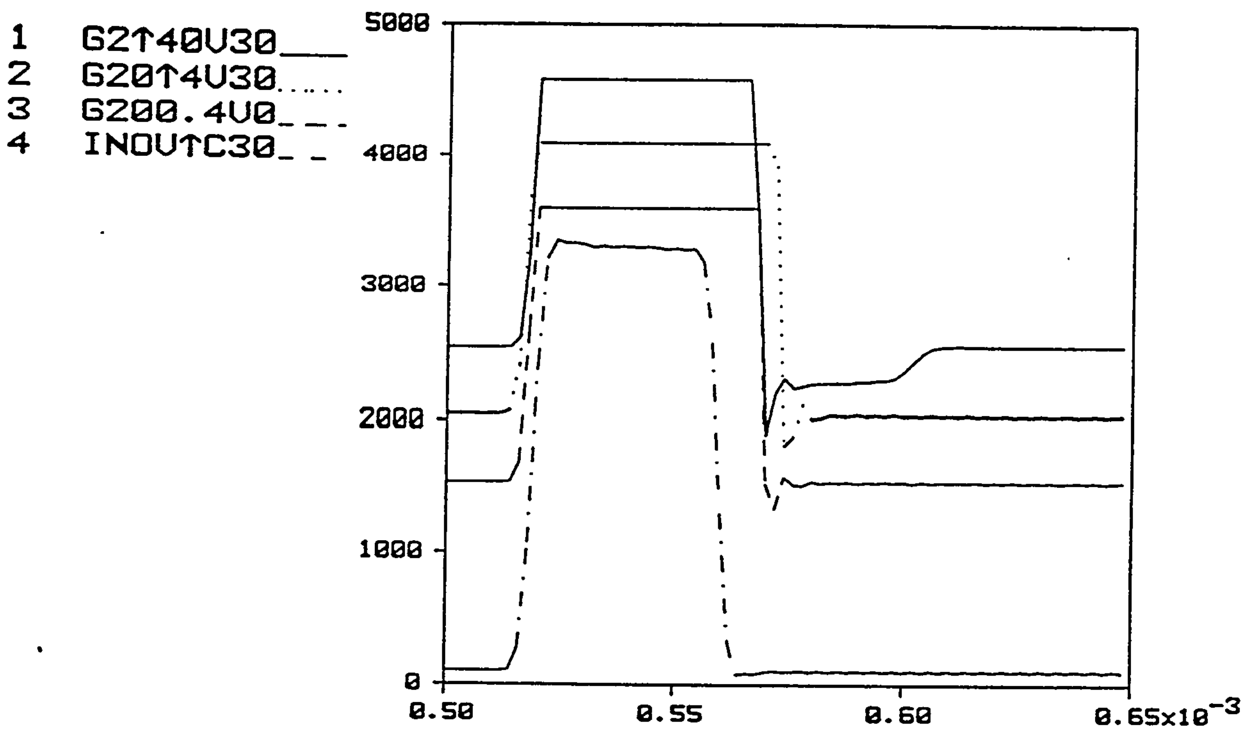

Figure 12: WFD591 Overvoltage recovery for 16X overdrive; Gain 2X, 20X, and 200X

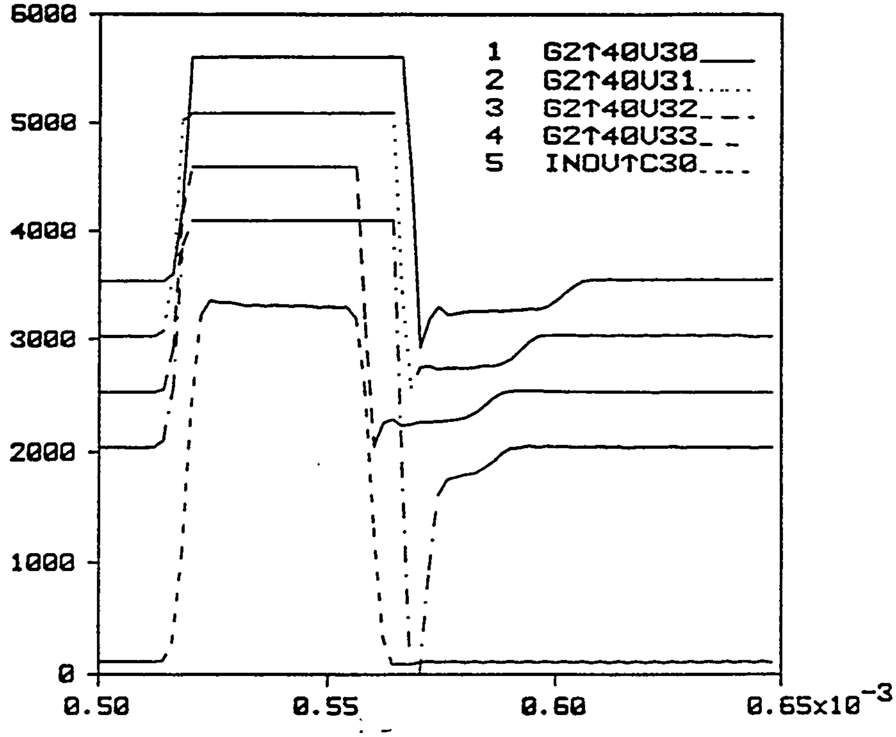

Figure 13: WFD591 Overvoltage recovery for 16X overdrive; Comparison of recovery baseline distortions for four different channels for a gain of 2X and a 40 volt input

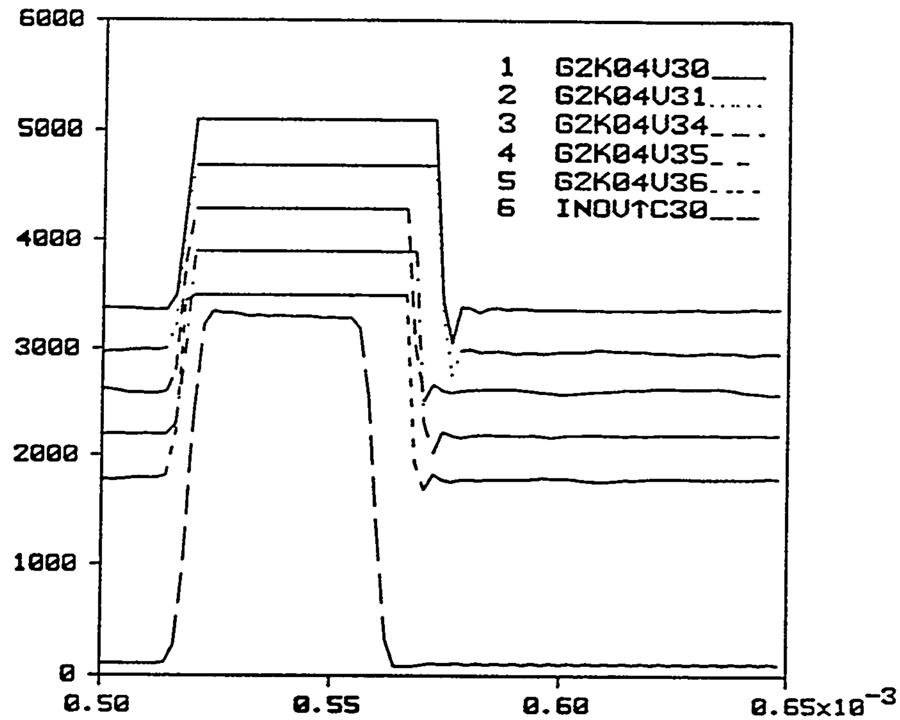

Figure 14: WFD591 Overvoltage recovery; comparison of the recovery characteristics of five different channels set at gain 2000X and a 0.4 volt input to produce an overdrive of 16X

4. WFD592 PERFORMANCE CHARACTERISTICS (10 MEGAHERTZ CHANNELS)

The high frequency channels used in SANDUS have 8 sample interval choices from 20 nanoseconds (50 Msps) down to 4 microseconds (250 Ksps). The 9 gain settings range from 1 to 500 in standard 1:2:5 multiples. Typically they are not used at gains exceeding 100. Above this value the baselines are difficult to stabilize. The antialiasing filter settings range from 10 Mhz down to 200 Khz. To test the performance characteristics of the WFD592 channels, we have focused on the highest speed settings. Since the digitizing capabilities of a waveform digitizer tend to degrade at their highest digitizing rates, we tested the channels exclusively at the 50 Megasamples/second rate. Most tests were done at the maximum filter setting of 10 Mhz although some were done with filter settings of 5 Mhz and 2 Mhz to show the effects of the filtering on timing delay.

