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CEA SMAD 2016 Digitizer Evaluation

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CEA SMAD 2016 Digitizer Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated an updated SMAD digitizer, developed by the French Alternative Energies and Atomic Energy Commission (CEA). The SMAD digitizers are intended to record sensor output for seismic and infrasound monitoring applications. The purpose of this digitizer evaluation is to measure the performance characteristics in such areas as power consumption, input impedance, sensitivity, full scale, self-noise, dynamic range, system noise, response, passband, and timing. The SMAD digitizers have been updated since their last evaluation by Sandia to improve their performance when recording at a sample rate of 20 Hz for infrasound applications and 100 Hz for hydro-acoustic seismic stations. This evaluation focuses primarily on the 20 Hz and 100 Hz sample rates. The SMAD digitizers are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

ACKNOWLEDGMENTS

This work was sponsored under Fund-In Agreement between Sandia National Laboratories and the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

We would like to thank CEA for providing the SMAD digitizers to evaluate and for their presence and support in conducting the evaluation.

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NOMENCLATURE

BB	Broadband
CEA	French Alternative Energies and Atomic Energy Commission
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
dB	Decibel
DOE	Department of Energy
HNM	High Noise Model
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SP	Short-period

1 INTRODUCTION

Sandia National Laboratories has tested and evaluated an updated SMAD digitizer, developed by the French Alternative Energies and Atomic Energy Commission (CEA).

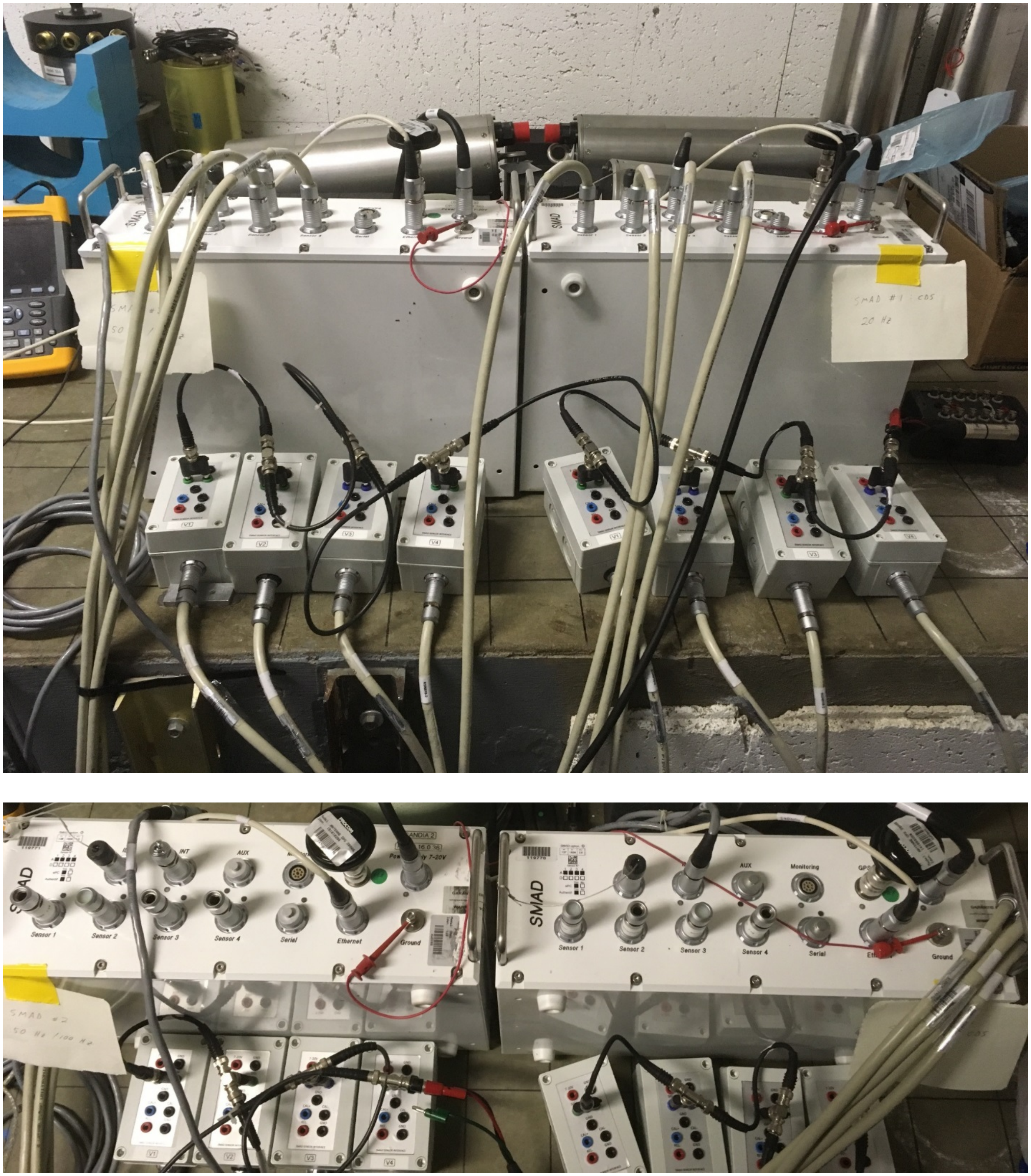

Figure 1 SMAD Digitizers

The SMAD digitizers are intended to record sensor output for seismic and infrasound monitoring applications. The purpose of this digitizer evaluation is to measure the performance characteristics in such areas as power consumption, input impedance, sensitivity, full scale, self-noise, dynamic range, system noise, response, passband, and timing. The SMAD digitizers have been updated since their last evaluation by Sandia to improve their performance when recording at a sample rate of 20 Hz for infrasound applications and 100 Hz for hydro-acoustic seismic stations. This evaluation focuses primarily on the 20 Hz and 100 Hz sample rates. The SMAD digitizers are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

The evaluation of the two SMAD digitizers, serial numbers 137 and 138 shown in the figure above, has identified that the digitizer's performance is consistent with their manufacturer's specifications.

2 TEST PLAN

This section describes the overall scope and process for how the testing of the SMAD digitizers will be performed. For a description of the individual test configurations details, see the relevant section for each test.

2.1 Test Facility

Testing of the SMAD digitizers was performed at Sandia National Laboratories' Facility for Acceptance, Calibration and Testing (FACT) located near Albuquerque, New Mexico, USA. The FACT site is at approximately 1830 meters in elevation.

Sandia National Laboratories (SNL), Ground-based Monitoring R&E Department has the capability of evaluating the performance of preamplifiers, digitizing waveform recorders and analog-to-digital converters/high-resolution digitizers for geophysical applications.

Tests are based on the Institute of Electrical and Electronics Engineers (IEEE) Standard 1057 for Digitizing Waveform Recorders and Standard 1241 for Analog to Digital Converters. The analyses based on these standards were performed in the frequency domain or time domain as required. When appropriate, instrumentation calibrations are traceable to the National Institute for Standards Technology (NIST).

The majority of the SMAD testing, with the exception of tests performed in the temperature chamber, were performed within the FACT sites underground bunker due to the bunker's stable temperature.

Figure 2 FACT Site Bunker

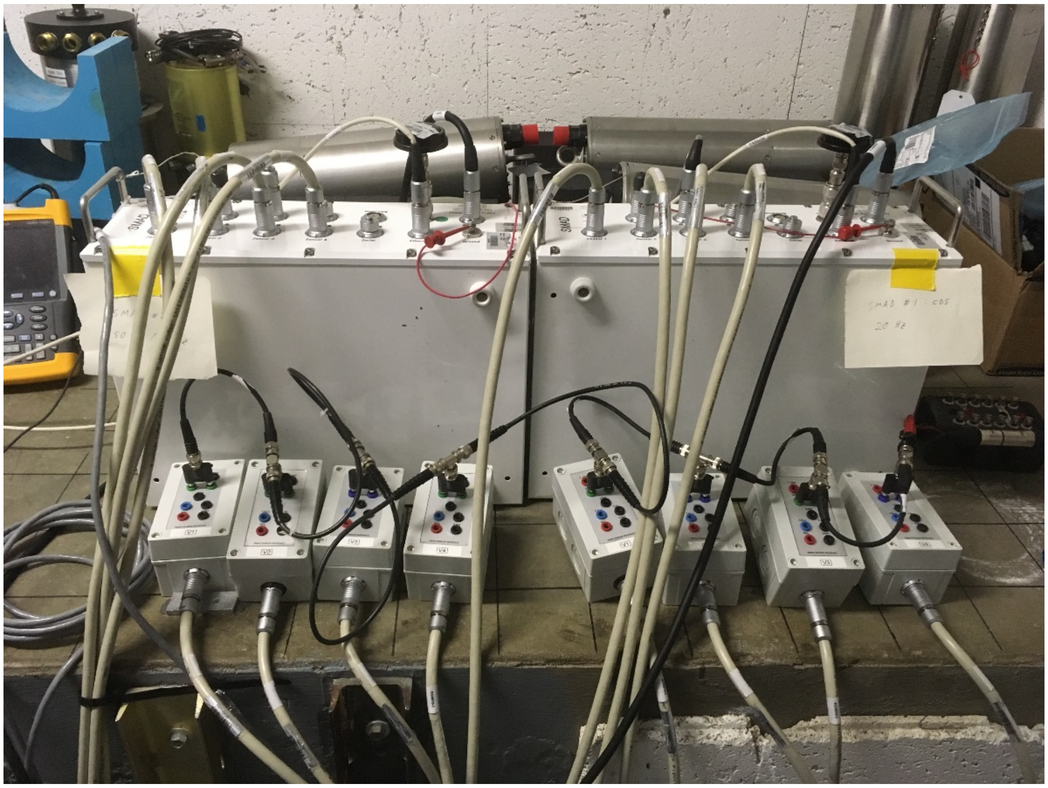

Figure 3 SMAD Digitizers within FACT Bunker

The temperature was recorded continuously throughout the testing by a calibrated Vaisala PT300U sensor and was maintained between 22 and 23 degrees Celsius.

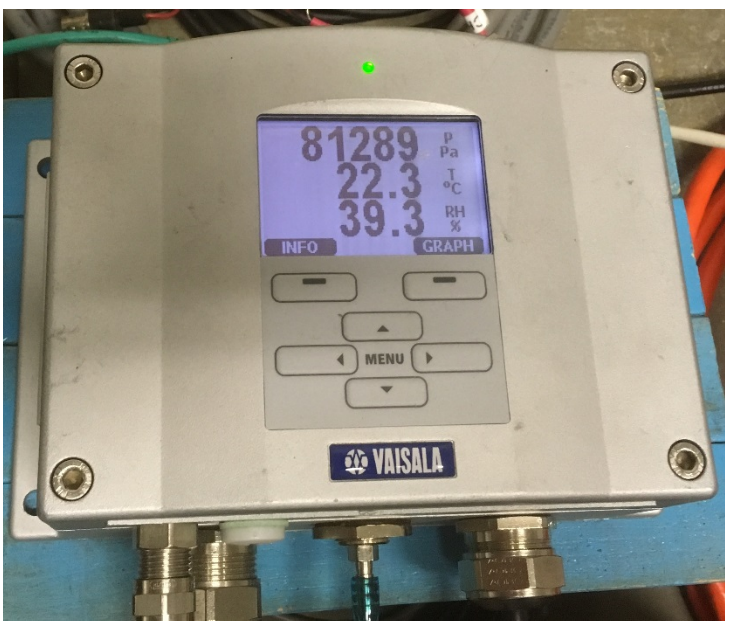

Figure 4 Vaisala Temperature Monitor within FACT Bunker

A GPS re-broadcaster operates within the bunker to provide the necessary timing source for the SMAD digitizers and other recording equipment present.

Figure 5 GPS Re-broadcaster

The SMAD digitizers were powered off of a BK Precision Model 1735A S/N 204F13116 laboratory power supply providing approximately 13 Volts.

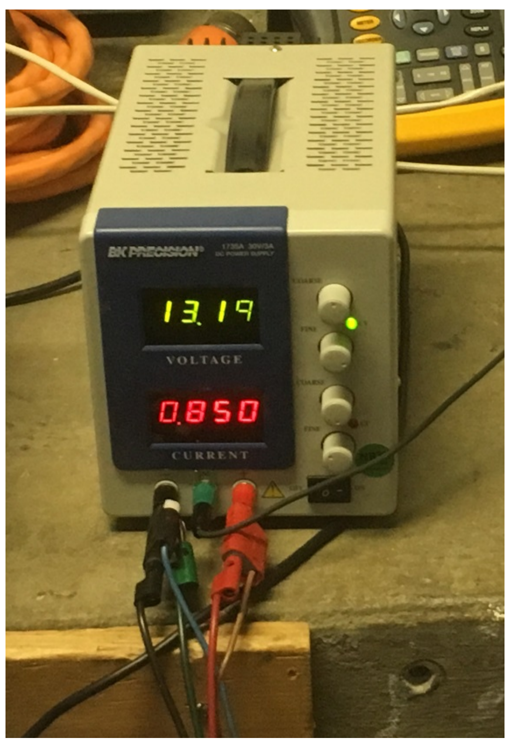

Figure 6 Laboratory Power Supply

2.2 Scope

The following table lists the tests and resulting evaluations that were performed at the various gain levels and sample rates of the SMAD digitizer.

Table 1 SMAD Tests performed

		Sample Rate		
Test	**Gain**	**50 Hz**	**20 Hz**	**100 Hz**
Power Consumption	G1		x	x
	G8	x		
Input Impedance **DC Accuracy, 10% of full scale** **AC Accuracy, 10% of full scale** **AC Full Scale, 100% of full scale** **AC Over Scale (Clip), 110% of full scale**	G1	x	x	x
	G2	x	x	x
	G4	x	x	x
	G8	x	x	x
Input Terminated Noise at 2x50 Ohms **System Noise (STS2, ZM500, MB2005, MB3a)** **Dynamic Range**	G1		x	x
	G2		x	x
	G4		x	x
	G8		x	x
Response Verification **Relative Transfer Function** **Passband** **Incoherent Noise (3-channel)**	G1		x	x
	G2			
	G4			
	G8	x		x
Common-Mode Rejection **Crosstalk**	G1			
	G2			
	G4			
	G8		x	x
Total Harmonic Distortion	G1	x	x	x
Sine Calibrator Amplitude	-		x	
Time-Tag Accuracy / Statistics	G1	x	x	x
	G8		x	
Time-Tag Drift	G1		x	x
Temperature Chamber – Input Terminated Noise	G1		x	x
	G2		x	x
	G4		x	x
	G8		x	x

2.3 Timeline

Testing of the SMAD digitizer was performed at Sandia National Laboratories between November 28 – December 4, 2017. Testing was performed using two SMAD digitizers, #137 and #138, so that the testing could be performed at different sample rates on each of digitizers simultaneously. The following schedule of testing was followed:

Table 2 Timeline of Testing

Day	Time	SMAD #137	SMAD #138
Monday November 28, 2016	Morning	Equipment setup and checkout 20 Hz at gains 1, 2, 4, 8 Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip	Equipment setup and checkout
	Lunch	20 Hz at gain 1 Total Harmonic Distortion	50 Hz (Channels 1 and 2) at gain 1 100 Hz (Channels 3 and 4) at gain 1 Total Harmonic Distortion
	Afternoon		50 Hz at gains 1, 2, 4, 8 Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip 100 Hz at gains 1, 2, 4, 8 Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip 100 Hz at gain 8 Power Consumption
	Overnight	20 Hz at gains 1, 2, 4, 8 Input Terminated Noise	100 Hz at gains 1, 2, 4, 8 Input Terminated Noise Identified issue with terminators used, test needs to be repeated
Tuesday November 29, 2016	Morning	20 Hz at gain 8 Crosstalk Common Mode Rejection	100 Hz at gain 8 Crosstalk Common Mode Rejection
	Lunch	20 Hz at gain 1 Analog Bandwidth Relative Transfer Function Response Incoherent Noise	100 Hz at gain 1 Analog Bandwidth Relative Transfer Function Response Incoherent Noise
	Afternoon	20 Hz at gain 8 Time Tag Statistics	50 Hz at gain 1 Time Tag Statistics

		20 Hz at gain 1 Time Tag Statistics	100 Hz at gain 1 Time Tag Statistics
	Overnight	20 Hz at gain 1 Time Tag Drift	100 Hz at gain 1 Time Tag Drift
Wednesday November 30, 2016	Morning	20 Hz at gain 1 Time Tag Recovery Calibrator Tests Sine Amplitude Sine Frequency Random Binary	100 Hz at gain 1 Time Tag Recovery
	Lunch	50 Hz at gain 8 Analog Bandwidth Relative Transfer Function Response Incoherent Noise	100 Hz at gain 8 Analog Bandwidth Relative Transfer Function Response Incoherent Noise
	Afternoon	Verify status bits in CD1 frames Power Consumption Tests	
	Overnight	20 Hz at gains 1, 2, 4, 8 Input Terminated Noise	100 Hz at gains 1, 2, 4, 8 Input Terminated Noise (repeated with corrected terminators)
Thursday December 1, 2016	Morning	Moved equipment out of FACT bunker and into temperature chamber	
	Lunch	Setup and validation of temperature chamber operation	
	Afternoon	Temperature chamber: -20 C, 40 C, 50 C, and 60 C 20 Hz at gains 1, 2, 4, 8 Input Terminated Noise	Temperature chamber: -20 C, 40 C, 50 C, and 60 C 100 Hz at gains 1, 2, 4, 8 Input Terminated Noise
	Overnight		
Friday December 2, 2016	Morning	Reviewed data from overnight. Packed up equipment and prepared for shipment back to CEA	

2.4 Evaluation Frequencies

The frequency range of the measurements is from 0.01 Hz to 40 Hz. Specifically, the frequencies from the function below which generates standardized octave-band values in Hz (ANSI S1.6-1984) with F_0 = 1 Hz:

$$F(n) = F_0 \times 10^{(n/10)}$$

For measurements taken using either broadband or tonal signals, the following frequency values shall be used for n = -20, -19, …, 16, 17. The nominal center frequency values, in Hz, are:

0.01,	0.0125,	0.016,	0.020,	0.025,	0.0315,	0.040,	0.050,	0.063,	0.08,
0.10,	0.125,	0.16,	0.20,	0.25,	0.315,	0.40,	0.50,	0.63,	0.8,
1.0,	1.25,	1.6,	2.0,	2.5,	3.15,	4.0,	5.0,	6.3,	8.0,
10.0,	12.5,	16.0,	20.0,	25.0,	31.5,	40.0			

3 TEST EVALUATION

3.1 Power Consumption

The Power Consumption test is used to measure the amount of power that an actively powered digitizer consumes during its operation.

3.1.1 Measurand

The quantity being measured is the average watts of power consumption via the intermediary measurements of voltage and current.

3.1.2 Configuration

The digitizer is connected to a power supply, current meter, and voltage meter as shown in the diagram below.

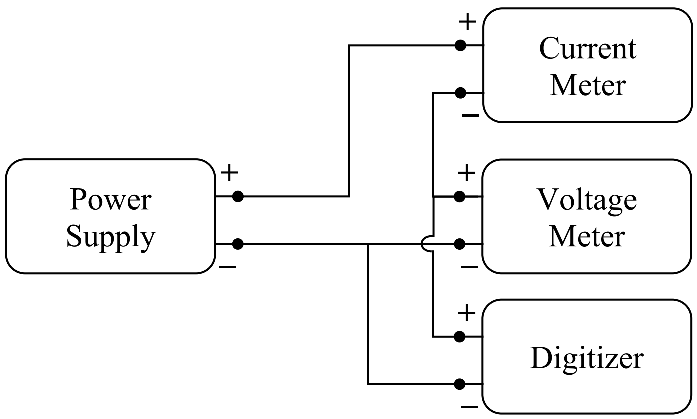

Figure 7 Power Consumption Configuration Diagram

Figure 8 Power Consumption Configuration Picture

Table 3 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Power Supply	BK Precision 1735A DC Power Supply	204F13116	12 V
Current Meter	Agilent 3458A	MY45048372	DC Current Mode
Voltage Meter	Agilent 3458A	MY45048371	DC Voltage Mode

The meters used to measure current and voltage have active calibrations from the Primary Standard Laboratory at Sandia.

3.1.3 Analysis

Measurements of the average current and voltage from the power supply are taken from the respective meters, preferably from a time-series recording:

$V \text{ and } I$

The average power in watts is then calculated as the product of the current and voltage:

$P = V * I$

3.1.4 Result

The resulting voltage, current, and power consumption levels are shown in the table below.

Table 4 Power Consumption Results

	Voltage	Current	Power
#137, 20 Hz, gain 1	12.8 V	350 – 410 mA	4.48 W - 5.25 W
#138, 100 Hz, gain 8	12.67 V	520 – 520 mA	6.59 W - 6.97 W
#137, 50 Hz, gain 8, 4 channels	13.07 V	330 – 420 mA	4.31 W- 5.49 W
#137, 50 Hz, gain 8, 3 channels	13.07 V	325 – 400 mA	4.25 W - 5.23 W
#137, 50 Hz, gain 8, 2 channels	13.07 V	320 – 380 mA	4.18 W- 4.97 W
#137, 50 Hz, gain 8, 1 channels	13.07 V	315 – 380 mA	4.12 W- 4.97 W

The SMAD digitizers were observed to consume between 4 and 7 watts of power during operation depending upon their configuration. In general, it appears that higher sample rates result in greater power consumption such as 20 Hz consuming between 4.5 – 5.25 W, 50 Hz consuming between 4.3 and 5.5 W, and 100 Hz consuming between 6.5 and 7 W. Disabling unneeded channels appears to result in some improvement in reducing power consumption. However, the reduction is only on the order of 0.1 – 0.2 W per channel.

3.2 Input Impedance

The Input Impedance test is used to measure the real DC input impedance of a digitizer recording channel during its operation.

3.2.1 Measurand

The quantity being measured is ohms of impedance of the digitizer input channel.

3.2.2 Configuration

The digitizer is connected to a meter configured to measure impedance as shown in the diagram below.

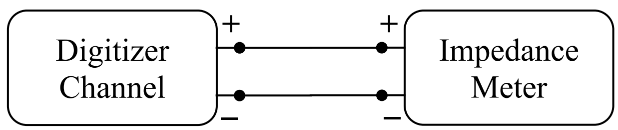

Figure 9 Input Impedance Configuration Diagram

Table 5 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Impedance Meter	Agilent 3458A	MY45048372	DC Impedance

The meter used to measure impedance has an active calibration from the Primary Standard Laboratory at Sandia.

3.2.3 Analysis

Measurements of the average impedance from each digitizer input channel are read from the meter, preferably averaged from a time-series recording.

3.2.4 Result

The measured impedance for each of the digitizer channels are shown in the table below.

Table 6 Input Impedance Results

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	32.0030 kOhm	32.0060 kOhm	32.0045 kOhm	32.0040 kOhm
#137, 20 Hz, gain 2	32.0025 kOhm	32.0160 kOhm	32.0045 kOhm	32.0040 kOhm
#137, 20 Hz, gain 4	32.0023 kOhm	32.0160 kOhm	32.0044 kOhm	32.0035 kOhm
#137, 20 Hz, gain 8	32.0022 kOhm	32.0159 kOhm	32.0043 kOhm	32.0034 kOhm
#138, 50 Hz, gain 1	32.0109 kOhm	32.0079 kOhm	32.0025 kOhm	32.0068 kOhm
#138, 50 Hz, gain 2	32.0108 kOhm	32.0076 kOhm	32.0025 kOhm	32.0067 kOhm
#138, 50 Hz, gain 4	32.0108 kOhm	32.0076 kOhm	32.0024 kOhm	32.0067 kOhm
#138, 50 Hz, gain 8	32.0107 kOhm	32.0076 kOhm	32.0024 kOhm	32.0066 kOhm
#138, 100 Hz, gain 1	32.0107 kOhm	32.0081 kOhm	32.0023 kOhm	32.0066 kOhm
#138, 100 Hz, gain 2	32.0107 kOhm	32.0078 kOhm	32.0023 kOhm	32.0065 kOhm
#138, 100 Hz, gain 4	32.0107 kOhm	32.0079 kOhm	32.0022 kOhm	32.0065 kOhm
#138, 100 Hz, gain 8	32.0106 kOhm	32.0076 kOhm	32.0022 kOhm	32.0064 kOhm

The measured input impedance of the SMAD digitizer channels were all within 0.05 % of their nominal specification of 32 kOhm. There do not appear to be any significant differences in channel impedance due to changes in gain level or sample rate.

3.3 DC Accuracy

The DC Accuracy test is used to measure the DC offset and bit weight of a digitizer channel by recording a known positive and negative dc signal at a reference voltage from a precision voltage source.

3.3.1 Measurand

The quantity being measured is the digitizer input channels DC offset in volts and the bit weight in volts/count.

3.3.2 Configuration

The digitizer is connected to a DC signal source and a meter configured to measure voltage as shown in the diagram below.

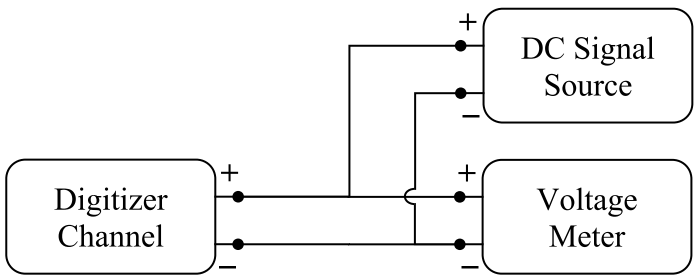

Figure 10 DC Accuracy Configuration Diagram

Figure 11 DC Accuracy Configuration Picture

Table 7 DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	SRS DS360	123669	DC Voltage, 10% FS
Voltage Meter	Agilent 3458A	MY45048372	10 V full scale

The DC Signal Source is configured to generate a DC voltage with an amplitude of approximately 10% of the digitizer input channel's full scale. One minute of data is recorded with a positive amplitude followed by one minute of data with a negative amplitude.

The meter and the digitizer channel record the described DC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz.

The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.3.3 Analysis

A minimum of a thirty-second-time window is defined on the data for each of the positive and negative voltage signal segment.

The average of each of the positive and negative segments are computed from the reference meter in volts:
V_{pos} and V_{neg}

The average of each of the positive and negative segments are computed from the digitizer channel in counts:
C_{pos} and C_{neg}

The digitizer bit weight in Volts / count is computed:

$$Bitweight = \frac{V_{pos} - V_{neg}}{C_{pos} - C_{neg}}$$

The digitizer DC offset is computed:

$$DC\ Offset = Bitweight * \frac{(C_{pos} + C_{neg})}{2}$$

3.3.4 Result

The figure below shows a representative waveform time series for the recording made on the reference meter and a digitizer channel under test. The window regions bounded by the red and green lines indicate the segment of data used to evaluate the positive and negative regions of data, respectively.

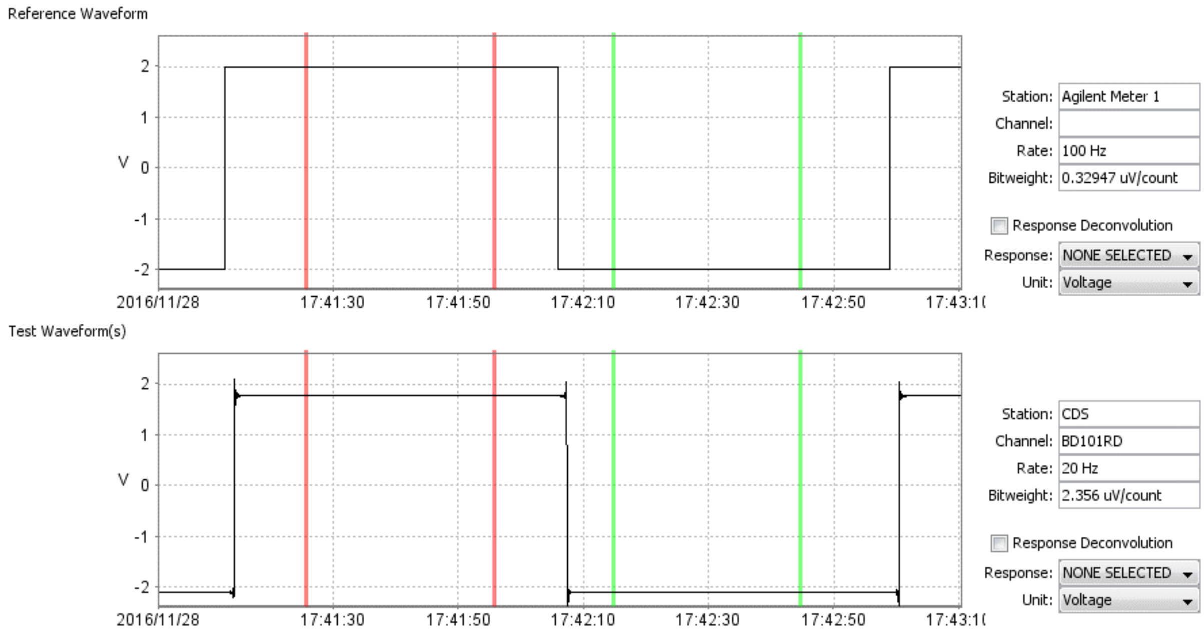

Figure 12 DC Accuracy Time Series

The following table contains the computed bit weights for each of the channels, sample rates, and gain levels.

Table 8 DC Accuracy Bitweight

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	2.4293 uV/count	2.4275 uV/count	2.4259 uV/count	2.4284 uV/count
#137, 20 Hz, gain 2	1.2148 uV/count	1.2138 uV/count	1.2131 uV/count	1.2144 uV/count
#137, 20 Hz, gain 4	0.6080 uV/count	0.6073 uV/count	0.6070 uV/count	0.6073 uV/count
#137, 20 Hz, gain 8	0.3041 uV/count	0.3031 uV/count	0.3034 uV/count	0.3031 uV/count
#138, 50 Hz, gain 1	2.4202 uV/count	2.4183 uV/count	2.4197 uV/count	2.4202 uV/count
#138, 50 Hz, gain 2	1.2108 uV/count	1.2096 uV/count	1.2102 uV/count	1.2104 uV/count
#138, 50 Hz, gain 4	0.6053 uV/count	0.6052 uV/count	0.6056 uV/count	0.6050 uV/count
#138, 50 Hz, gain 8	0.3029 uV/count	0.3028 uV/count	0.3028 uV/count	0.3027 uV/count
#138, 100 Hz, gain 1	2.4219 uV/count	2.4201 uV/count	2.4215 uV/count	2.4220 uV/count
#138, 100 Hz, gain 2	1.2117 uV/count	1.2105 uV/count	1.2111 uV/count	1.2113 uV/count
#138, 100 Hz, gain 4	0.6058 uV/count	0.6056 uV/count	0.6060 uV/count	0.6054 uV/count
#138, 100 Hz, gain 8	0.3030 uV/count	0.3030 uV/count	0.3030 uV/count	0.3031 uV/count

The nominal bit weights provided by CEA were specified according to the following formula:

$$bit\ weight = \frac{39.53\ V}{Gain\ \times\ 2^{24}}$$

This results in nominal bit weights of 2.3562 uV/count for a gain of 1, 1.1781 uV/count for a gain of 2, 0.5890 uV/count for a gain of 4, and 0.2945 uV/count for a gain of 8. The observed bit weights were between 2.7 % and 3.3 % greater than the nominal values.

Table 9 DC Accuracy Offset

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	-179.40 mV	-177.28 mV	-170.38 mV	-178.69 mV
#137, 20 Hz, gain 2	-85.17 mV	-84.11 mV	-80.66 mV	-84.83 mV
#137, 20 Hz, gain 4	-43.21 mV	-42.66 mV	-40.94 mV	-42.99 mV
#137, 20 Hz, gain 8	-22.18 mV	-21.86 mV	-21.04 mV	-22.03 mV
#138, 50 Hz, gain 1	-175.75 mV	-171.27 mV	-171.32 mV	-174.70 mV
#138, 50 Hz, gain 2	-83.36 mV	-81.10 mV	-81.12 mV	-82.81 mV
#138, 50 Hz, gain 4	-42.26 mV	-41.15 mV	-41.18 mV	-41.97 mV
#138, 50 Hz, gain 8	-21.59 mV	-21.16 mV	-21.16 mV	-21.71 mV
#138, 100 Hz, gain 1	-175.51 mV	-171.04 mV	-171.09 mV	-174.47 mV
#138, 100 Hz, gain 2	-83.24 mV	-80.98 mV	-81.01 mV	-82.69 mV
#138, 100 Hz, gain 4	-42.20 mV	-41.09 mV	-41.12 mV	-41.91 mV
#138, 100 Hz, gain 8	-21.68 mV	-21.13 mV	-21.13 mV	-21.56 mV

The observed DC offsets corresponding to approximately 0.42 % of the nominal full-scale value at each of the gain levels.

3.4 AC Accuracy

The AC Accuracy test is used to measure the bit weight and DC offset of a digitizer channel by recording a known AC signal at a reference voltage from a precision voltage source.

3.4.1 Measurand

The quantity being measured is the digitizer input channels bit weight in volts/count and DC offset in volts.

3.4.2 Configuration

The digitizer is connected to a AC signal source and a meter configured to measure voltage as shown in the diagram below.

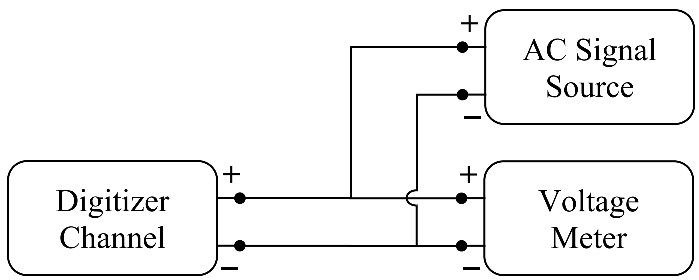

Figure 13 AC Accuracy Configuration Diagram

Figure 14 AC Accuracy Configuration Picture

Table 10 AC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 10% FS
Voltage Meter	Agilent 3458A	MY45048372	10 V full scale

The AC Signal Source is configured to generate a AC voltage with an amplitude of approximately 10% of the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. One minute of data is recorded.

The meter and the digitizer channel record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz, which is a minimum of 100 times the frequency of the signal of interest in order to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.01 %.

The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.4.3 Analysis

A minimum of a 10 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment.

A four parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference meter in Volts and the digitizer channel in Counts in order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

$$V_{ref} \sin\left(2\, pi\, f_{ref}\, t + \theta_{ref}\right) + V_{dc}$$

$$C_{meas} \sin\left(2\, pi\, f_{meas}\, t + \theta_{meas}\right) + C_{dc}$$

The digitizer bit weight in Volts / count is computed:

$$Bitweight = \frac{V_{ref}}{C_{meas}}$$

3.4.4 Result

The figure below shows a representative waveform time series for the recording made on the reference meter and a digitizer channel under test. The window regions bounded by the red lines indicate the segment of data used for analysis.

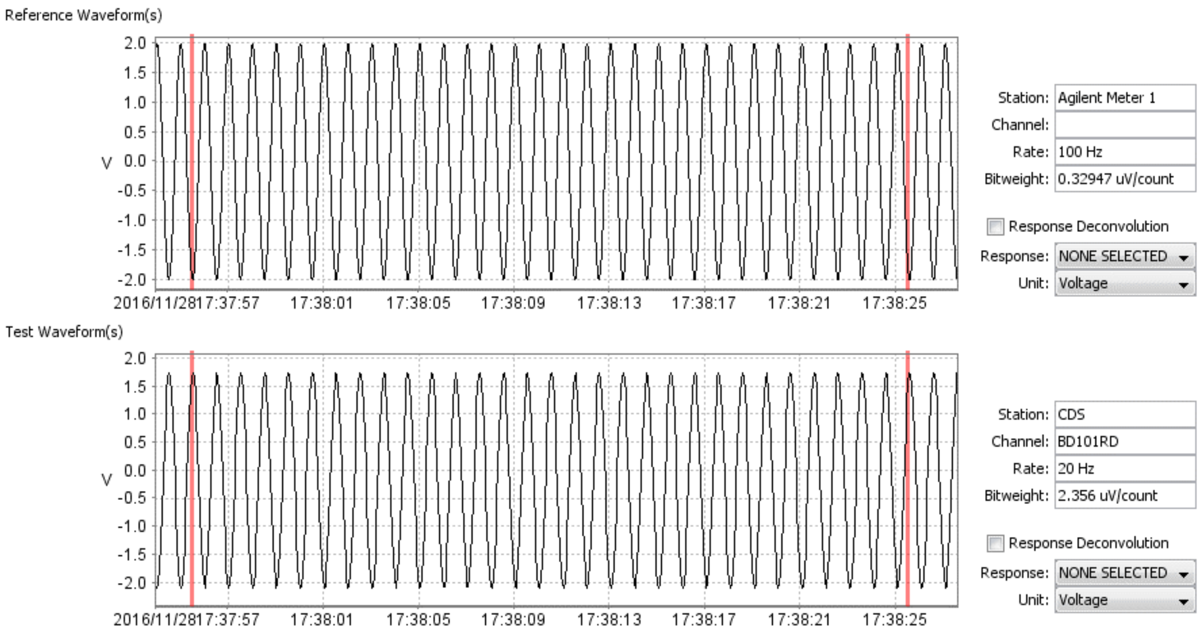

Figure 15 AC Accuracy Time Series

The following table contains the computed bit weights for each of the channels, sample rates, and gain levels.