4.1 GAIN ERRORS - WFD592

In DHTEST offsets at seven levels are input and the digitally recorded output is required to be within ±8 counts (out of 256) of a nominal value at the highest and lowest offsets. This acceptance window reduces to ±5 counts at the center of the analog window. To be considered acceptable, the gain results must be satisfied at all seven levels. Statistically, this implies that deviations from linearity will be significantly smaller than the allowed window at any single level. Furthermore, the full calibration procedures followed in system operation remove any gain-error concerns.

4.2 STEP RESPONSE AND FREQUENCY RESPONSE - WFD592

The frequency response of the WFD592 was determined in a manner similar to that described for the WFD591. Because of the factor of 100 higher digitizing rate, we had to use a higher speed arbitrary waveform generator (AWG) to generate multiple step inputs to the system. Also, the AWG output rate is 200 Megapoints/second. This is only a factor of four higher than the 50 Msps digitizing rate. This limited our equivalent sampling technique but we were able to obtain 4-fold interleaving to more clearly define the step transitions. Figure 15 shows the equivalent input pulse obtained by overlapping some 40 pulses from the AWG contained in a single record of the WFD591. The next figure, 16, shows detail of the step showing the 5 nanosecond resolution obtained by interleaving. From this step function we obtain the response curve of figure 17. Note here that the filter characteristic frequency is 10 Mhz but at this frequency the output is down to 40% of low frequency value or 8 dB. This resultant attenuation at 10 Mhz comes from a filter designed for 6 dB attenuation at 10 Mhz coupled with the fact that the amplifiers themselves are down nearly 2 dB at 10 Mhz.

4.3 EFFECTIVE BITS (DIGITIZATION ACCURACY) - WFD592

The AWG of the frequency response test for the WFD592 was also used to input a series of 12 sinewave frequencies from 267 Khz to 11 Mhz. Sinewave fitting techniques are used to determine the effective-bits performance at each frequency. Figure 18 shows the effective bits performance as a function of frequency for an input amplitude of 80% of full scale. For the frequencies below 1 Mhz the result is near 7 effective bits. However, at the high input frequencies, the performance drops to a low of nearly 4 effective bits. The correlation between effective bits and accuracy is basically the following. For an effective bits value of 4.2, the accuracy of a single digitization could be expected to be 1/(2**4.2) or ±2.7%. Figure 19 shows the digitizing accuracy for 20% full-scale signals. As expected, the lower amplitude signals have 2 bits better performance at the highest input frequencies. At 11 Mhz., the effective bits result for 20% full-scale is 6.2 compared to 4.2 for the 80% amplitude. This is ±0.7% accuracy for small scale signals.

4.4 OVERVOLTAGE RECOVERY CHARACTERISTICS - WFD592

The input range for the WFD591 is 4 volts. The input protection diodes are 3.9 volt units which protect a symmetric 7.8 volt input window. Overdrives exceeding ± 3.9 volts will turn on a protection diode. The amplifier is made up of three stages having fixed gains of 10X. The various gain settings from 1 to 500 are obtained by switching in the correct attenuation and number of stages of amplification. We tested the units at gains of 1, 10, and 100 to get the recovery characteristics as a function of number of stages enabled. For any gain setting, and especially for gain settings above 1, it is easy to overdrive the amplifier without overdriving the input protection circuitry. Furthermore, the extent of the overdrive is significant. Figure 20 shows the result of a 1.75X overdrive of a WFD592 channel. The figure of 1.75 comes from considering that the signal window of the WFD592 is 4 volts. Then the window for positive polarity pulses is 2 volts. A 3.5 volt input is an overdrive of 3.5/2.0 or 1.75. In figure 20 the top curve is for a gain of 1X and an input amplitude of 3.5 volts. The second curve is for a gain of 10X and an input of 0.35 volts. Finally the bottom curve is the overdrive result with a gain of 100X and an input of 0.035 volts. The input signal is not shown here but its width is nearly identical to the width of these three configurations. Figure 21 gives a similar comparison of configurations with one notable exception. In this case the overdrive is 17.5X (or 35.0/2.0). The top curve shows a gain 1X with input of 35 volts. This top curve is wider than the lower two curves because the 35 volt input enables the input protection circuitry and the extra 100 nanoseconds or so of width are caused by this protection circuitry recovery. Parameters such as these are somewhat component dependent and, consequently, vary among channels. Figure 22 shows a test result identical to that of Figure 21 but for another channel. The amplifier recovery time is smaller for this channel but the input protection circuitry recovery is noticeably larger.

It must be noted that for the WFD592, the amplifiers seem to have some ringing characteristics when more than one stage is required (i.e. gain of 10X or above). The lower two curves of figures 21 and 22 show this ringing for gains of 10 and 100. The width of the input pulse overdriving the channels was nominally 1 microsecond. From figures 21 and 22 one can see can see that the overdrive recovery time maximizes near 1 microsecond if ringing effects are not included. Allowing another microsecond for amplifier ringing, the time to return to normal response for a WFD592 amplifier does not appear to exceed 2 microseconds.

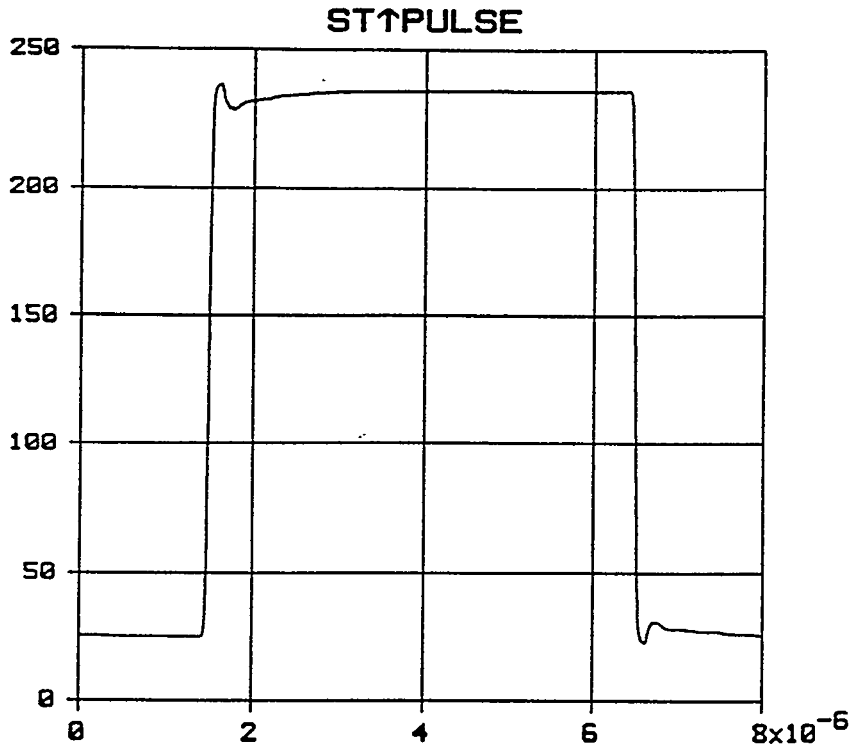

Figure 15: Recorded pulse to WFD592, equivalent-time sampled with filter setting of 10 Mhz