Table 11 AC Accuracy Bitweight

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	2.4263 uV/count	2.4244 uV/count	2.4229 uV/count	2.4254 uV/count
#137, 20 Hz, gain 2	1.2133 uV/count	1.2123 uV/count	1.2116 uV/count	1.2129 uV/count
#137, 20 Hz, gain 4	0.6072 uV/count	0.6066 uV/count	0.6062 uV/count	0.6065 uV/count
#137, 20 Hz, gain 8	0.3041 uV/count	0.3031 uV/count	0.3034 uV/count	0.3031 uV/count
#138, 50 Hz, gain 1	2.4252 uV/count	2.4234 uV/count	2.4248 uV/count	2.4252 uV/count
#138, 50 Hz, gain 2	1.2133 uV/count	1.2121 uV/count	1.2128 uV/count	1.2129 uV/count
#138, 50 Hz, gain 4	0.6066 uV/count	0.6064 uV/count	0.6068 uV/count	0.6062 uV/count
#138, 50 Hz, gain 8	0.3034 uV/count	0.3034 uV/count	0.3034 uV/count	0.3035 uV/count
#138, 100 Hz, gain 1	2.4236 uV/count	2.4218 uV/count	2.4232 uV/count	2.4236 uV/count
#138, 100 Hz, gain 2	1.2125 uV/count	1.2113 uV/count	1.2120 uV/count	1.2121 uV/count
#138, 100 Hz, gain 4	0.6062 uV/count	0.6060 uV/count	0.6064 uV/count	0.6058 uV/count
#138, 100 Hz, gain 8	0.3032 uV/count	0.3032 uV/count	0.3032 uV/count	0.3033 uV/count

The nominal bit weights provided by CEA were specified according to the following formula:

$$bit\ weight = \frac{39.53\ V}{Gain\ \times\ 2^{24}}$$

This results in nominal bit weights of 2.3562 uV/count for a gain of 1, 1.1781 uV/count for a gain of 2, 0.5890 uV/count for a gain of 4, and 0.2945 uV/count for a gain of 8. The observed bit weights were between 3.0 % and 3.1 % greater than the nominal values.

Table 12 AC Accuracy Offset

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	-191.89 mV	-189.77 mV	-182.87 mV	-191.18 mV
#137, 20 Hz, gain 2	-91.43 mV	-90.37 mV	-86.92 mV	-91.09 mV
#137, 20 Hz, gain 4	-46.34 mV	-45.80 mV	-44.07 mV	-46.13 mV
#137, 20 Hz, gain 8	-23.75 mV	-23.43 mV	-22.61 mV	-23.60 mV
#138, 50 Hz, gain 1	-188.34 mV	-183.86 mV	-183.91 mV	-187.30 mV
#138, 50 Hz, gain 2	-89.65 mV	-87.38 mV	-87.41 mV	-89.10 mV
#138, 50 Hz, gain 4	-45.40 mV	-44.29 mV	-44.32 mV	-45.12 mV
#138, 50 Hz, gain 8	-23.28 mV	-22.73 mV	-22.74 mV	-23.16 mV
#138, 100 Hz, gain 1	-188.13 mV	-183.66 mV	-183.71 mV	-187.09 mV
#138, 100 Hz, gain 2	-89.53 mV	-87.28 mV	-87.30 mV	-88.99 mV
#138, 100 Hz, gain 4	-45.35 mV	-44.24 mV	-44.27 mV	-45.06 mV
#138, 100 Hz, gain 8	-23.25 mV	-22.71 mV	-22.71 mV	-23.14 mV

The observed DC offsets corresponding to approximately 0.45 % of the nominal full-scale value at each of the gain levels.

3.5 Input Shorted Offset

The Input Shorted Offset test measures the amount of DC offset present on a digitizer by collecting waveform data from an input channel that has been terminated. Thus, any signal present on the recorded waveform should be solely due to any internal offset of the digitizer.

3.5.1 Measurand

The quantity being measured is the digitizer input channels DC offset in volts.

3.5.2 Configuration

The digitizer input channel is connected to a shorting resistor as shown in the diagram below.

Figure 16 Input Shorted Offset Configuration Diagram

Figure 17 Input Shorted Offset Configuration Picture

Table 13 Input Shorted Offset Testbed Equipment

	Impedance
Resistor	100 ohm

Two hours of data is recorded at the very end of an over-night termination test so that the channels have sufficient time to settle.

3.5.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$$x[n],\ 0 \leq n \leq N-1$$

The mean value, in volts, is evaluated:

$$Offset = \frac{1}{N}\sum_{n=0}^{N-1} x[n]$$

3.5.4 Result

The figure below shows a representative waveform time series for the recording made on a digitizer channel under test. The window regions bounded by the red lines indicate the segment of data used for analysis.

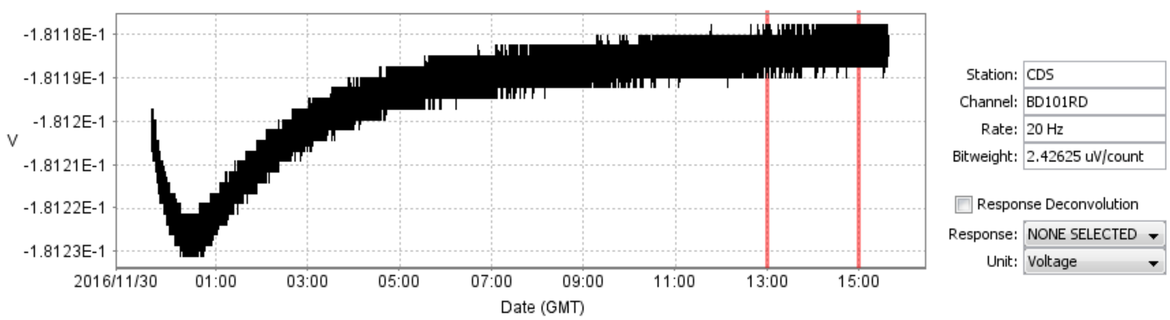

Figure 18 Input Shorted Offset Time Series

The following table contains the computed DC offsets in volts for each of the channels, sample rates, and gain levels.

Table 14 Input Shorted Offset

	BD1 (gain 1)	BD2 (gain2)	BD3 (gain 4)	BD4 (gain 8)
#137, 20 Hz	-181.18 mV	-89.51 mV	-43.06 mV	-22.52 mV
#138, 100 Hz	-177.21 mV	-86.37 mV	-43.23 mV	-22.04 mV

The observed Input Shorted Offsets corresponding to approximately 0.45 % of the nominal full-scale at each of the gain levels.

3.6 AC Full Scale

The AC Full Scale test is used to validate the nominal full scale of a digitizer channel by recording a known AC signal with a voltage equal to the manufacturer's nominal full scale.

3.6.1 Measurand

The quantity being measured is the digitizer input channels full scale in volts.

3.6.2 Configuration

The digitizer is connected to an AC signal source and a meter configured to measure voltage as shown in the diagram below.

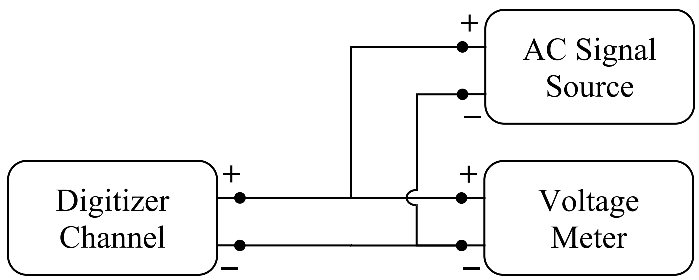

Figure 19 AC Full Scale Configuration Diagram

Figure 20 AC Full Scale Configuration Picture

Table 15 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal

			Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 100% FS
Voltage Meter	Agilent 3458A	MY45048372	1 V full scale

The AC Signal Source is configured to generate a AC voltage with an amplitude equal to the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. One minute of data is recorded.

The meter and the digitizer channel record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz, which is a minimum of 100 times the frequency of the signal of interest in order to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.01 %.

The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.6.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \leq n \leq N-1$

A short window is defined on the data around one of peak of the positive and negative peaks. The value within each positive and negative window is recorded.

The time series data is compared against the reference to verify that there is no visible limiting of the values near the full scale.

3.6.4 Result

The figure below shows a representative waveform time series for the recording made on the reference meter and a digitizer channel under test. The window regions bounded by the red and green lines indicate the segment of data used to evaluate the positive and negative regions of data, respectively.

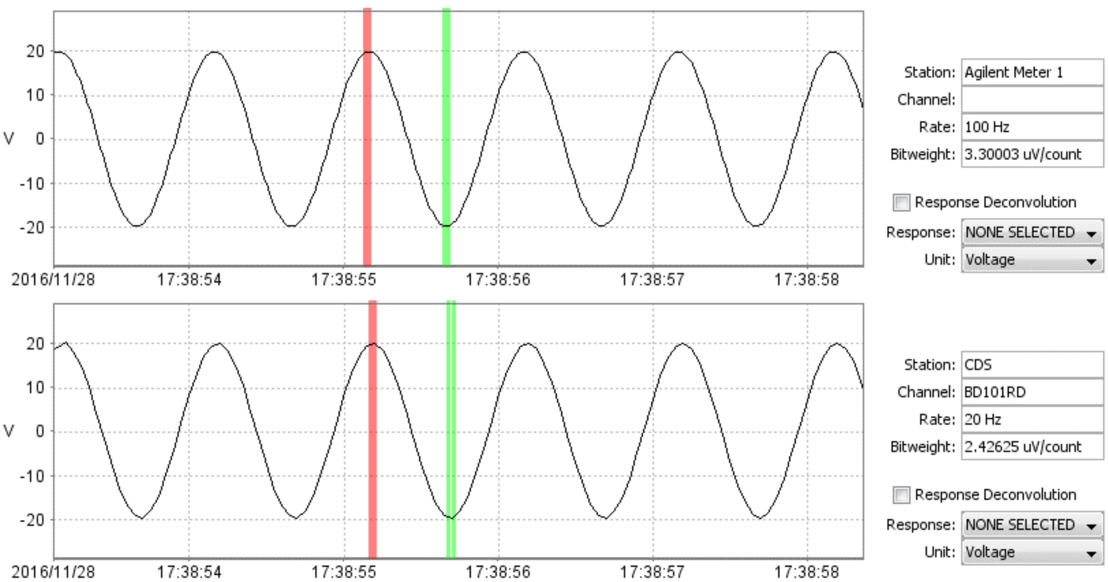

Figure 21 AC Full Scale Time Series

The following tables contain the computed positive peak, negative peak, and peak-to-peak voltages ranges for each of the channels, sample rates, and gain levels.

Table 16 AC Full Scale Positive Peak

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	19.73 V	19.62 V	19.63 V	19.63 V	19.62 V
#137, 20 Hz, gain 2	9.85 V	9.70 V	9.70 V	9.71 V	9.70 V
#137, 20 Hz, gain 4	4.93 V	4.85 V	4.86 V	4.85 V	4.85 V
#137, 20 Hz, gain 8	2.46 V	2.43 V	2.42 V	2.42 V	2.42 V
#138, 50 Hz, gain 1	19.81 V	19.67 V	19.62 V	19.61 V	19.61 V
#138, 50 Hz, gain 2	9.90 V	9.83 V	9.83 V	9.83 V	9.83 V
#138, 50 Hz, gain 4	4.91 V	4.91 V	4.91 V	4.91 V	4.91 V
#138, 50 Hz, gain 8	2.47 V	2.45 V	2.45 V	2.45 V	2.45 V
#138, 100 Hz, gain 1	19.79 V	19.67 V	19.68 V	19.68 V	19.67 V
#138, 100 Hz, gain 2	9.91 V	9.55 V	9.56 V	9.56 V	9.55 V
#138, 100 Hz, gain 4	4.95 V	4.91 V	4.91 V	4.91 V	4.91 V
#138, 100 Hz, gain 8	2.47 V	2.45 V	2.45 V	2.45 V	2.45 V

Table 17 AC Full Scale Negative Peak

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	-19.83 V	-20.01 V	-20.00 V	-20.00 V	-20.00 V
#137, 20 Hz, gain 2	-9.88 V	-9.90 V	-9.94 V	-9.93 V	-9.94 V
#137, 20 Hz, gain 4	-4.95 V	-4.96 V	-4.96 V	-4.96 V	-4.96 V
#137, 20 Hz, gain 8	-2.48 V	-2.48 V	-2.49 V	-2.48 V	-2.49 V
#138, 50 Hz, gain 1	-19.81 V	-20.04 V	-20.03 V	-19.96 V	-20.04 V
#138, 50 Hz, gain 2	-9.92 V	-10.02 V	-10.02 V	-10.02 V	-10.02 V
#138, 50 Hz, gain 4	-4.96 V	-5.02 V	-5.02 V	-5.02 V	-5.02 V
#138, 50 Hz, gain 8	-2.49 V	-2.51 V	-2.51 V	-2.51 V	-2.51 V
#138, 100 Hz, gain 1	-19.79 V	-20.03 V	-20.03 V	-20.03 V	-20.03 V
#138, 100 Hz, gain 2	-9.93 V	-9.74 V	-9.75 V	-9.74 V	-9.74 V
#138, 100 Hz, gain 4	-4.97 V	-5.02 V	-5.02 V	-5.02 V	-5.02 V
#138, 100 Hz, gain 8	-2.49 V	-2.52 V	-2.51 V	-2.51 V	-2.52 V

Table 18 AC Full Scale Peak-to-Peak

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	39.56 V	39.63 V	39.63 V	39.63 V	39.63 V
#137, 20 Hz, gain 2	19.73 V	19.61 V	19.64 V	19.64 V	19.64 V
#137, 20 Hz, gain 4	9.87 V	9.81 V	9.82 V	9.81 V	9.81 V
#137, 20 Hz, gain 8	4.94 V	4.91 V	4.91 V	4.90 V	4.91 V
#138, 50 Hz, gain 1	39.62 V	39.71 V	39.65 V	39.58 V	39.65 V
#138, 50 Hz, gain 2	19.82 V	19.85 V	19.85 V	19.85 V	19.85 V
#138, 50 Hz, gain 4	9.87 V	9.92 V	9.92 V	9.92 V	9.92 V
#138, 50 Hz, gain 8	4.96 V	4.96 V	4.96 V	4.96 V	4.96 V
#138, 100 Hz, gain 1	39.58 V	39.70 V	39.71 V	39.71 V	39.71 V
#138, 100 Hz, gain 2	19.85 V	19.29 V	19.31 V	19.30 V	19.30 V
#138, 100 Hz, gain 4	9.92 V	9.93 V	9.93 V	9.93 V	9.93 V
#138, 100 Hz, gain 8	4.96 V	4.96 V	4.96 V	4.96 V	4.96 V

For all sample rates and gain levels, the digitizer channels were able to fully resolve the sinusoid with a peak-to-peak amplitude at or near the channels claimed full scale value without any signs of flattening that would indicate that clipping is occurring.

The nominal full scale provided by CEA were specified according to the following formula:

$$full\ scale = \frac{39.53\ V}{Gain}$$

3.7 AC Over Scale

The AC Over Scale test is used to validate the nominal full scale of a digitizer channel by recording a known AC signal with a voltage that exceeds the manufacturer's nominal full scale.

3.7.1 Measurand

The quantity being measured is the digitizer input channels full scale in volts.

3.7.2 Configuration

The digitizer is connected to an AC signal source and a meter configured to measure voltage as shown in the diagram below.

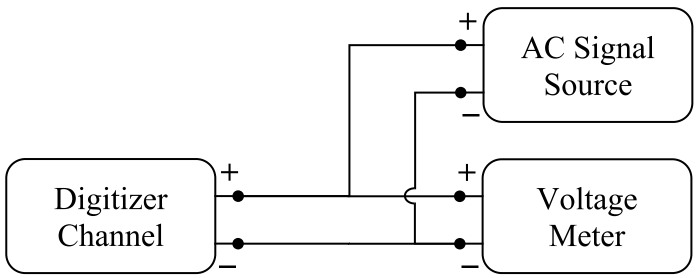

Figure 22 AC Over Scale Configuration Diagram

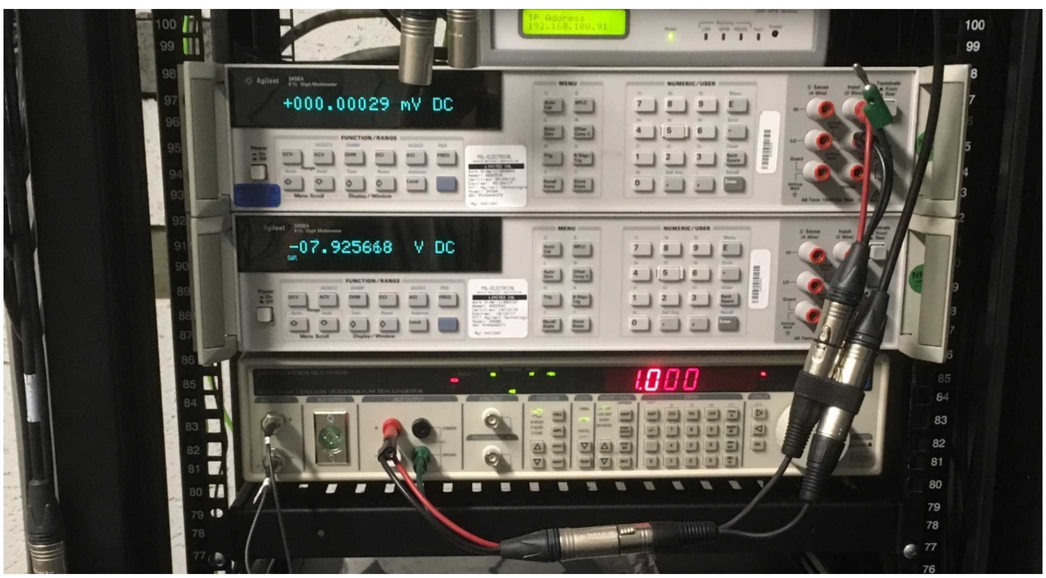

Figure 23 AC Over Scale Configuration Picture

Table 19 AC Over Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 110% FS
Voltage Meter	Agilent 3458A	MY45048372	1 V full scale

The AC Signal Source is configured to generate an AC voltage with an amplitude 110% of the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. 10 seconds of data is recorded.