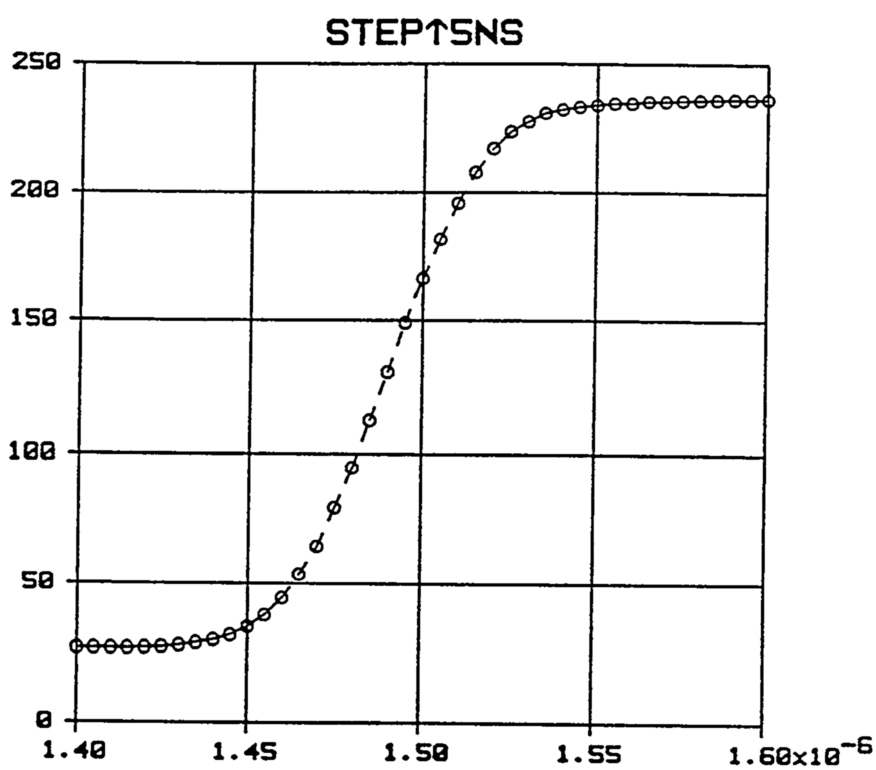

Figure 16: Recorded pulse to WFD592, detail of the leading-edge samples for 10 Mhz filter setting

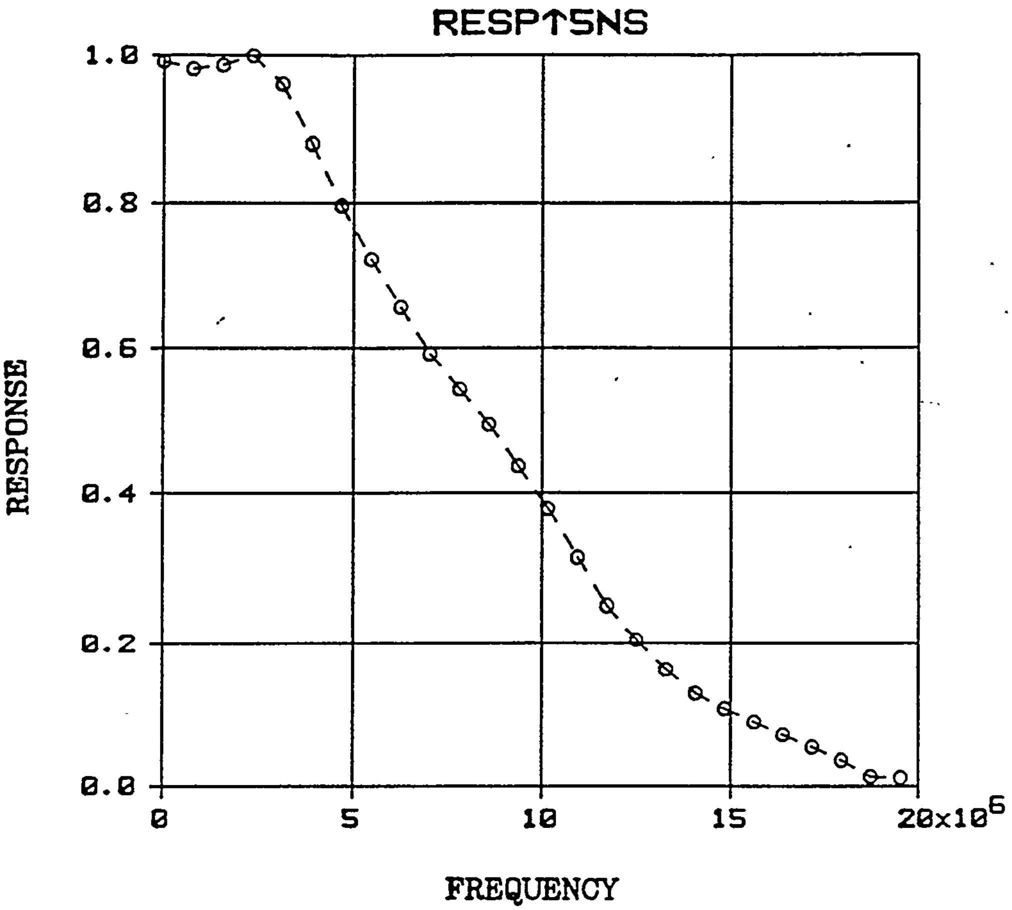

Figure 17: Frequency response curve for the WFD592, 10 Mhz filter setting

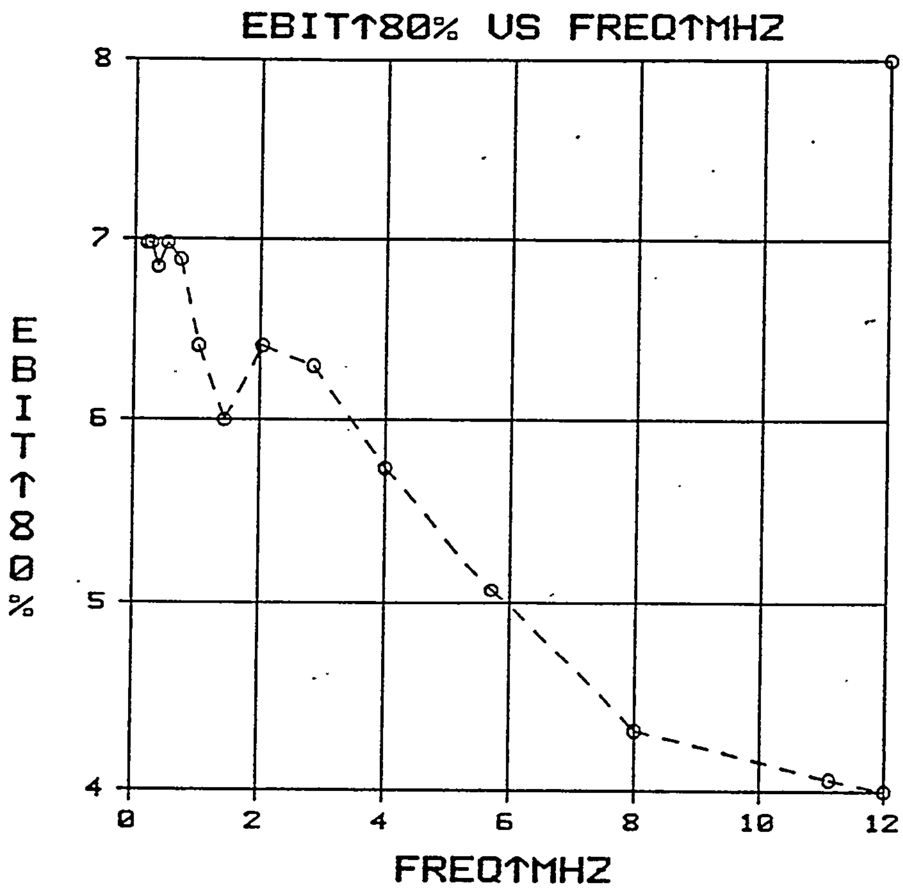

Figure 18: Effective bits as a function of frequency for the WFD592 at 80% full-scale and 10 Mhz filter setting

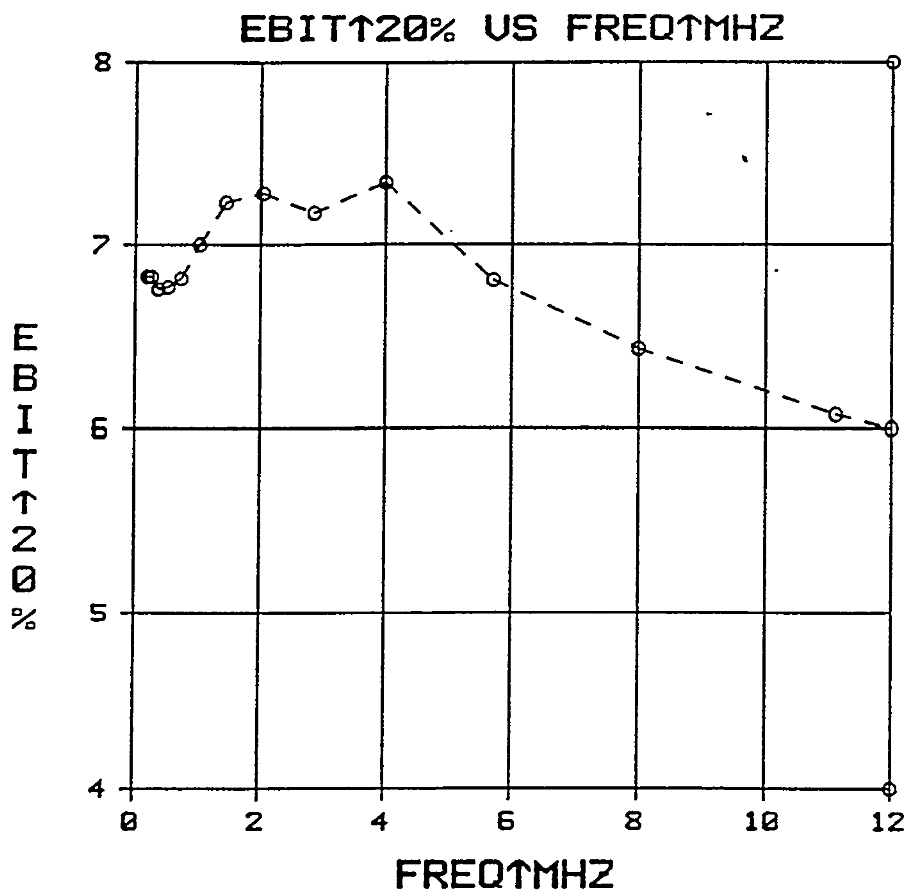

Figure 19: Effective bits as a function of frequency for the WFD592
at 20% full-scale and 10 Mhz filter setting

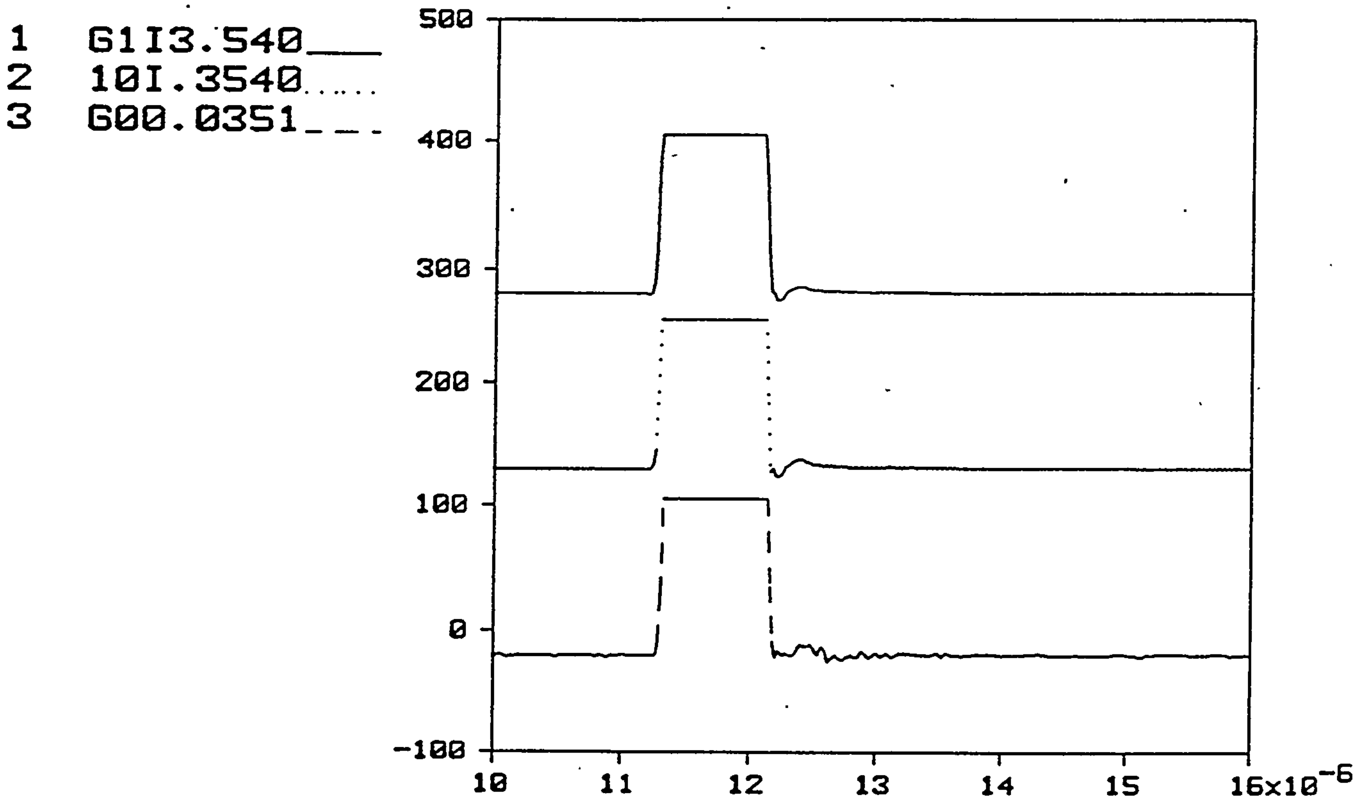

Figure 20: WFD592 Overvoltage recovery for 1.75X overdrive;
Gain 1X, 10X, and 100X