Caution is taken to ensure that the voltage amplitude does not exceed the safety limits of the recording channel and that the test is short in duration so as to minimize the potential for damage to the equipment. In the case of the SMAD, the voltage protection circuit is designed to protect against signals up to 45 Vpp. The largest signal generated was less than 44 Vpp.

The meter and the digitizer channel record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz, which is a minimum of 100 times the frequency of the signal of interest in order to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.01 %.

The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.7.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \leq n \leq N-1$

A short window is defined on the data around one of peak of the positive and negative peaks. The value within each positive and negative window is recorded.

The time series data is compared against the reference to verify that there is no visible limiting of the values near the full scale.

3.7.4 Result

The figure below shows a representative waveform time series for the recording made on the reference meter and a digitizer channel under test. The window regions bounded by the red and green lines indicate the segment of data used to evaluate the positive and negative regions of data, respectively.

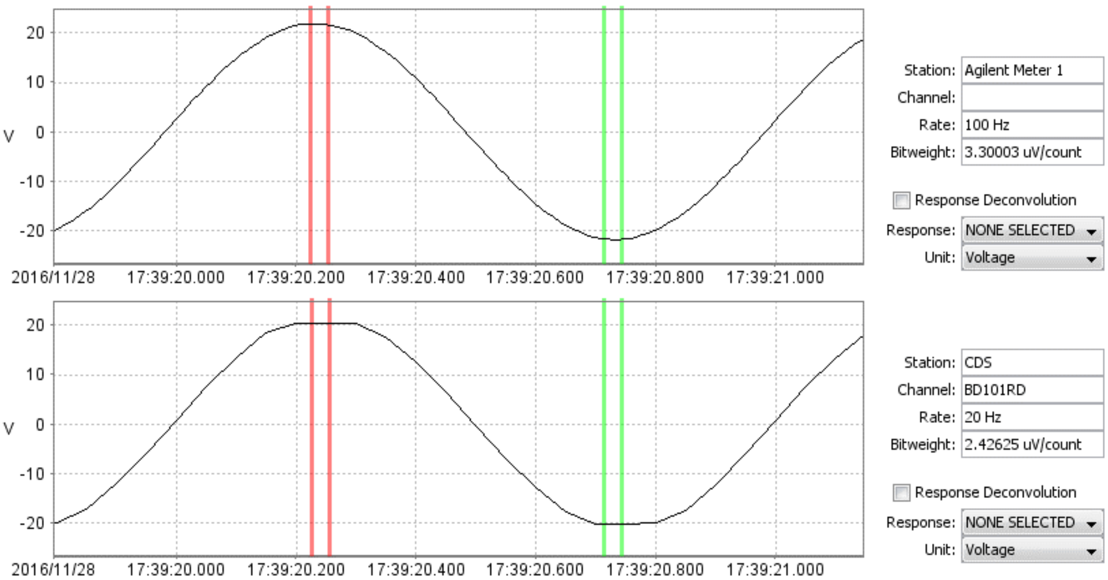

Figure 24 AC Over Scale Time Series

The following tables contains the computed positive peak, negative peak, and peak-to-peak voltages ranges for each of the channels, sample rates, and gain levels.

Table 20 AC Over Scale Positive Peak

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	21.80 V	20.37 V	20.36 V	20.34 V	20.37 V
#137, 20 Hz, gain 2	10.85 V	10.19 V	10.18 V	10.17 V	10.18 V
#137, 20 Hz, gain 4	5.42 V	5.10 V	5.09 V	5.09 V	5.09 V
#137, 20 Hz, gain 8	2.70 V	2.55 V	2.54 V	2.54 V	2.54 V
#138, 50 Hz, gain 1	21.81 V	20.29 V	20.27 V	20.28 V	20.28 V
#138, 50 Hz, gain 2	10.90 V	10.14 V	10.13 V	10.14 V	10.14 V
#138, 50 Hz, gain 4	5.43 V	5.08 V	5.07 V	5.07 V	5.07 V
#138, 50 Hz, gain 8	2.71 V	2.54 V	2.54 V	2.54 V	2.54 V
#138, 100 Hz, gain 1	21.75 V	20.28 V	20.27 V	20.28 V	20.28 V
#138, 100 Hz, gain 2	10.90 V	10.15 V	10.14 V	10.14 V	10.14 V
#138, 100 Hz, gain 4	5.44 V	5.07 V	5.07 V	5.08 V	5.07 V
#138, 100 Hz, gain 8	2.72 V	2.54 V	2.54 V	2.54 V	2.54 V

Table 21 AC Over Scale Negative Peak

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	-21.81 V	-20.31 V	-20.29 V	-20.28 V	-20.30 V
#137, 20 Hz, gain 2	-10.86 V	-10.18 V	-10.17 V	-10.16 V	-10.17 V
#137, 20 Hz, gain 4	-5.44 V	-5.09 V	-5.09 V	-5.09 V	-5.08 V
#137, 20 Hz, gain 8	-2.73 V	-2.55 V	-2.54 V	-2.54 V	-2.54 V
#138, 50 Hz, gain 1	-21.82 V	-20.28 V	-20.28 V	-20.29 V	-20.29 V
#138, 50 Hz, gain 2	-10.91 V	-10.15 V	-10.14 V	-10.15 V	-10.15 V
#138, 50 Hz, gain 4	-5.45 V	-5.08 V	-5.08 V	-5.08 V	-5.07 V
#138, 50 Hz, gain 8	-2.74 V	-2.54 V	-2.54 V	-2.54 V	-2.54 V
#138, 100 Hz, gain 1	-21.75 V	-20.28 V	-20.27 V	-20.28 V	-20.28 V
#138, 100 Hz, gain 2	-10.91 V	-10.15 V	-10.14 V	-10.14 V	-10.15 V
#138, 100 Hz, gain 4	-5.46 V	-5.07 V	-5.07 V	-5.08 V	-5.07 V
#138, 100 Hz, gain 8	-2.74 V	-2.54 V	-2.54 V	-2.54 V	-2.54 V

Table 22 AC Over Scale Peak-to-Peak

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	43.62 V	40.68 V	40.65 V	40.62 V	40.67 V
#137, 20 Hz, gain 2	21.71 V	20.37 V	20.35 V	20.33 V	20.36 V
#137, 20 Hz, gain 4	10.86 V	10.19 V	10.18 V	10.17 V	10.18 V
#137, 20 Hz, gain 8	5.43 V	5.10 V	5.08 V	5.09 V	5.08 V
#138, 50 Hz, gain 1	43.63 V	40.57 V	40.55 V	40.57 V	40.57 V
#138, 50 Hz, gain 2	21.81 V	20.29 V	20.28 V	20.28 V	20.29 V
#138, 50 Hz, gain 4	10.89 V	10.16 V	10.15 V	10.15 V	10.14 V
#138, 50 Hz, gain 8	5.45 V	5.08 V	5.08 V	5.08 V	5.08 V
#138, 100 Hz, gain 1	43.50 V	40.57 V	40.54 V	40.56 V	40.57 V
#138, 100 Hz, gain 2	21.81 V	20.30 V	20.28 V	20.29 V	20.29 V
#138, 100 Hz, gain 4	10.90 V	10.15 V	10.14 V	10.15 V	10.14 V
#138, 100 Hz, gain 8	5.45 V	5.07 V	5.08 V	5.07 V	5.08 V

For all sample rates and gain levels, the digitizer channels were determined to have a full scale amplitude that met or exceeded the nominally specified full scale.

The nominal full scale provided by CEA were specified according to the following formula:

$$full\ scale = \frac{39.53\ V}{Gain}$$

3.8 Self-Noise

The Self-Noise test measures the amount of noise present on a digitizer by collecting waveform data from an input channel that has been terminated with a resistor whose impedance matches the nominal impedance of a chosen sensor at 1 Hz. Thus, any signal present on the recorded waveform should be solely due to any internal noise of the digitizer.

3.8.1 Measurand

The quantity being measured is the digitizer input channels self-noise power spectral density in dB relative to 1 V^2/Hz versus frequency and the total noise in Volts RMS over an application pass-band.

3.8.2 Configuration

The digitizer input channel is connected to a shorting resistor as shown in the diagram below.

Figure 25 Self Noise Configuration Diagram

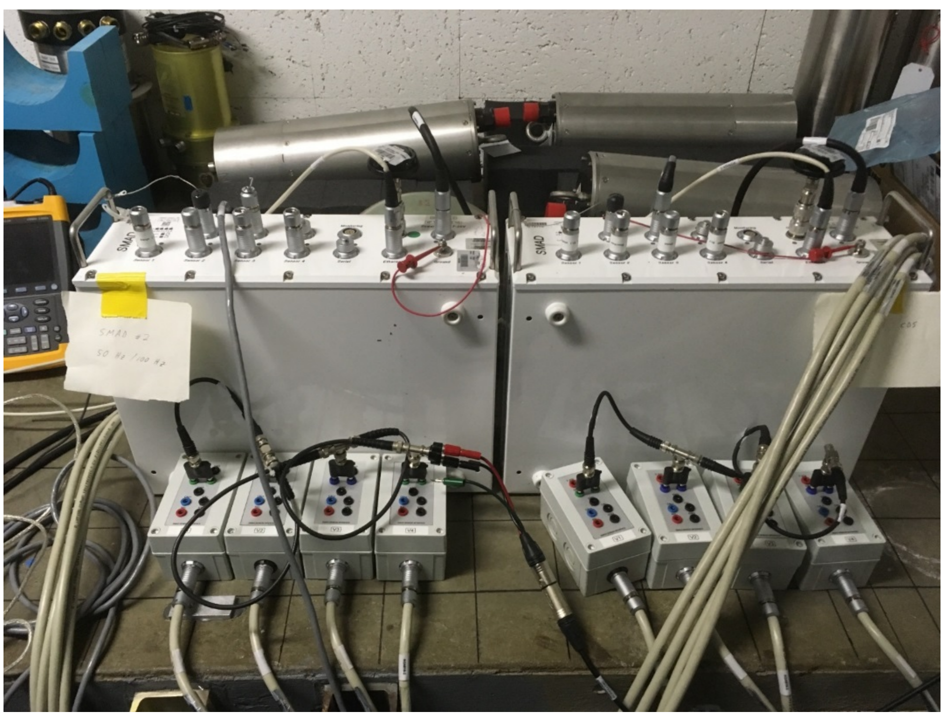

Figure 26 Self Noise Configuration Picture

Table 23 Self Noise Testbed Equipment

	Manufacturer / Model	Serial Number
100 ohm Resistor	N/A	N/A

A minimum of 12 hours of data is recorded.

3.8.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \leq n \leq N-1$

The PSD is computed from the time series (Merchant, 2011) from the time series using a 4k-sample Hann window for the 20 Hz sample rate and a 16-k window for the 100 Hz sample rate. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation pass-band of 0.01 Hz and the 90% confidence interval is less than 0.5 dB.

$P_{xx}[k], 0 \leq k \leq N-1$

Over frequencies (in Hertz):

$f[k], 0 \leq k \leq N-1$

In addition, the total RMS noise over the application pass-band of 0.02 to 4 Hz for a sample rate of 20 Hz and 0.02 to 16 Hz for a sample rate of 100 Hz:

$$rms = \sqrt{\frac{1}{T_s L} \sum_{k=n}^{m} |Pxx[k]|}$$

$where\ f[n]\ and\ f[m]\ are\ the\ pass-band\ limits$

3.8.4 Result

The figures below show the waveform time series and power spectra for the recording made on a digitizer channel under test at a sample rate of 20 Hz. The window regions bounded by the red lines indicate the segment of data used for analysis.

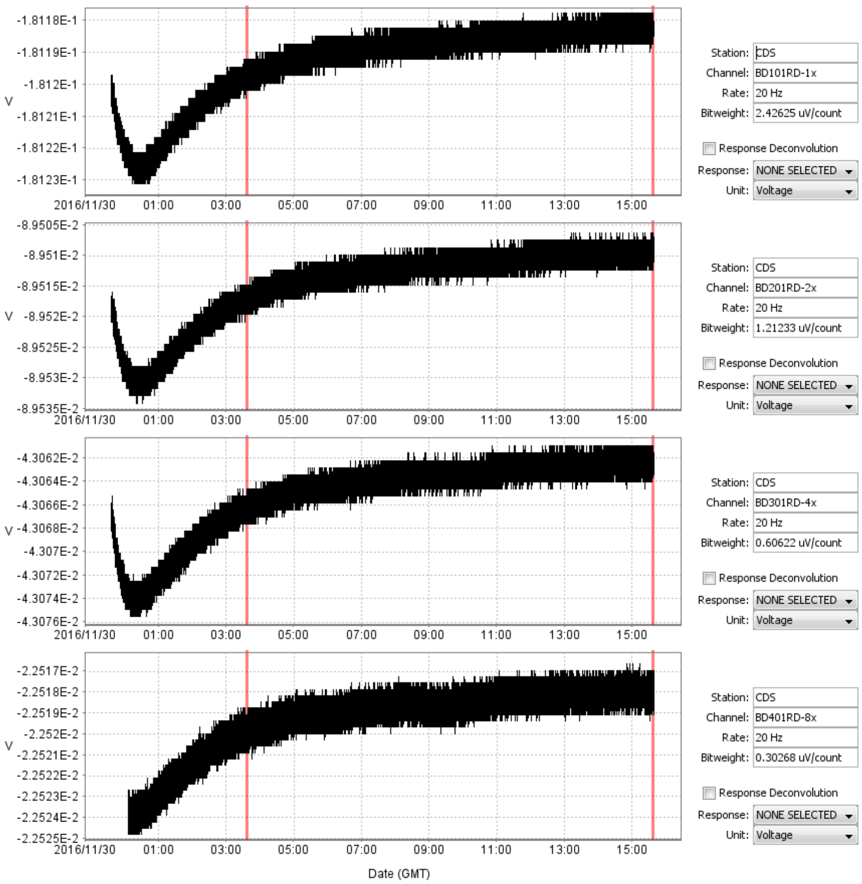

Figure 27 Self Noise 20 Hz Time Series

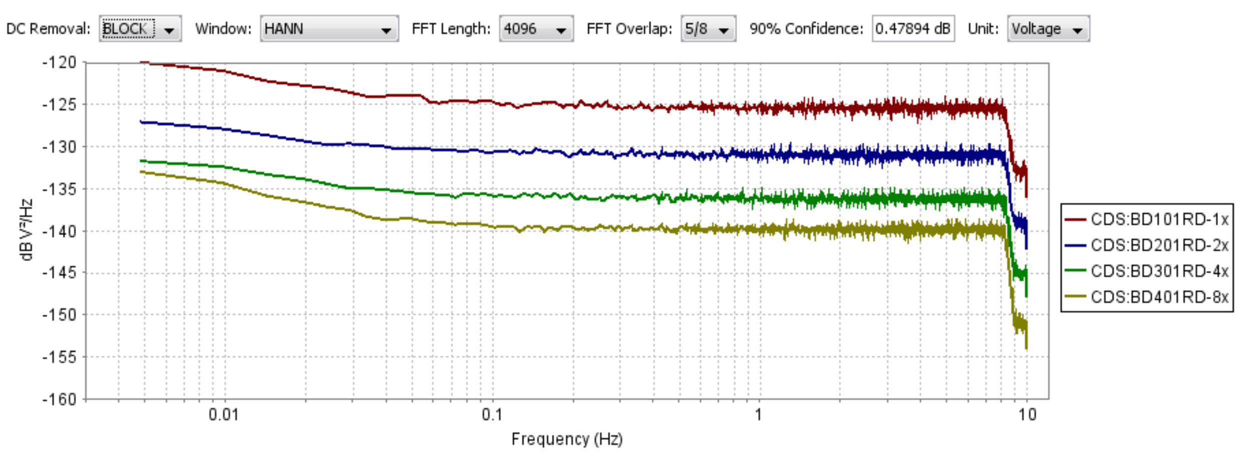

Figure 28 Self Noise 20 Hz Power Spectra

The figures below show the waveform time series and power spectra for the recording made on a digitizer channel under test at a sample rate of 100 Hz. The window regions bounded by the red lines indicate the segment of data used for analysis.