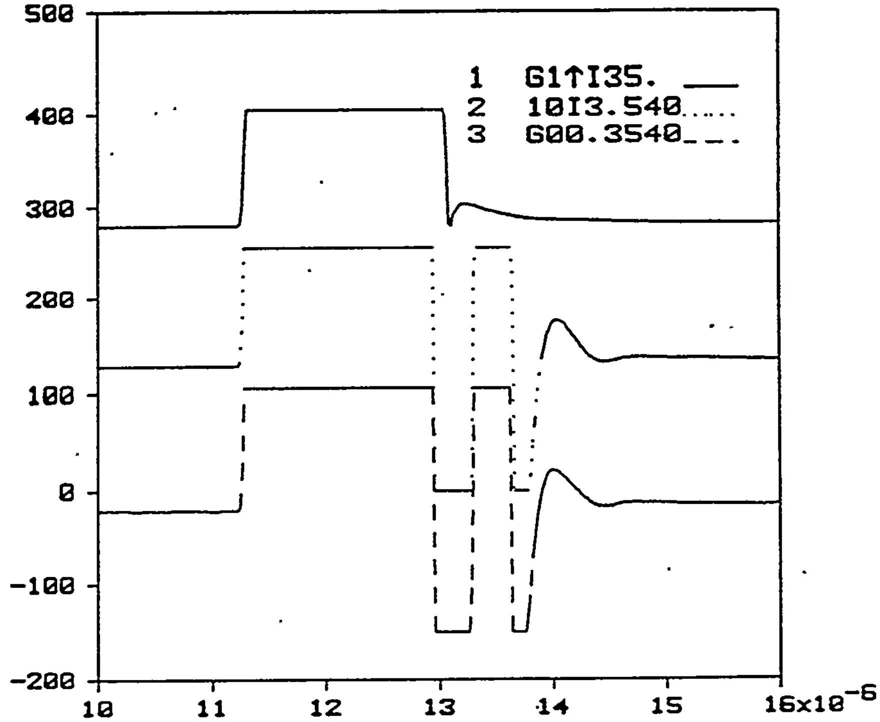

Figure 21: WFD592 Overvoltage recovery for 17.5X overdrive; Gain 1X, 10X, and 100X

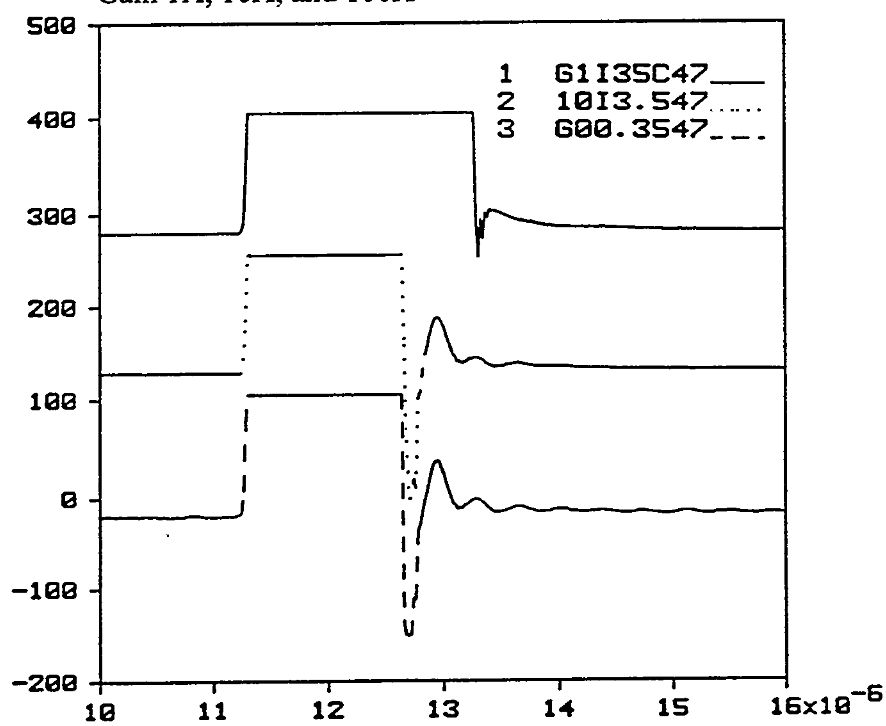

Figure 22: WFD592 Overvoltage recovery for 17.5X overdrive; Gain 1X, 10X, and 100X showing the variation in overdrive characteristics for a different channel

5. CHANNEL CROSSTALK - WFD591 and WFD592

It is very important in the waveform digitizing of analog signals that the analog electronics be very well isolated so that signals from one channel cannot couple any significant signal into another analog channel. This type of testing is normally done by arranging a number of high level input situations and examining for time correlated signals in adjacent channels which have intentionally had no signal coupled into their inputs. In the SANDUS system, channels may be configured to be WFD591 or WFD592 at a large number of gain settings. We focused on two particular crosstalk configurations. First of all we put a large amplitude signal into a channel in a single crate, set the adjacent channels (vertically and horizontally) to large gain, and looked for signals coupled into the high gain channels. The following diagram shows the configuration of channels:

Crosstalk monitor channels = X
Stimulated channel = S

X				
S	X	X	X	X
X				

The input amplitude was 40 volts and the adjacent channel gains across the rack were 2000X. Two further configuration differences were considered. Initially, the input pulse was injected using test equipment immediately at the SANDUS channel rack. This means that only short local cables were used to couple the signal into one channel and the other channels had no input (but were terminated in 50 ohms). A second configuration was to perform an identical test but insert the signal through the translator coupler at the window of the SANDUS. Correlation was maintained between the rack geometry and the translator coupler geometry at the window. Figure 23 shows the stimulated channel. There is no indication of crosstalk in this measurement.

The second test showed the same high degree of isolation. In figure 24 the top signal is the input signal, curves 2-4 are horizontally adjacent channels (at the translator coupler as well as in the rack), and curves 5 and 6 are immediately above and below the signal injection input. For this test, the cables were all connected from the window to the channels included in the test but were left open at the window. This would be the most susceptible arrangement for noise pickup at the window. Again, in summary, there is no evidence of significant crosstalk between channels in the SANDUS WFD591 channels.

The WFD592 high frequency modules were tested in a similar manner. A 150 volt fast input went into the first channel of a crate which was set at gain 1X. The surrounding 592 fast channels were set at gain 100X with no input but terminated in 50 ohms. The first test was to input the 150 volt pulse at the SANDUS crate. Figure 25 shows the stimulated channel on the bottom. The top three traces are the nearest three channels horizontally in the crate. The fourth and fifth traces are located in the rack immediately above and below the stimulated channel. There is some slight evidence for interference in the top trace correlated with the input stimulus.