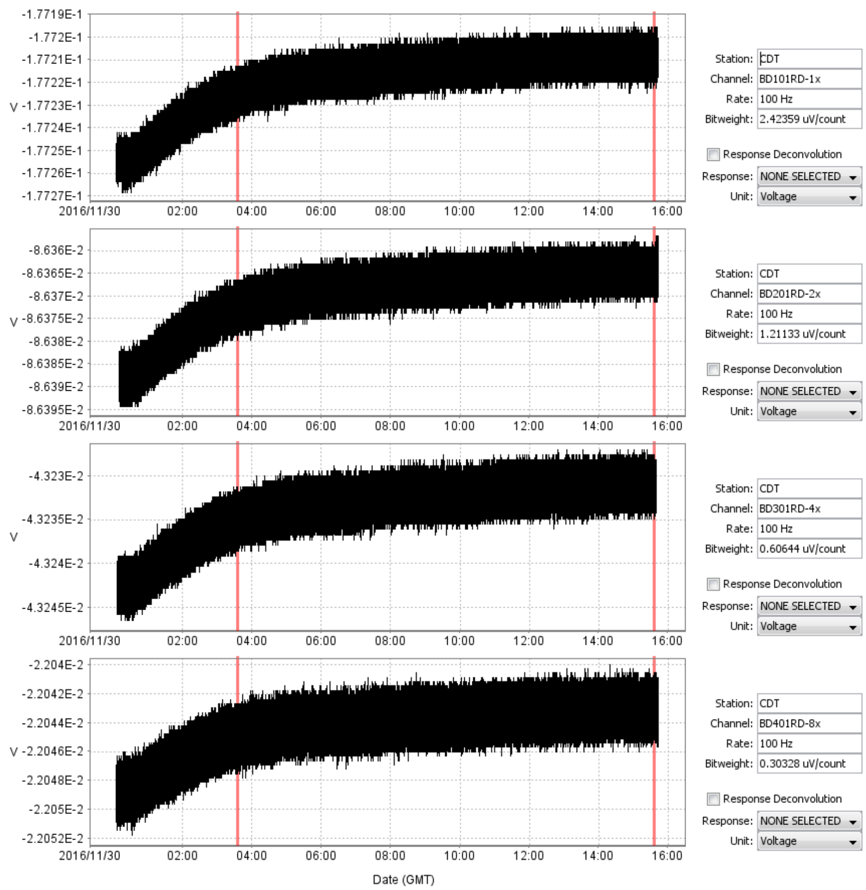

Figure 29 Self Noise 100 Hz Time Series

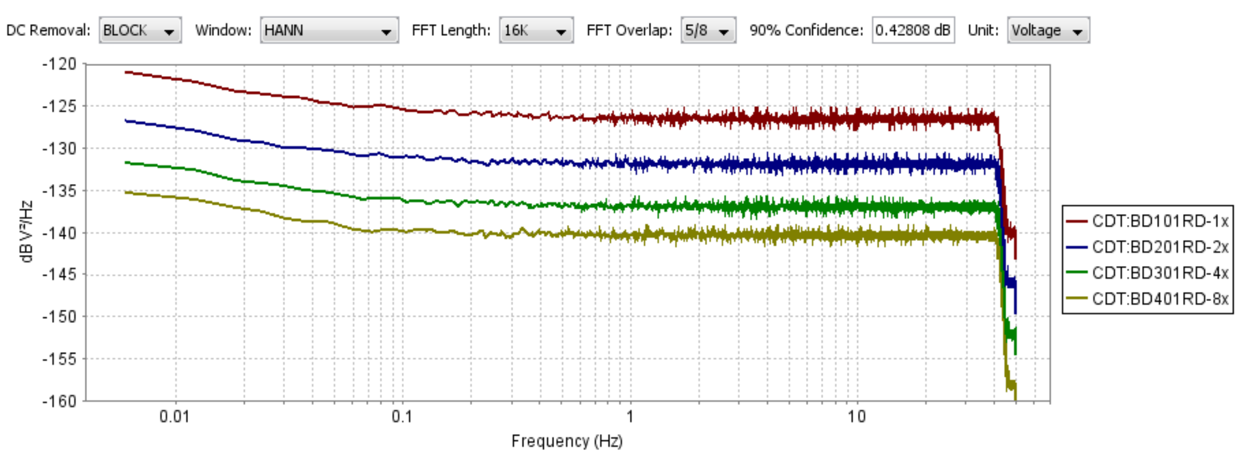

Figure 30 Self Noise 100 Hz Power Spectra

The following tables contains the computed RMS noise levels in both volts and counts for each of the evaluated sample rates and gain settings. A frequency pass-band consistent with IMS requirements for each of the seismic and infrasound applications were selected.

Table 24 Self Noise RMS 20 Hz over 0.02 to 4 Hz

	Noise Volts	Noise Counts
#137, 20 Hz, BD1, gain 1	1069.31 nV rms	0.44 count rms
#137, 20 Hz, BD2, gain 2	557.13 nV rms	0.46 count rms
#137, 20 Hz, BD3, gain 4	308.00 nV rms	0.51 count rms
#137, 20 Hz, BD4, gain 8	202.41 nV rms	0.67 count rms

Table 25 Self Noise RMS 100 Hz over 0.02 to 16 Hz

	Noise Volts	Noise Counts
#138, 100 Hz, BD1, gain 1	1886.55 nV rms	0.78 count rms
#138, 100 Hz, BD2, gain 2	1010.29 nV rms	0.83 count rms
#138, 100 Hz, BD3, gain 4	565.77 nV rms	0.93 count rms
#138, 100 Hz, BD4, gain 8	383.20 nV rms	1.26 count rms

The observed noise levels were consistent with expected estimates across the frequency pass-band. The PSD levels were unchanged between a sample rate of 20 Hz and 100 Hz, any differences in the total RMS noise level are due to the increased frequency pass-band. Changes in the gain level resulted in a corresponding decrease in the noise measured in volts. However, as expected, the noise measured in counts was observed to increase with gain indicating that there are diminishing returns to increasing the digitizer gain. Measured noise levels were consistent with the performance of a 24-bit digitizer.

3.9 Temperature Self-Noise

The Temperature Self-Noise test measures the amount of noise present on a digitizer by collecting waveform data from an input channel that has been terminated with a resistor whose impedance matches the nominal impedance of a chosen sensor at 1 Hz while the digitizer is being maintained at a specific temperature.

3.9.1 Measurand

The quantity being measured is the digitizer input channels self-noise power spectral density in dB relative to 1 V^2/Hz versus.

3.9.2 Configuration

The digitizer input channel is connected to a shorting resistor as shown in the diagram below.

Figure 31 Temperature Self Noise Configuration Diagram

Figure 32 Temperature Self Noise Configuration Picture

Table 26 Self Noise Testbed Equipment

	Manufacturer / Model	Serial Number
100 ohm Resistor	N/A	N/A
Temperature Chamber	ESPEC EPL-2H	ESPEC EPL-2H

The temperature chamber was programmed to cycle the SMAD digitizers through a range of temperatures during an overnight period.

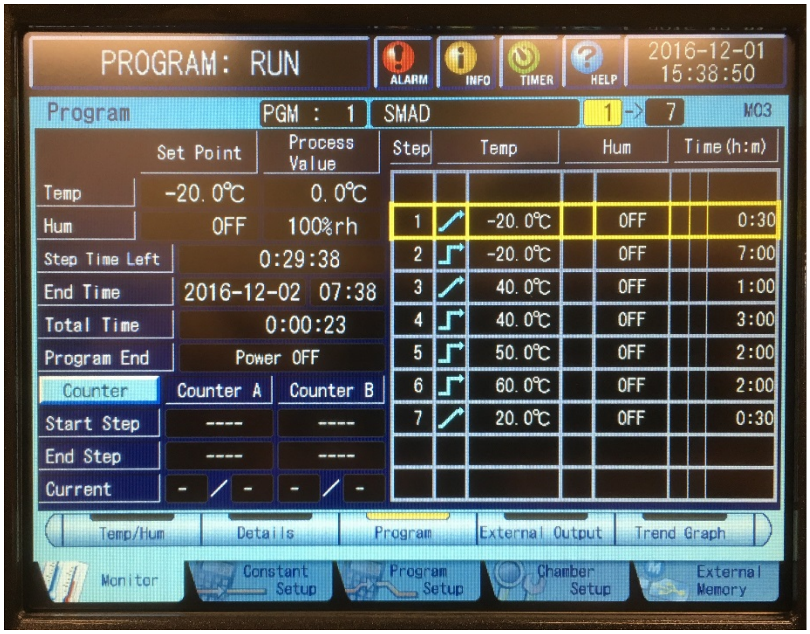

Figure 33 Temperature Chamber Program

The temperature chamber was programmed to operate for several hours at -20 C, 40 C, 50 C, and 60 C.

3.9.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \le n \le N-1$

The PSD is computed from the time series (Merchant, 2011) from the time series using a 4k-sample Hann window for the 20 Hz sample rate and a 16-k window for the 100 Hz sample rate. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation pass-band of 0.01 Hz and the 90% confidence interval is less than 0.5 dB.

$P_{xx}[k], 0 \le k \le N-1$

Over frequencies (in Hertz):

$f[k], 0 \le k \le N-1$

The digitizers were verified to be operating at each of the temperature levels and its noise levels were compared to the ambient 23 C operation.

3.9.4 Result

An example plot of time-series of the digitizer self-noise is shown below. All of the time series were similar, the only difference being the level of DC offset.

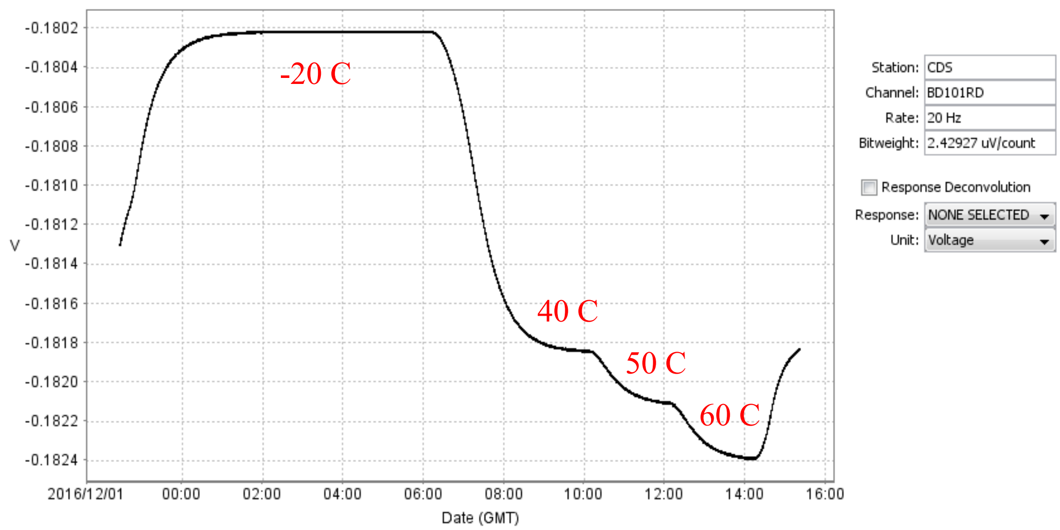

Figure 34 Temperature Self Noise Time Series, 20 Hz gain 1

The power spectra for the data collected at each gain level, sample rate, and temperature are shown in the plots below.