The identical test was performed but the 150 volt pulse was injected at the translator coupler or "window" of the SANDUS. Figure 26 again indicates that there is some small coupling into the horizontally adjacent channel but the magnitude of the coupling in figure 26 is no larger than

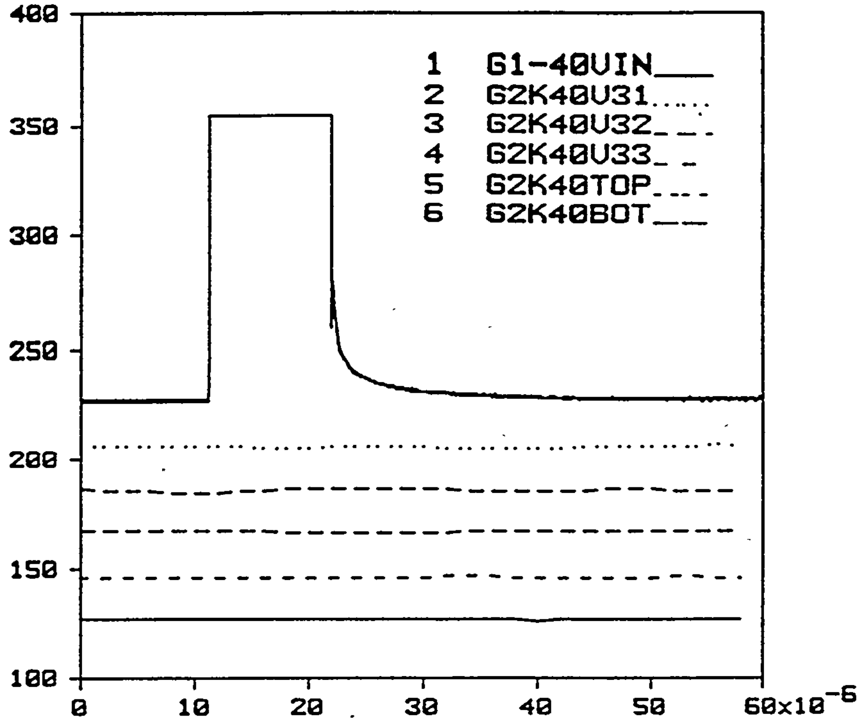

Figure 23: Crosstalk - WFD591; 40 volt input pulse and six nearest channels (horizontally and vertically) set at gains of 2000X. Input directly at the SANDUS crate.

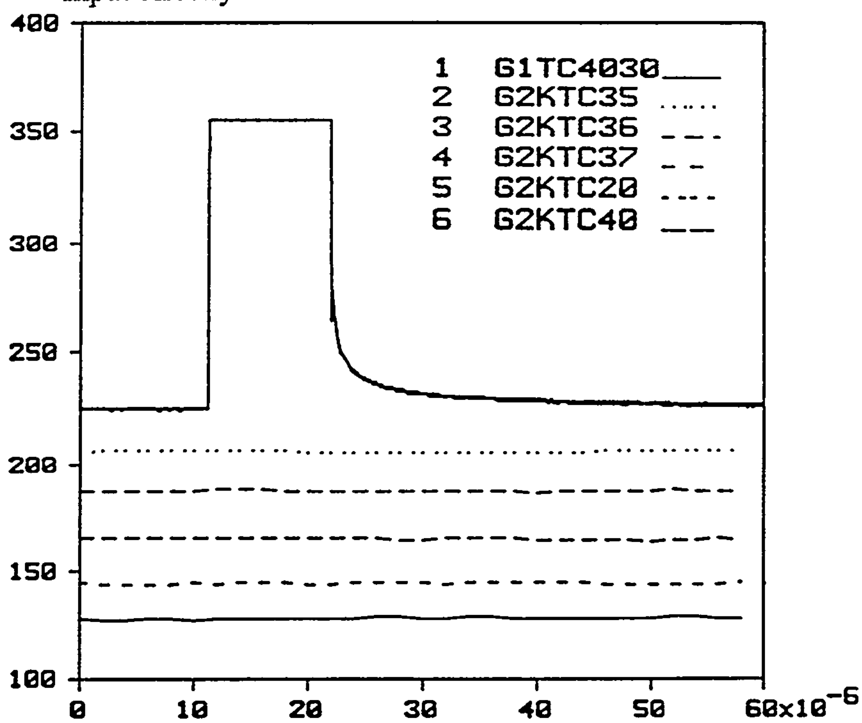

Figure 24: Crosstalk - WFD591; 40 volt input pulse and six nearest channels (horizontally and vertically) set at gains of 2000X. Input through the SANDUS "window" at the translator coupler.

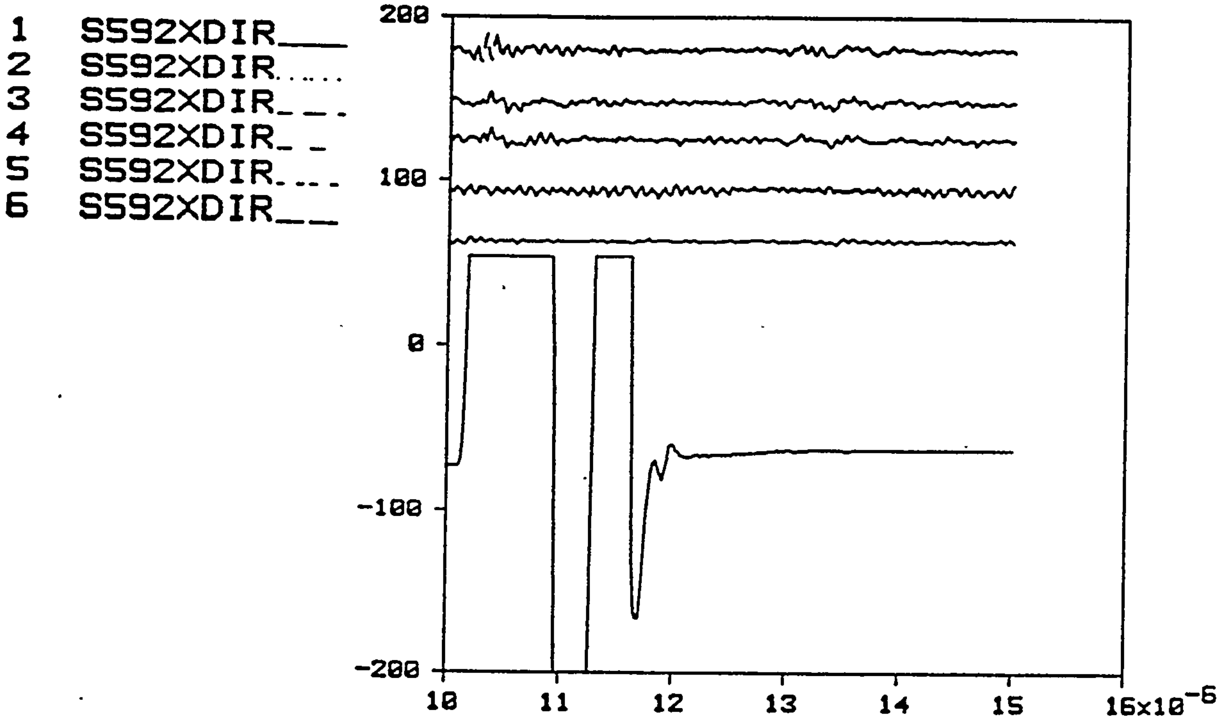

Figure 25: Crosstalk - WFD592; 150 volt input pulse and six nearest channels (horizontally and vertically) set at gains of 1000X. Input directly at the SANDUS crate

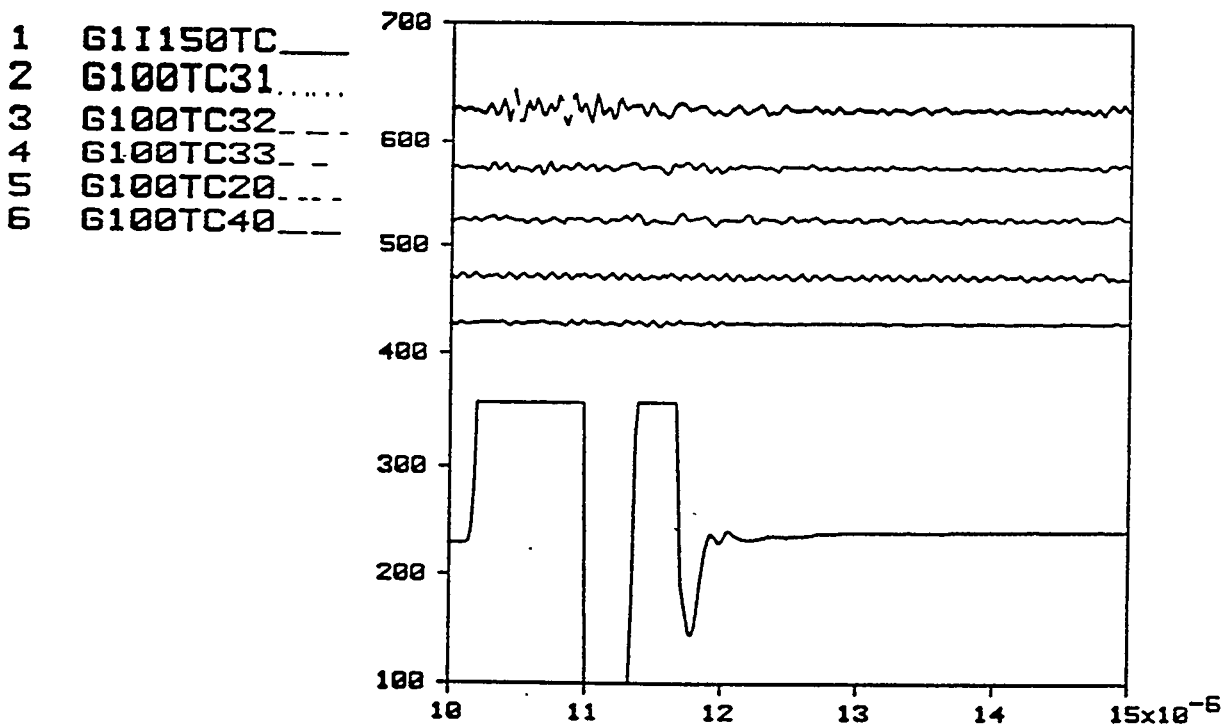

Figure 26: Crosstalk - WFD592; 150 volt input pulse and six nearest channels (horizontally and vertically) set at gains of 100X. Input through the SANDUS "window" at the translator

that in figure 25. We can conclude that the translator coupler is not a vulnerable point for crosstalk pickup.

6. TIMING CHARACTERISTICS

The SANDUS waveform recording channels are triggered systems. It is, therefore, important to know precisely how the waveform data array correlates to the trigger in time. There is an inherent uncertainty that is not avoidable in these systems.

6.1 SYSTEM THROUGHPUT DELAY

The trigger comes to the SANDUS trigger generator system totally asynchronous to the waveform digitizer clocks. The fundamental clock for the system has a frequency of 50 Mhz or 20 nanosecond period. We can determine how much delay there is between the input trigger and the first sample recorded only to within 20 ns. The test was performed by setting the pretrigger count to 512 samples and inputting a fast-rise pulse step into a WFD592 channel and into the trigger generator. This was done for a number of channels and the results obtained were similar to the plot of figure 27. The first sample above baseline occurs at the -100 ns point on the plot. Since the sample interval is 20 ns, this means that the trigger delay is approximately 5 samples or 100 ns. Repeating the test a number of times showed that the trigger delay is between 5 and 6 samples. This uncertainty is consistent with the synchronous nature of the trigger to the clock.

6.2 DEPENDENCE OF DELAY ON FILTER SETTINGS

Another time correlation issue arises when one uses various filter settings. The "start time" for a pulse is defined to be the point in time when the leading edge of the pulse reaches its 50% amplitude level. The highest filter setting for the WFD592 is 10Mhz. If lower values are selected, the rise time of an input step pulse will be reduced. This has the effect of introducing delay in the input trigger and the initiation of digitization. In Figure 28, a fast rise pulse was injected into a WFD592 channel for three different filter settings, 10 Mhz, 5 Mhz, and 2 Mhz. The delay of the 50% amplitude point is quite obvious. The 5Mhz filtered pulse is delayed about 50 ns relative to the 10 Mhz filtered pulse. The 2 Mhz filtered pulse is delayed nearly 150 ns from the 10 Mhz filtered pulse.

6.3 DEPENDENCE OF DELAY ON GAIN SETTING

In figure 29 we compare the output pulse for three different amplifier gain settings. The top curve is gain 1X, the next two are 10X and 100X. The input was appropriately attenuated to keep the pulse on scale. We see that there is a small increase in timing delay for gains above 1X but the 10X and 100X timing is essentially identical. If we do a pulse analysis of these three arrays, we find the pulse start times of the 10X and 100X pulses to be within +-20 ns or within a single sample interval of the 1X pulse. Since these pulses are for the same channel but at different gains, they had to come from separate "tests" and consequently separate triggers. The asynchronous nature of the pulse trigger relative to the digitizing clock leads to a timing delay