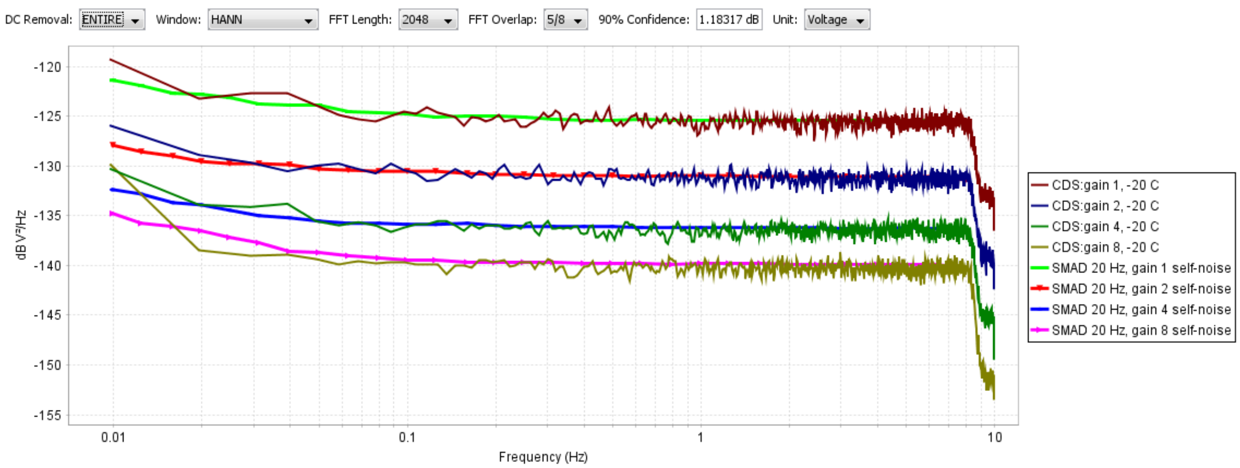

Figure 35 Temperature Self Noise Power Spectra, 20 Hz, -20 C

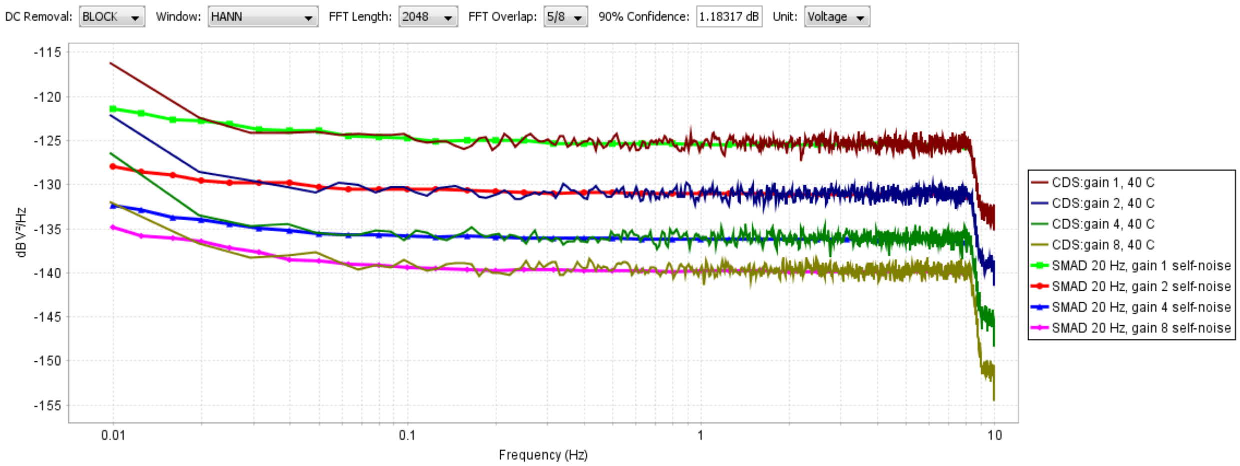

Figure 36 Temperature Self Noise Power Spectra, 20 Hz, 40 C

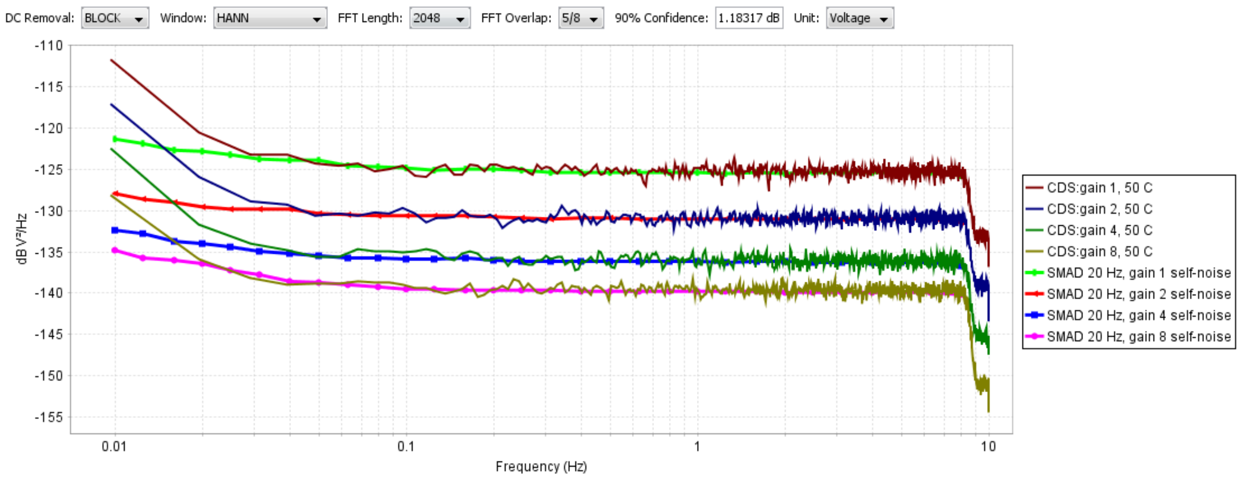

Figure 37 Temperature Self Noise Power Spectra, 20 Hz, 50 C

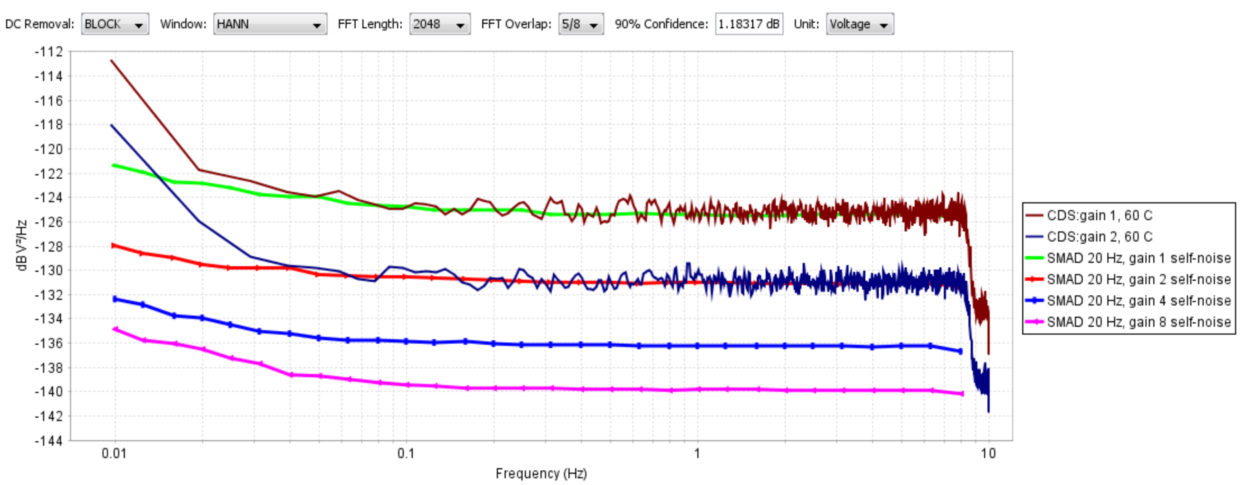

Figure 38 Temperature Self Noise Power Spectra, 20 Hz, 60 C

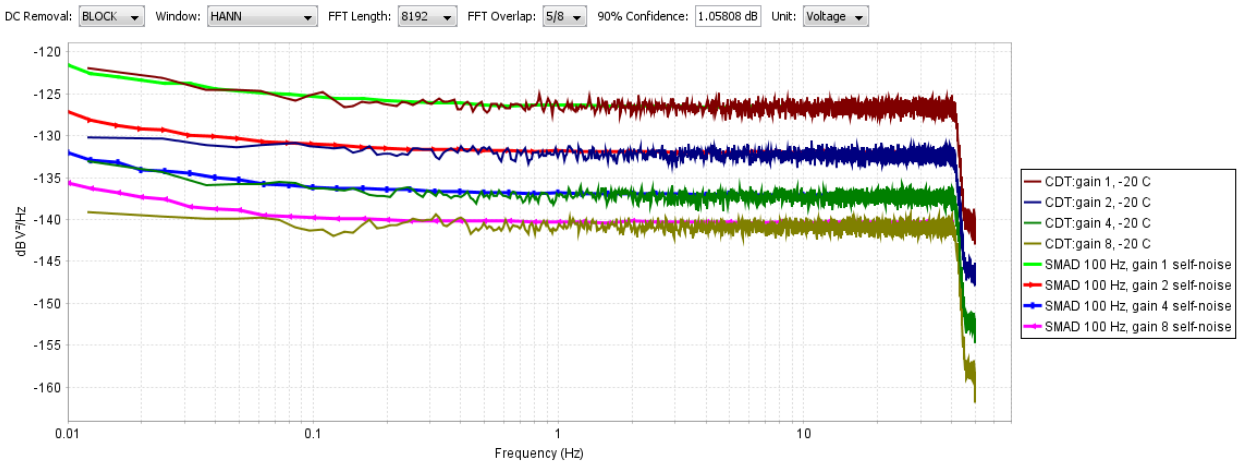

Figure 39 Temperature Self Noise Power Spectra, 100 Hz, -20 C

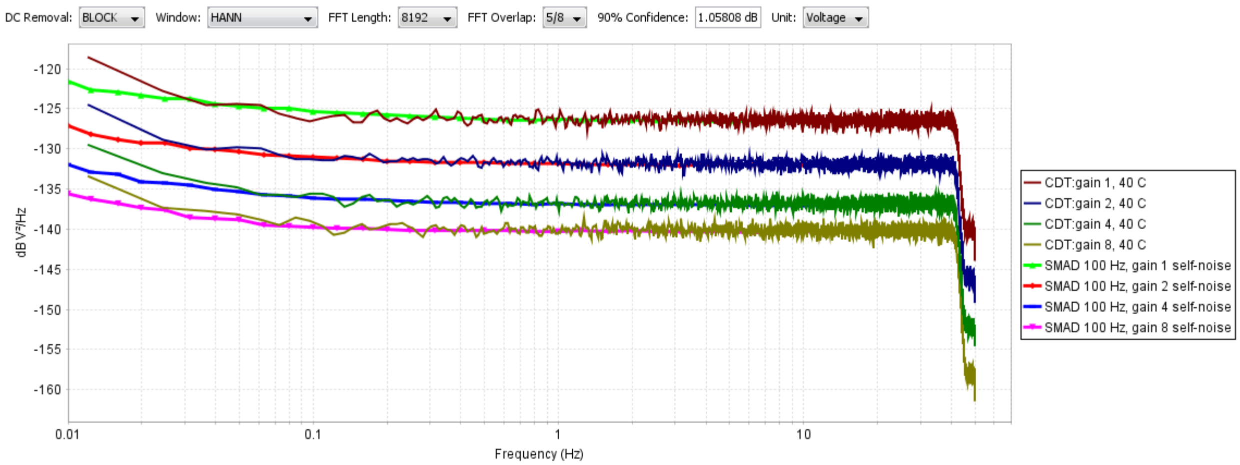

Figure 40 Temperature Self Noise Power Spectra, 100 Hz, 40 C

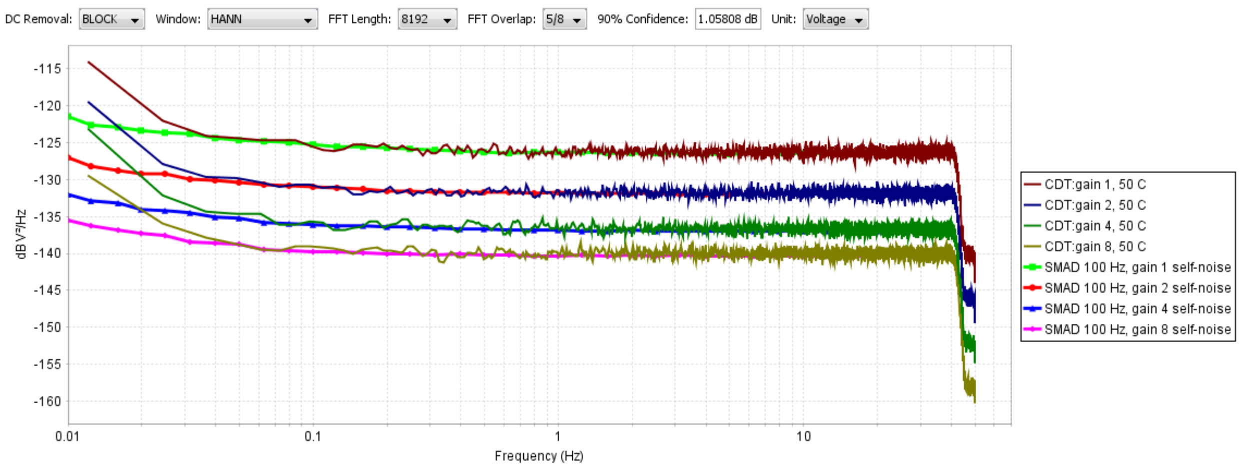

Figure 41 Temperature Self Noise Power Spectra, 100 Hz, 50 C

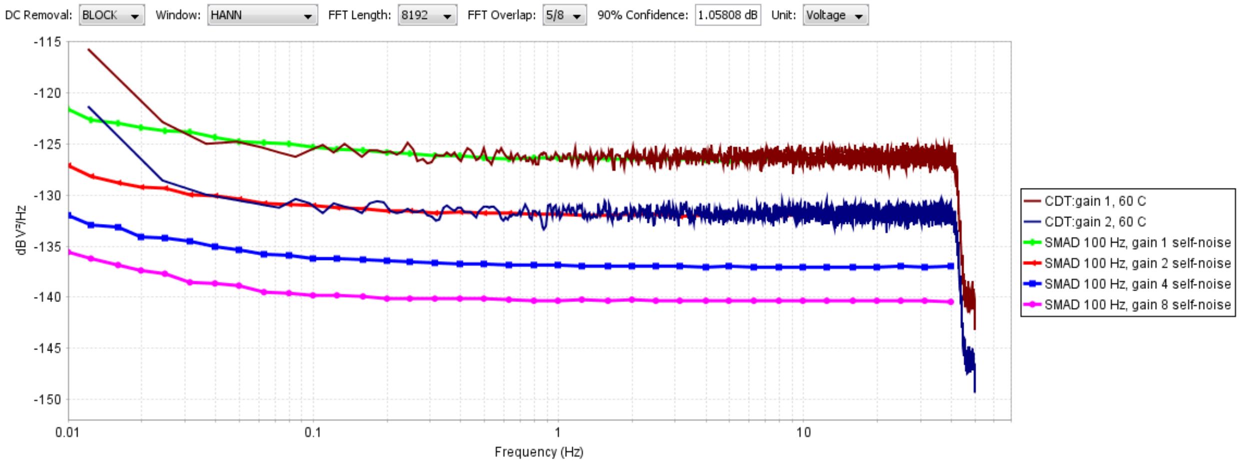

Figure 42 Temperature Self Noise Power Spectra, 100 Hz, 60 C

As may be seen, the power spectra collected was very similar to the comparison self-noise levels obtained at 23 C. The only variation observed was a slight increase in power at low frequencies due to insufficient time for the temperature to stabilize at 40, 50 and 60 C.

Note that the channels of both digitizers configured for gains of 4 and 8 stopped recording as the temperature was approaching 60 C. The SMAD digitizer is supposed to be able to operate at 60 C ambient temperatures, it is unknown why these units did not. CEA has reported that it has identified and corrected the cause; however, these changes have not been evaluated by Sandia.

Table 27 Temperature Self Noise DC Offset

Temperature	SMAD	BD1 (gain 1)	BD2 (gain2)	BD3 (gain 4)	BD4 (gain 8)
-20 C	#137, 20 Hz	-180.22 mV	-89.03 mV	-42.81 mV	-22.40 mV
	#138, 100 Hz	-175.98 mV	-85.74 mV	-42.93 mV	-21.90 mV
40 C	#137, 20 Hz	-181.84 mV	-89.83 mV	-43.23 mV	-22.60 mV
	#138, 100 Hz	-177.63 mV	-86.58 mV	-43.34 mV	-22.10 mV
50 C	#137, 20 Hz	-182.11 mV	-89.96 mV	-43.30 mV	-22.64 mV
	#138, 100 Hz	-177.89 mV	-86.71 mV	-43.40 mV	-22.13 mV
60 C	#137, 20 Hz	-182.39 mV	-90.09 mV		
	#138, 100 Hz	-178.17 mV	-86.86 mV		

The DC offset of the SMAD digitizer channels was observed to shift as a function as temperature. Interpreting the DC offset data in Table 27, it appears that the change in DC offset is linear with respect to temperature. At gains of 1, 2, 4, and 8 the DC offset changed by approximately 0.027 mV / C, 0.0135 mV / C, 0.00675 mV / C, and 0.00335 mV / C, respectively. Taking into account the bit-weight at each of the gain settings, this corresponds to between 10.5 and 11.5 counts per degree Celsius.

3.10 Dynamic Range

Dynamic Range is defined to be the ratio between the power of the largest and smallest signals that may be measured on the digitizer channel.

3.10.1 Measurand

The Dynamic Range is measured in dB as the ratio between the power in the largest and smallest signals. The largest signal is defined to be a sinusoid with amplitude equal to the full scale input of the digitizer channel. The smallest signal is defined to have power equal to the self-noise of the digitizer channel. This definition of dynamic range is consistent with the definition of signal-to-noise and distortion ratio (SINAD) for digitizers (IEEE Std 1241-2010 section 9.2).

3.10.2 Configuration

There is no test configuration for the dynamic range test.

The full scale value used for the largest signal comes from the manufacturer's nominal specifications, validated in section 3.6 AC Full Scale. The value for the smallest signal comes from the evaluated digitizer channel self-noise determined in section 3.8 Self-Noise.

3.10.3 Analysis

The dynamic range over a given pass-band is:

$$Dynamic\ Range = 10 \cdot \log_{10}\left(\frac{signal\ power}{noise\ power}\right)$$

Where

$$signal\ power = (peak\ fullscale/\sqrt{2})^2$$

$$noise\ power = (RMS\ Noise)^2$$

Note that full scale peak-to-peak values must be divided by 2 in order to convert them to full scale peak values.

The application pass-band over which the noise is integrated should be selected to be consistent with the application pass-band.

3.10.4 Result

The following tables contain the peak-to-peak full scales, noise levels, and dynamic ranges that were identified in the evaluations of the sample rates and gain levels.

Table 28 Dynamic Range at 20 Hz over 0.02 to 4 Hz

	Full Scale (Vpp)	Noise	Dynamic Range
#137, 20 Hz, BD1, gain 1	40.68 V	1069.31 nV rms	142.57 dB
#137, 20 Hz, BD2, gain 2	20.35 V	557.13 nV rms	142.22 dB
#137, 20 Hz, BD3, gain 4	10.17 V	308.00 nV rms	141.34 dB
#137, 20 Hz, BD4, gain 8	5.08 V	202.41 nV rms	138.96 dB

Table 29 Dynamic Range at 100 Hz over 0.02 to 16 Hz

	Full Scale (Vpp)	Noise	Dynamic Range
#138, 100 Hz, BD1, gain 1	40.57 V	1886.55 nV rms	137.62 dB
#138, 100 Hz, BD2, gain 2	20.28 V	1010.29 nV rms	137.02 dB
#138, 100 Hz, BD3, gain 4	10.15 V	565.77 nV rms	136.05 dB
#138, 100 Hz, BD4, gain 8	5.08 V	383.20 nV rms	133.42 dB

The observed dynamic range values were between 139 and 142 dB at a 20 Hz sample rate and between 133 and 138 dB at a 100 Hz sample rate.

3.11 System Noise

The System Noise test determines the amount of digitizer self-noise expressed in units of a sensor.

3.11.1 Measurand

The quantity being measured is the digitizer input channels self-noise power spectral density, corrected by a sensor's response to some geophysical unit, in dB relative to 1 $(m/s)^2/Hz$ or 1 $(Pa/s)^2/Hz$ versus frequency.

3.11.2 Configuration

There is no test configuration for the dynamic range test. The time-series data and PSD are obtained from the evaluated digitizer channel self-noise determined in section 3.8 Self-Noise.

3.11.3 Analysis

The time-series data and PSD computed in section 3.8 Self-Noise are corrected for a desired sensor's amplitude response model. The resulting PSD in the sensor's geophysical unit is then compared against an application requirement or background noise model to determine whether the resulting system noise meets the requirement.

3.11.4 Result

The PSD of the system noise is shown in the plots below. The 100 Hz data is shown with several seismometer responses: STS-2 and ZM500. The 20 Hz data is shown with several infrasound responses: MB2005, MB3a, and MB3a derivative output. Where available, reference sensor and background noise models are provided for comparison.