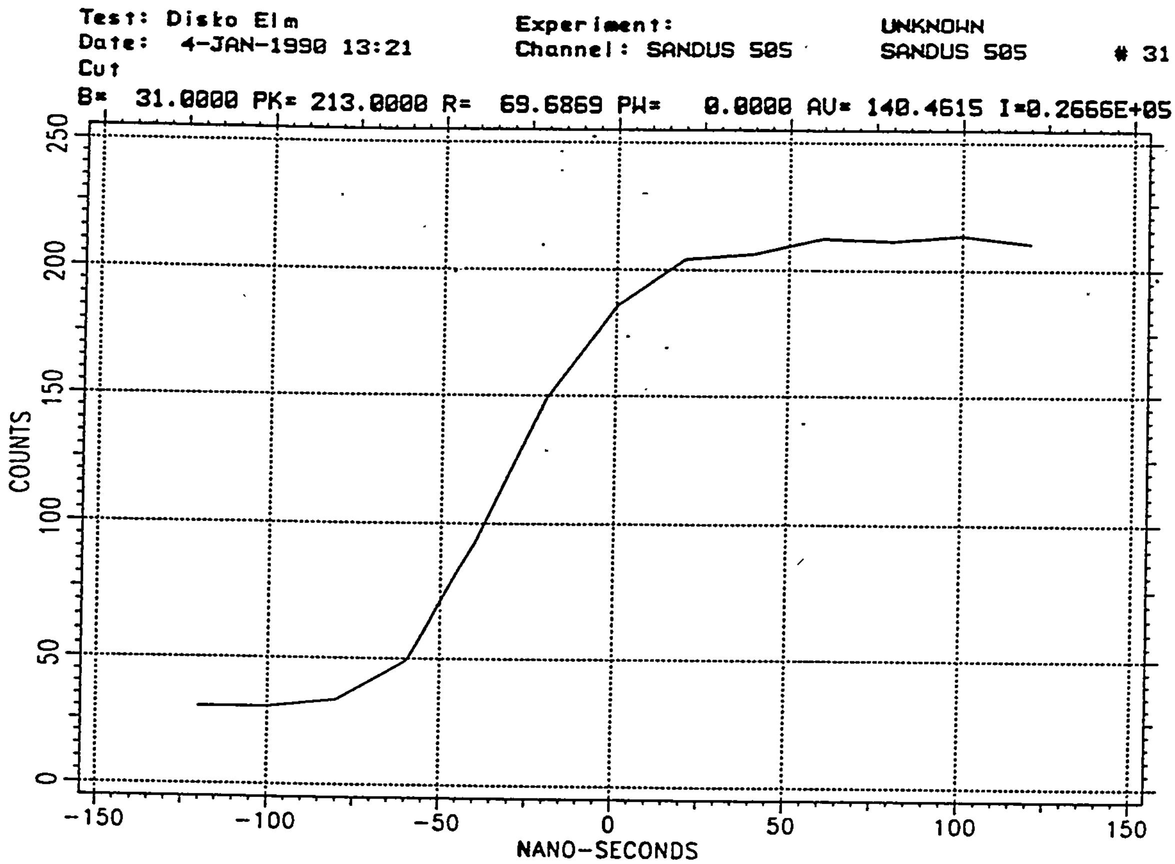

Figure 27: Timing measure; trigger zero time compared to first digitized data

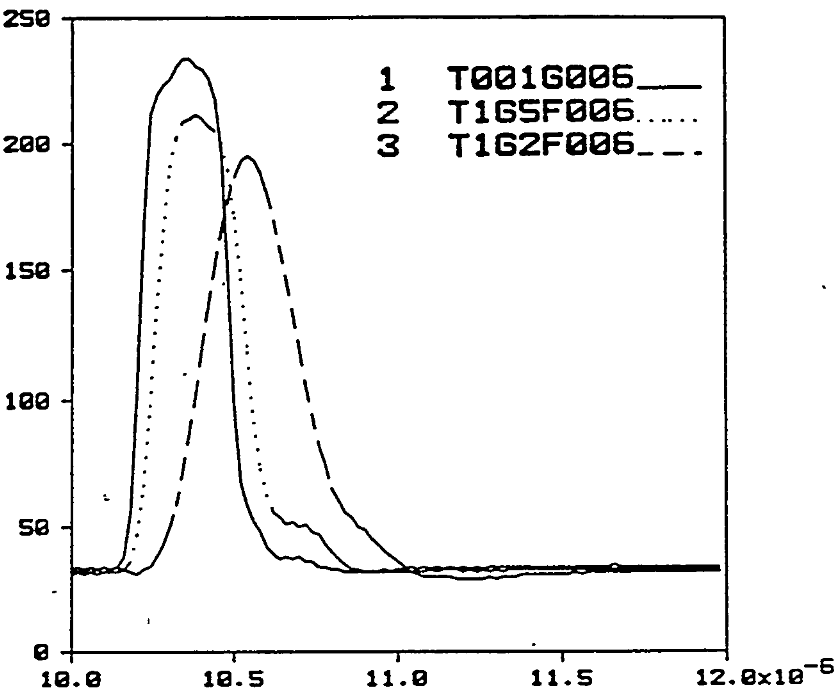

Figure 28: Timing measure; Effects of filtering on pulse edge timing

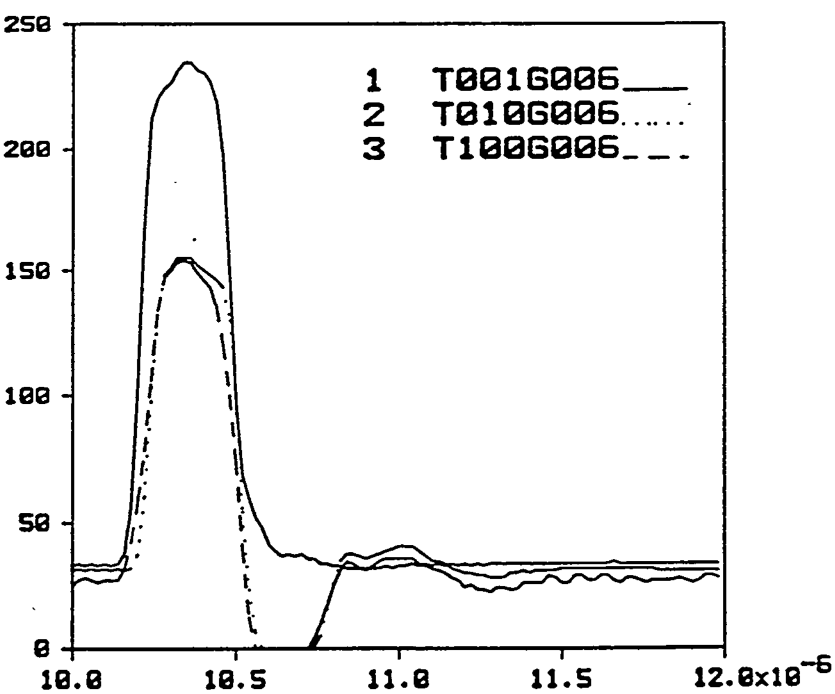

Figure 29: Timing measure; Effects of including amplifier stages on pulse edge timing; Gain 1X=1 stage, 10X=2 stages, 100X=3 stages

uncertainty of one sample interval so we can only determine that the timing delays introduced by using gains of 10X and 100X are within a single sample interval or do not exceed 20 ns.

7. SUMMARY

We have surveyed the general performance characteristics of the SANDUS 591(100 Khz) channels and the SANDUS 592(10 Mhz) channels. The quantitative results have only been samples from a few channels but they have indicated general levels of performance that can be expected. We have shown results for frequency response, effective bits, overvoltage recovery, crosstalk, and timing accuracy. Some summary remarks regarding strengths and weaknesses of the SANDUS waveform digitizing system are in order.

On the side of system strengths we note the following. The system is totally remote controlled and includes a wide range of digitizing parameters. The internal functional test, DHTEST, does a thorough job of insuring that the channels are set up as desired and that the channels are performing reasonably. The timing synchronization within the system is very good. The entire system runs on a distributed synchronized 50 Mhz clock. The timing delay between trigger input and first sample digitization is acceptable. No data is missed because of the pretrigger capability of the channels. The effective bits performance of the 10 Mhz system is satisfactory, although is would be possible in today's market to find higher effective bits at these bandwidths. The channel-to-channel isolation is quite good throughout the system. We find no evidence of crosstalk vulnerability of any significant value from the window of the SANDUS back to the crates.

The following weaknesses should be noted. The frequency responses of both the 10 Mhz and the 100 Khz systems are somewhat surprising. Although the filters were especially designed to be monotonic antialiasing filters, the broad slow rolloff is somewhat disturbing. One normally expects the response to be down 3 dB at the characteristic frequency of the filter. The overvoltage recovery parameters are not unsuitably high but there is a wide range of variation from channel to channel. This applies both to the amplifier saturation recovery and the input protection circuitry saturation recovery. Also, the amplifier stages past stage 1 of the WFD592 show noticeable ringing as noted in figures 20, 21, and 29. The effective bits performance of the slower 12-bit system is somewhat disappointing. However, we noted that under the conditions of this test, it was not possible to validate the purity of the input sinewaves to better than 8.5 bits. Characterizing the input sinewaves to 10-bit accuracy is non-trivial but further investigation of this is required.

Finally, considering that the SANDUS systems were designed over 12 years ago (a time when even 50 megasample digitization had to be done by interleaving two 25 Mhz converters), the capabilities of the systems are quite good The replacement of these systems is inevitable because the time will come when we will not be able to procure support components. There are a number of special requirements caused by the underground test conditions that are not routinely designed into industrial systems. We need to be able to read data out before ground shock arrival or typically within 100 milliseconds. The standard "off-the-shelf" digitizer has a GPIB bus with very limited data transfer bandwidth. We need to have non-volatile storage memory in case of power failure. We also require complete remote programmability for both waveform digitizers and signal conditioners. Built-in calibration systems are very desirable. The signal conditioning portions of the digitizers need to have excellent overvoltage recovery characteristics. Modules are needed which control bridge excitations. Many existing commercial systems have some number of these features but none has all. The SANDUS system meets all of these requirements.

In summary, considering the extensive flexibility, the complete programmability, and the performance capability of the SANDUS system, its replacement will be no easy task.

8. REFERENCES

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[2]. "IEEE Trial-Use Standard for Digitizing Waveform Recorders", IEEE STD 1057, drafted by Waveform Measurement and Analysis Committee of the IEEE Instrumentation and Measurement Society, published by Institute of Electrical and Electronics Engineers, Inc., 345 East 45th Street, New York, NY 10017.

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