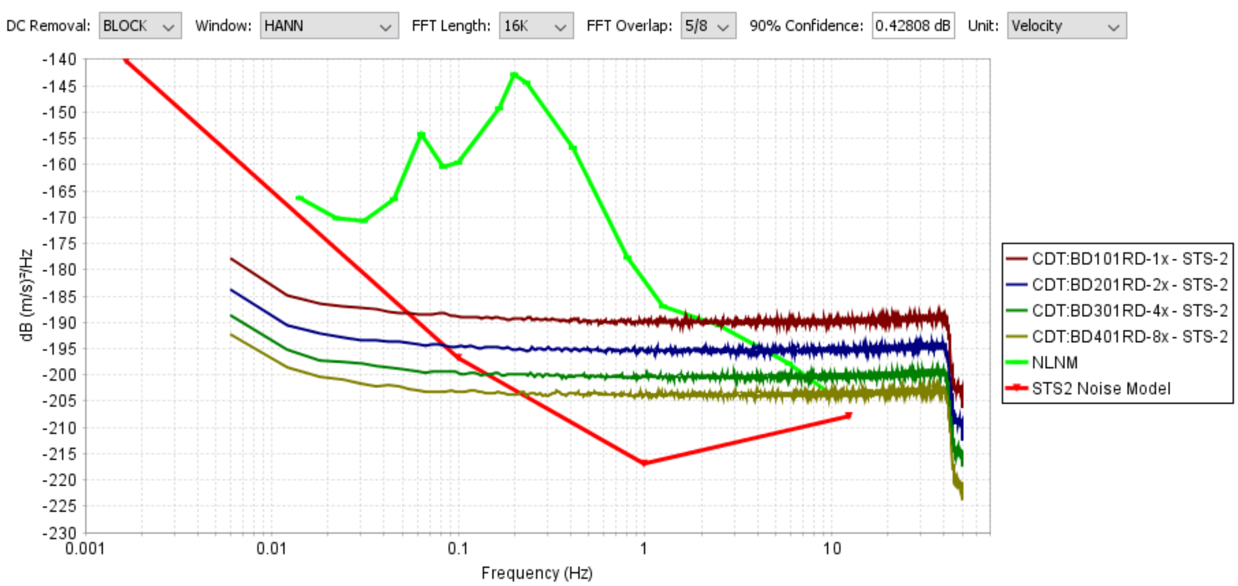

Figure 43 Seismic System Noise for STS-2 at gains of 1, 2, 4, and 8

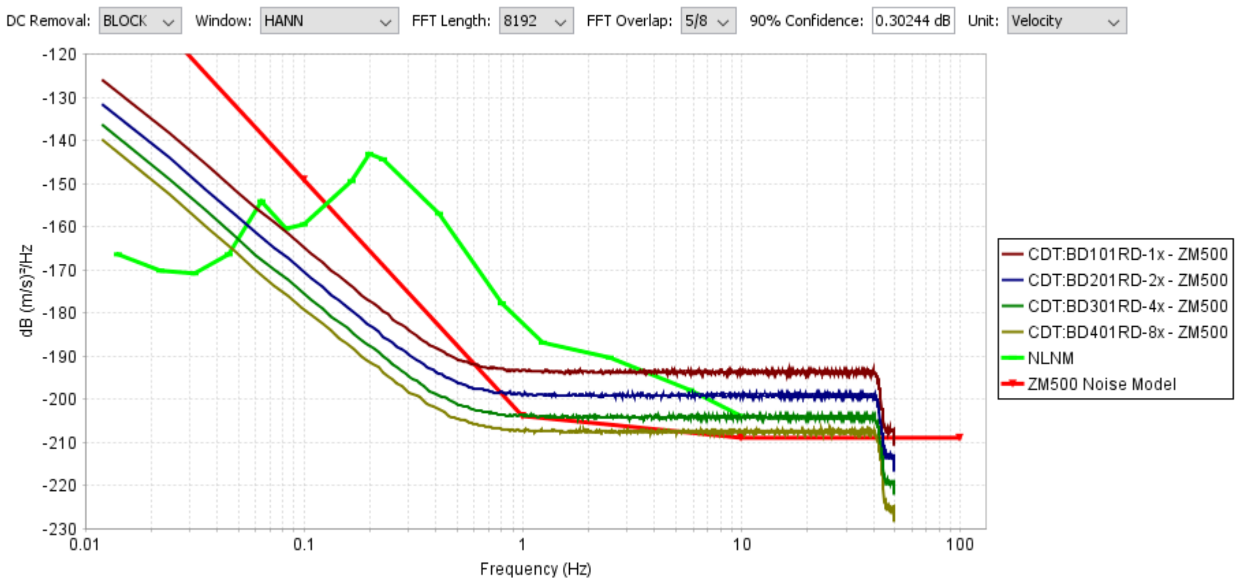

Figure 44 Seismic System Noise for ZM500 at gains of 1, 2, 4, and 8

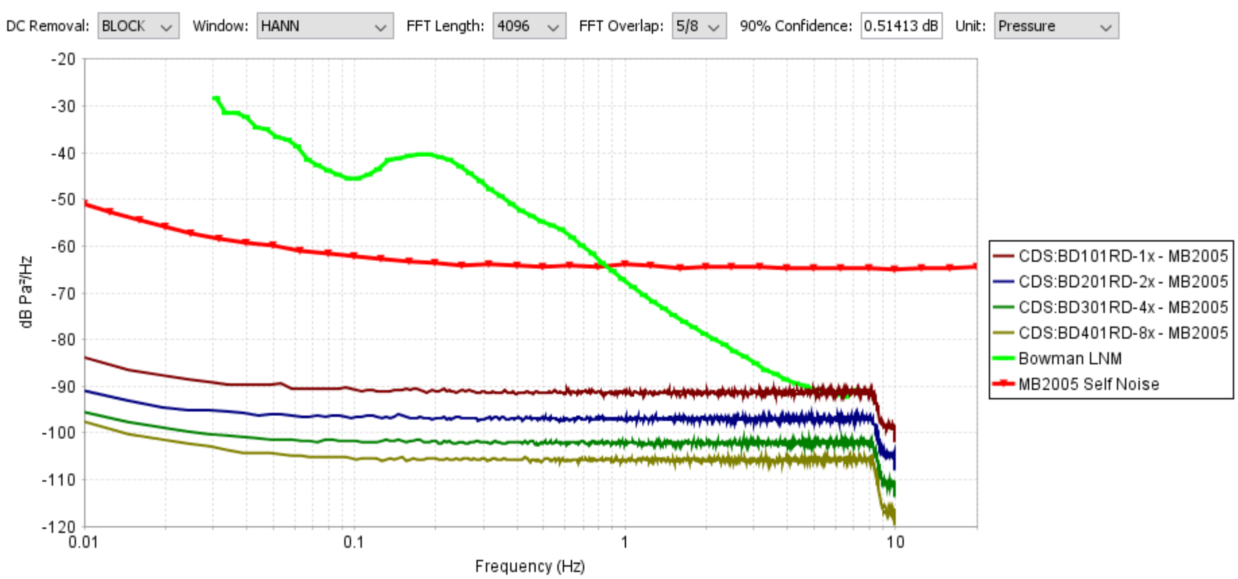

Figure 45 Infrasound System Noise for MB2005 at gains of 1, 2, 4, and 8

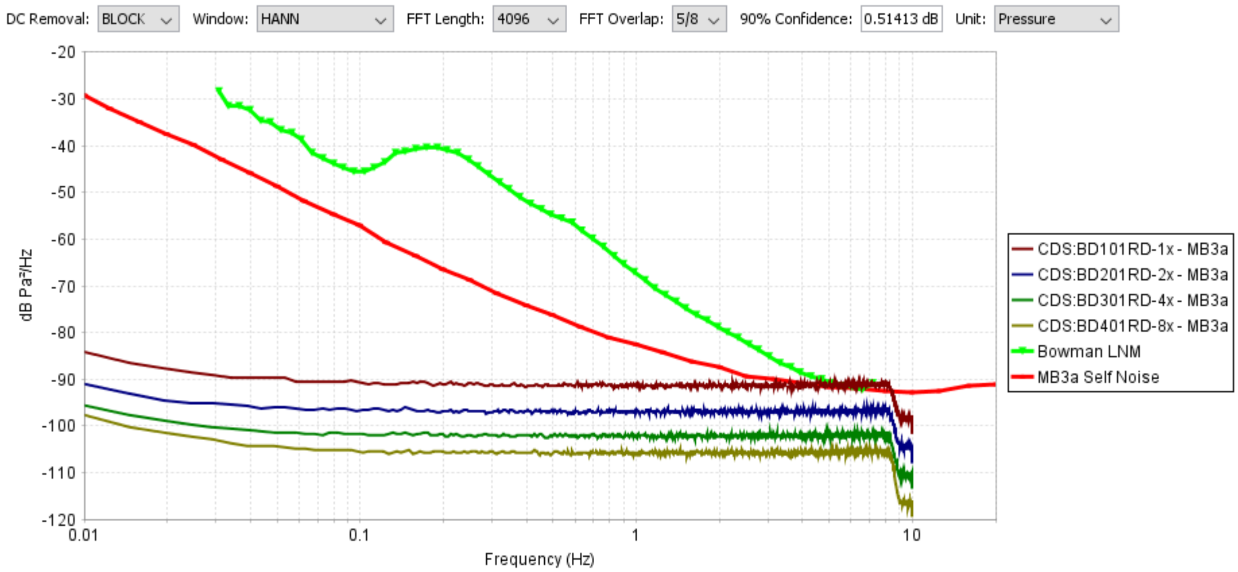

Figure 46 Infrasound System Noise for MB3a at gains of 1, 2, 4, and 8

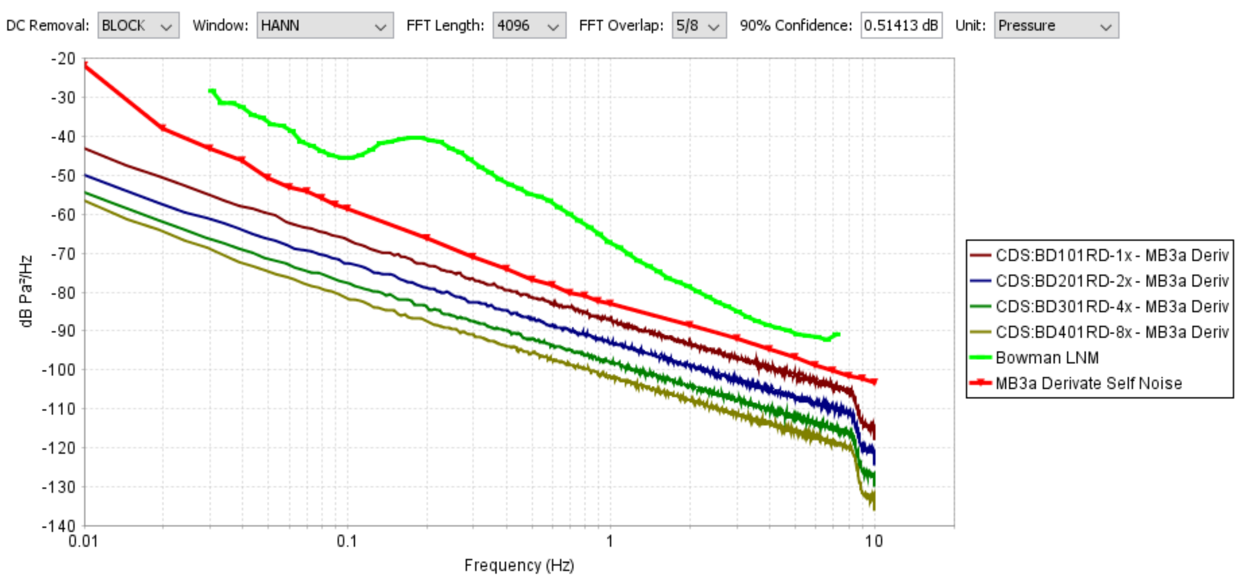

Figure 47 Infrasound System Noise for MB3a Derivative at gains of 1, 2, 4, and 8

3.12 Response Verification

The Response Verification test measures the amplitude and phase response versus frequency that is present on the digitizer channels, relative to a reference channel.

3.12.1 Measurand

The quantity being measured is the unit-less relative amplitude and relative phase in degrees versus frequency for each digitizer channel relative to the first channel.

3.12.2 Configuration

Multiple digitizer channels are connected to a white noise signal source as shown in the diagram below.

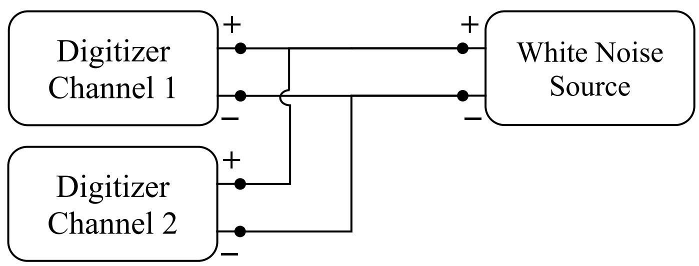

Figure 48 Response Verification Configuration Diagram

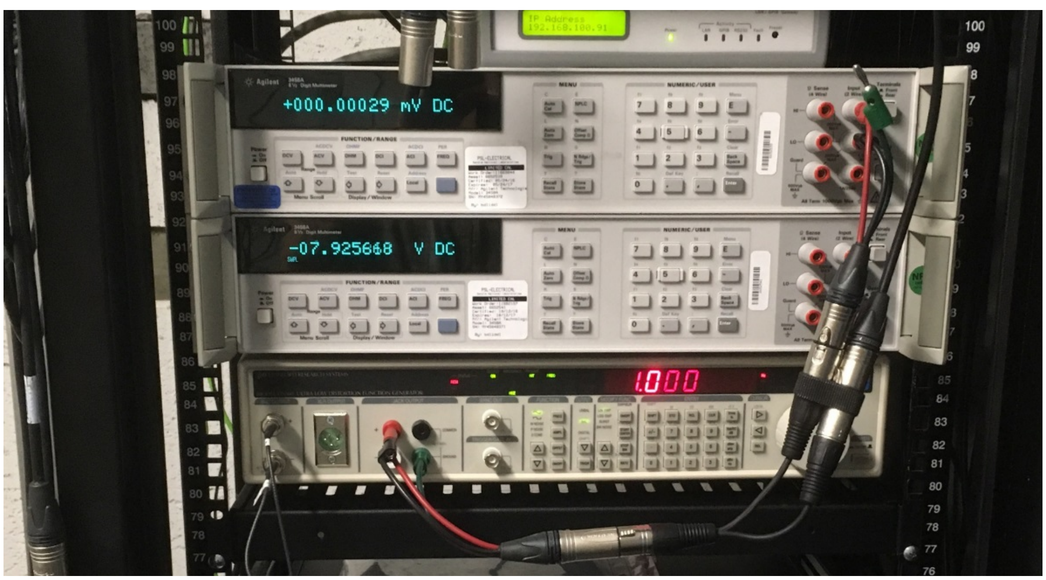

Figure 49 Response Verification Configuration Picture

Table 30 Response Verification Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	123669	Bandlimited white noise

The White Noise Source is configured to generate a band-width limited white noise voltage with an amplitude equal to approximately 10% of the digitizer input channel's full scale. One hour of data is recorded.

3.12.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \leq n \leq N-1$

The relative transfer function, both amplitude and phase, is computed between the two digitizer channels (Merchant, 2011) from the power spectral density:

$H[k],\ 0 \leq k \leq N-1$

3.12.4 Result

The coherence and relative amplitude and phase response were computed between channel 1 and the remaining three channels for all of the evaluated sample rate and gain configurations. In all cases, the coherence was identically 1.0 across the entire pass-band. The coherence, relative amplitude, and relative phase are shown in the plots below.

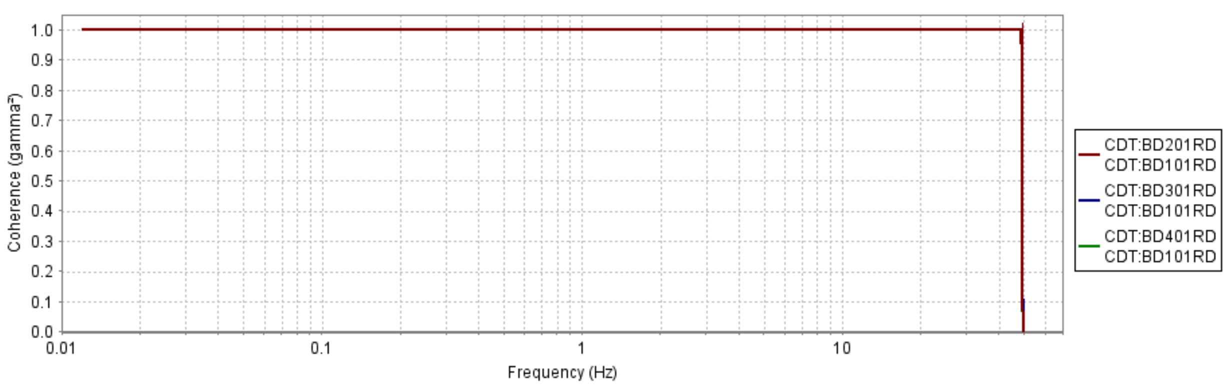

Figure 50 White Noise Coherence

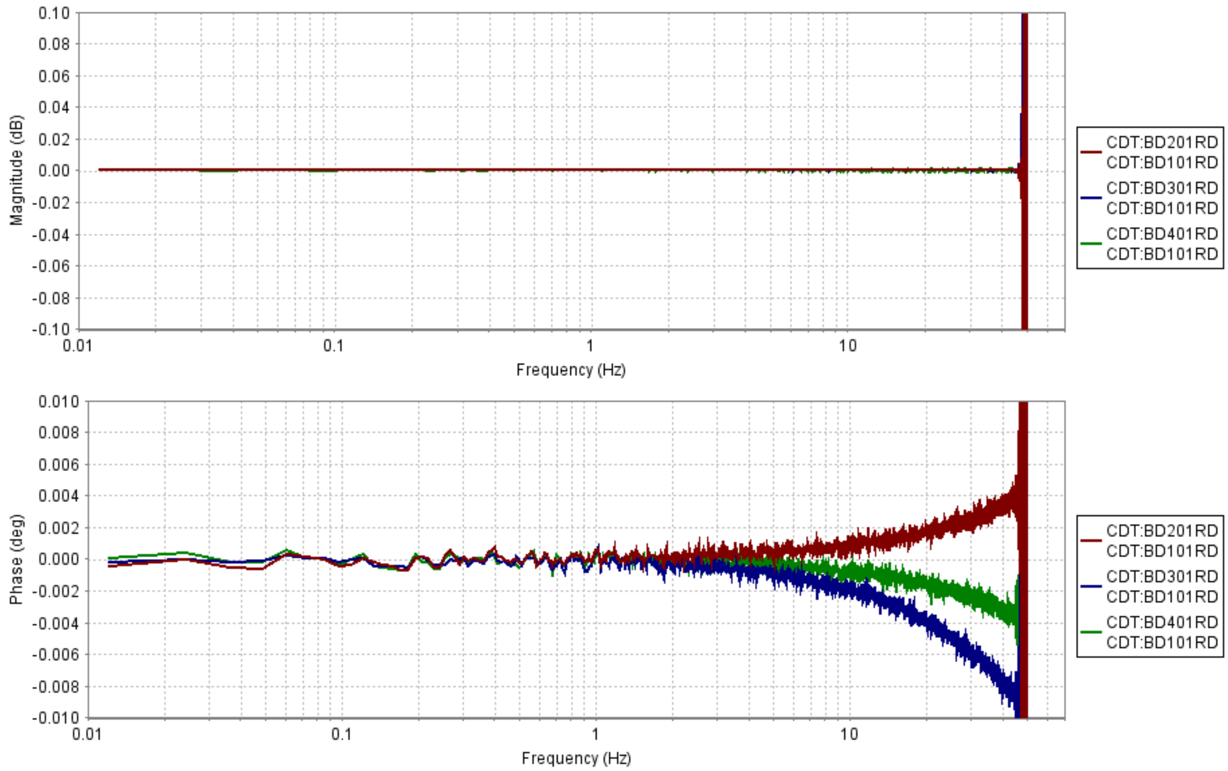

Figure 51 Relative Amplitude and Phase 20 Hz, Gain 1

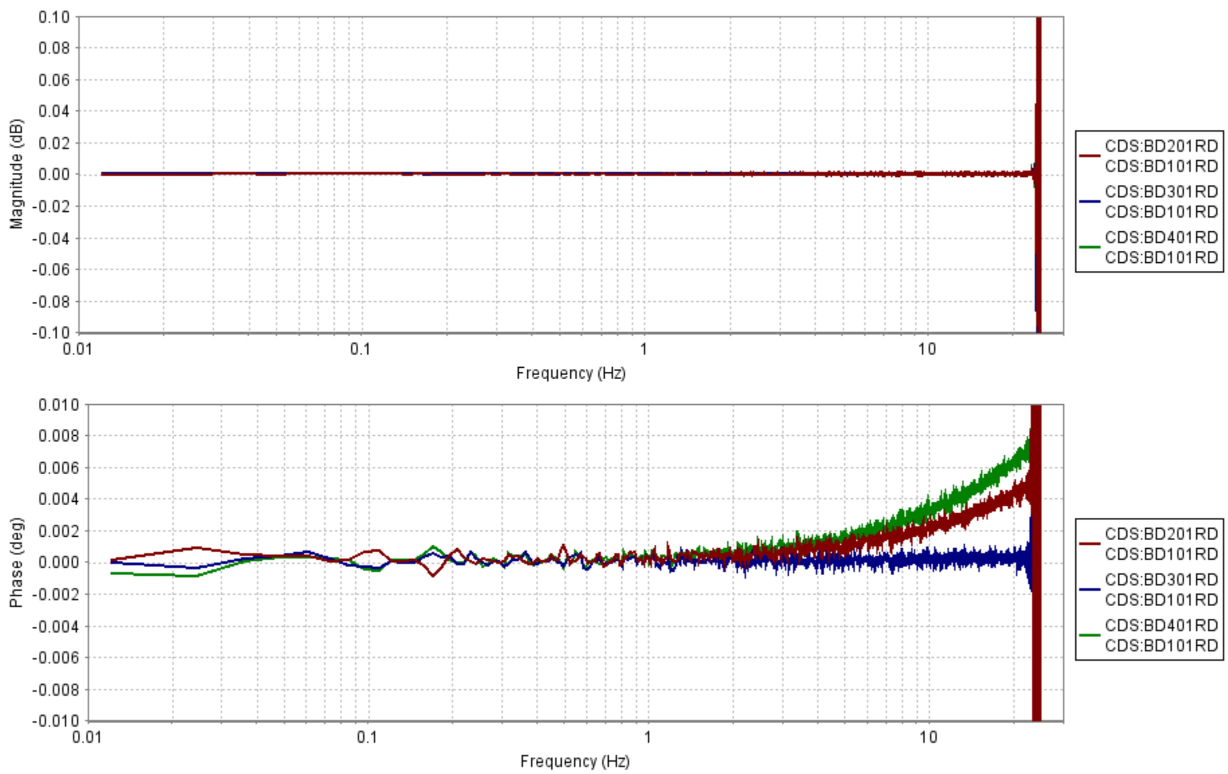

Figure 52 Relative Amplitude and Phase 50 Hz, Gain 8

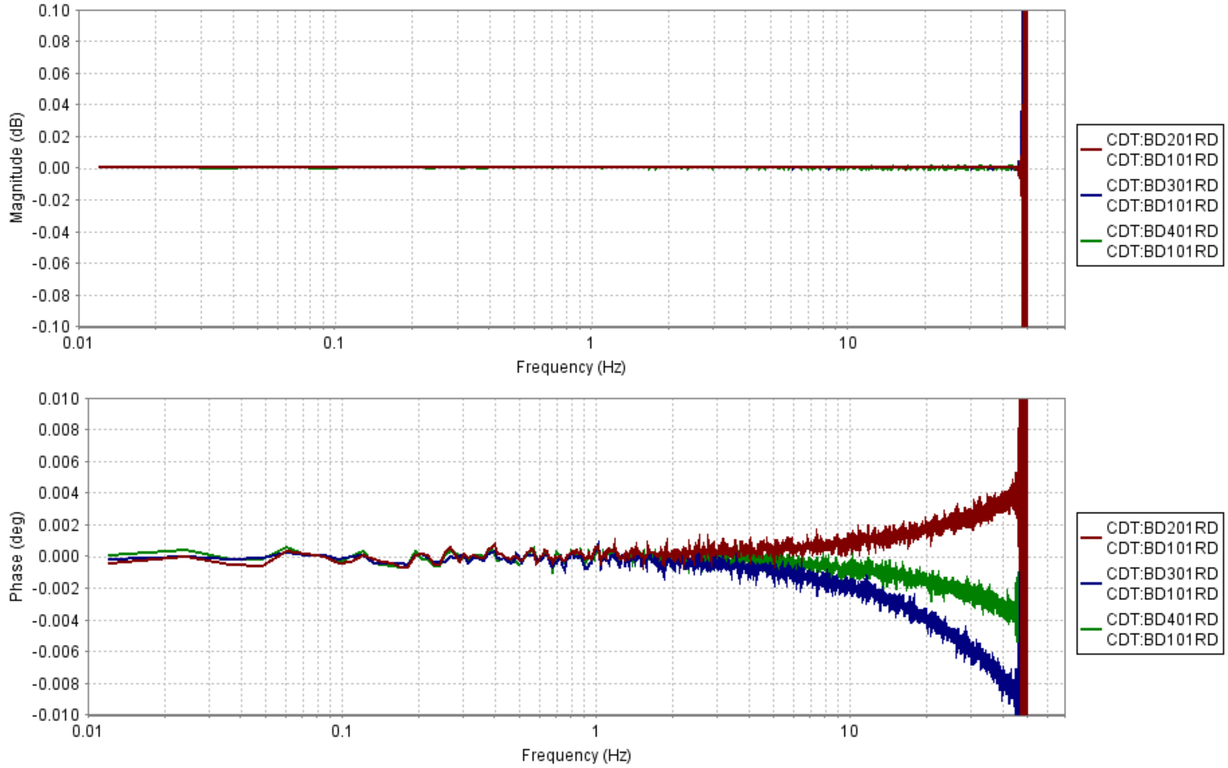

Figure 53 Relative Amplitude and Phase 100 Hz, Gain 1

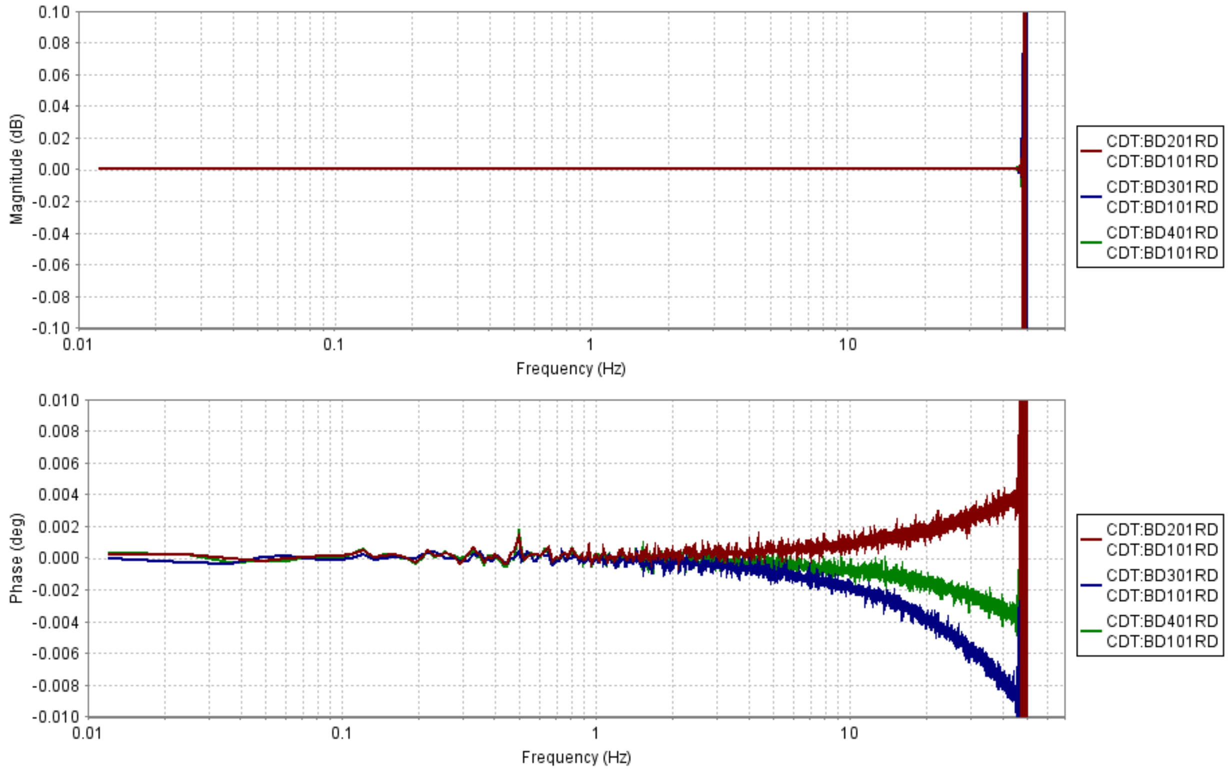

Figure 54 Relative Amplitude and Phase 100 Hz, Gain 8

In all cases, the relative amplitudes were effectively zero across the pass-band. This indicates that there were no differences in response between the digitizer channels. There were some slight roll-offs in the phase response. However, this phase delay is indicative of a small difference in timing between the channels, as further investigated in section 3.13 Relative Transfer Function.

3.13 Relative Transfer Function

The Relative Transfer Function test measures the amount of channel-to-channel timing skew present on a digitizer.

3.13.1 Measurand

The quantity being measured is the timing skew in seconds between the digitizer input channels.

3.13.2 Configuration

Multiple digitizer channels are connected to a white noise signal source as shown in the diagram below.

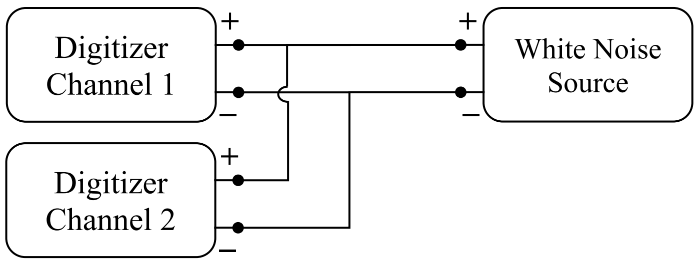

Figure 55 Relative Transfer Function Configuration Diagram

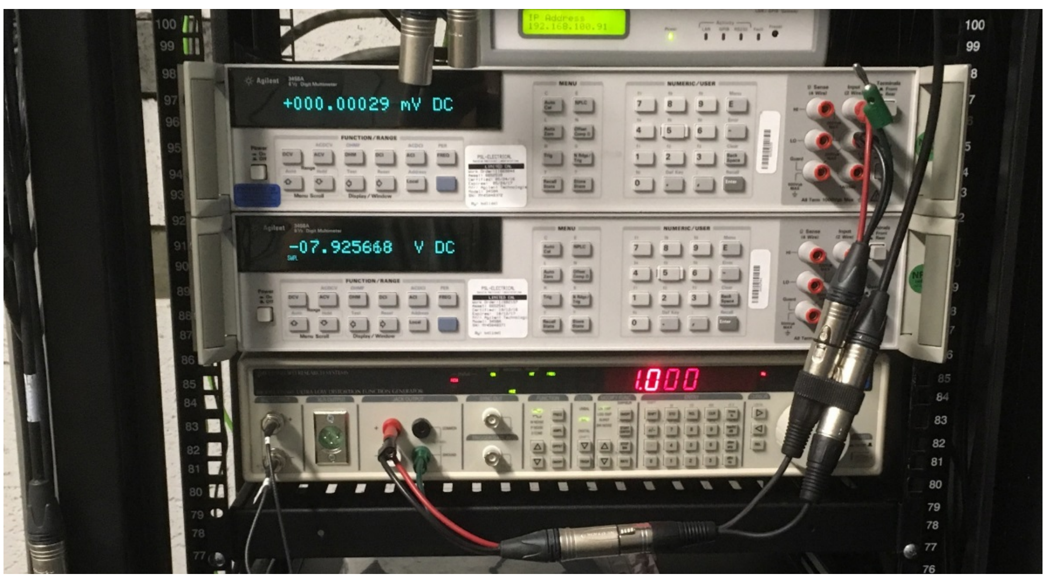

Figure 56 Relative Transfer Function Configuration Picture

Table 31 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	123669	Bandlimited white noise

The White Noise Source is configured to generate a band-width limited white noise voltage with an amplitude equal to approximately 10% of the digitizer input channel's full scale. At least one hour of data is recorded.

3.13.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \le n \le N-1$

The relative transfer function, both amplitude and phase, is computed between the two digitizer channels:

$H[k],\ 0 \le k \le N-1$

The tester defines a frequency range over which to measure the skew:

$f[k],\ 0 \le k \le N-1$

The amount of timing skew, in seconds, is computed by averaging the relative phase delay between the two channels over a frequency band from f[n] to f[m] over which the relative phase delay is observed to be linear:

$$skew = \frac{1}{m-n+1}\sum_{k=n}^{m}\frac{\measuredangle(H[k])}{2\pi\, f[k]}$$

3.13.4 Result

The phase delay versus frequency is shown for all of the evaluated sample rates and gains in the plots below. To the extent that delay is a constant time offset, the phase delay is observed to be linear with respect to frequency.

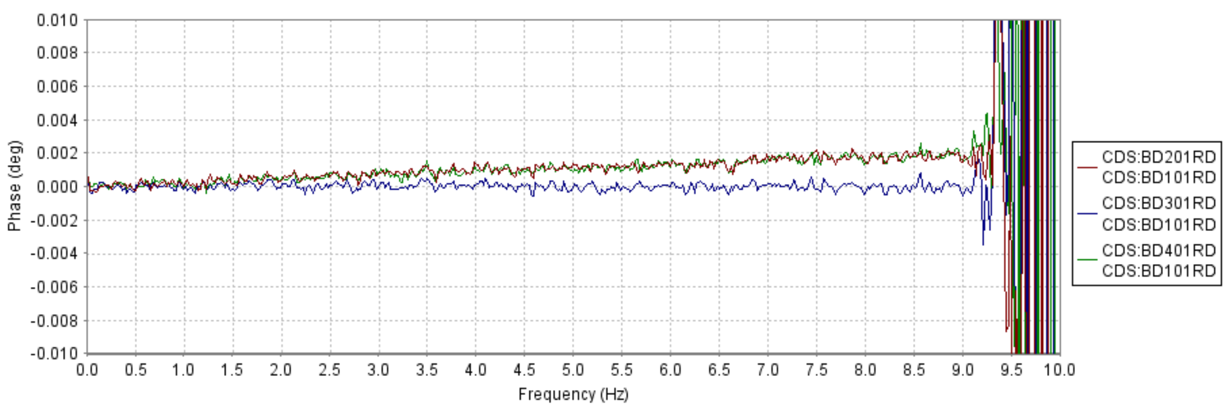

Figure 57 Relative Transfer Function 20 Hz, Gain 1

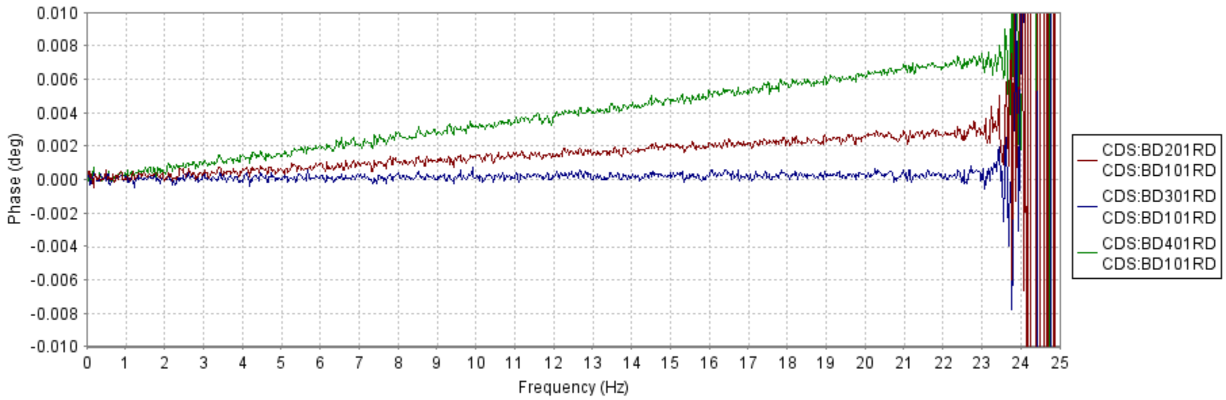

Figure 58 Relative Transfer Function 50 Hz, Gain 8

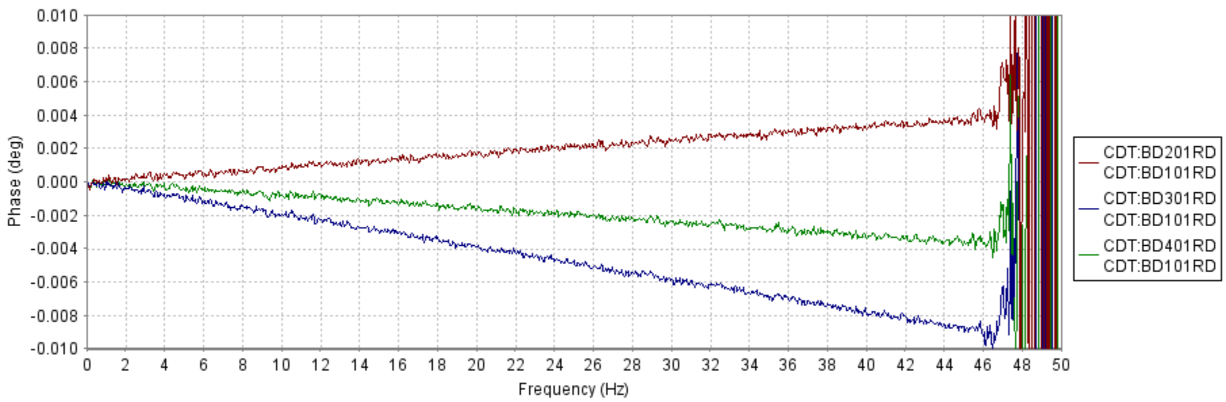

Figure 59 Relative Transfer Function 100 Hz, Gain 1

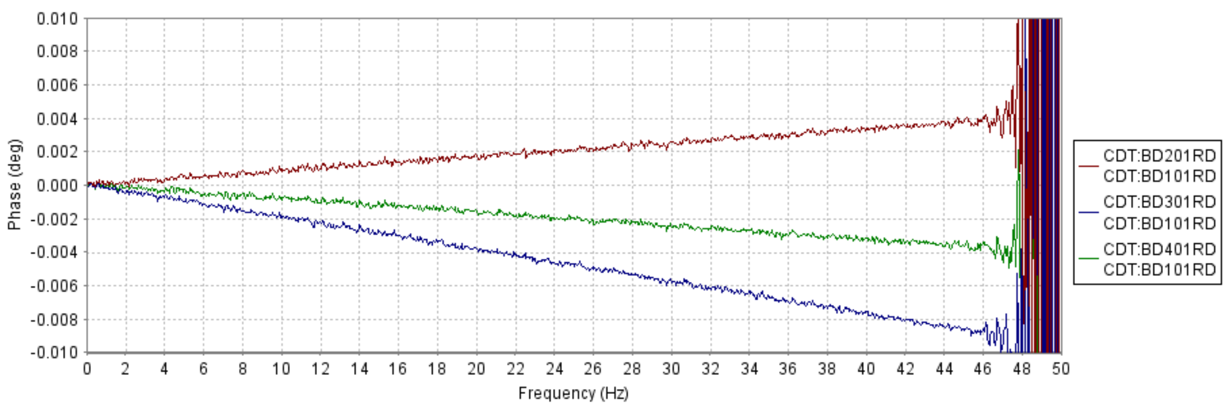

Figure 60 Relative Transfer Function 100 Hz, Gain 8

All of the phase delays are indeed linear with respect to frequency. The constant channel-to-channel timing skew corresponding to these phase delays is shown in the table below.

Table 32 Relative Transfer Function Timing Skew relative to Channel 1

	BD2	BD3	BD4
#137, 20 Hz, gain 1	0.64 us	0.01 us	0.61 us
#137, 50 Hz, gain 8	0.35 us	0.04 us	0.87 us
#138, 100 Hz, gain 1	0.23 us	-0.54 us	-0.22 us
#138, 100 Hz, gain 8	0.24 us	-0.53 us	-0.22 us

All of the SMAD channels were observed to have a timing skew that was within approximately 1 microsecond of one another.

3.14 Analog Bandwidth

The Analog Bandwidth test measures the bandwidth of the digitizers analog and digital filter.

3.14.1 Measurand

The quantity being measured is the upper limit of the frequency pass-band in Hertz.

3.14.2 Configuration

Multiple digitizer channels are connected to a white noise signal source as shown in the diagram below.

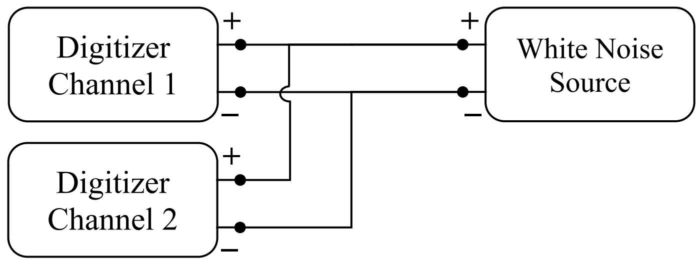

Figure 61 Analog Bandwidth Configuration Diagram

Table 33 Analog Bandwidth Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	123669	Bandlimited white noise

The White Noise Source is configured to generate a band-width limited white noise voltage with an amplitude equal to approximately 10% of the digitizer input channel's full scale. One hour of data is recorded.

3.14.3 Analysis

The measured bit-weight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \leq n \leq N - 1$

The PSD is computed from the time series (Merchant, 2011) from the time series and the 3 dB point in the power spectra is measured.

3.14.4 Result

The power spectra of the white noise signal recorded on the SMAD digitizer channels are shown in the plots below.

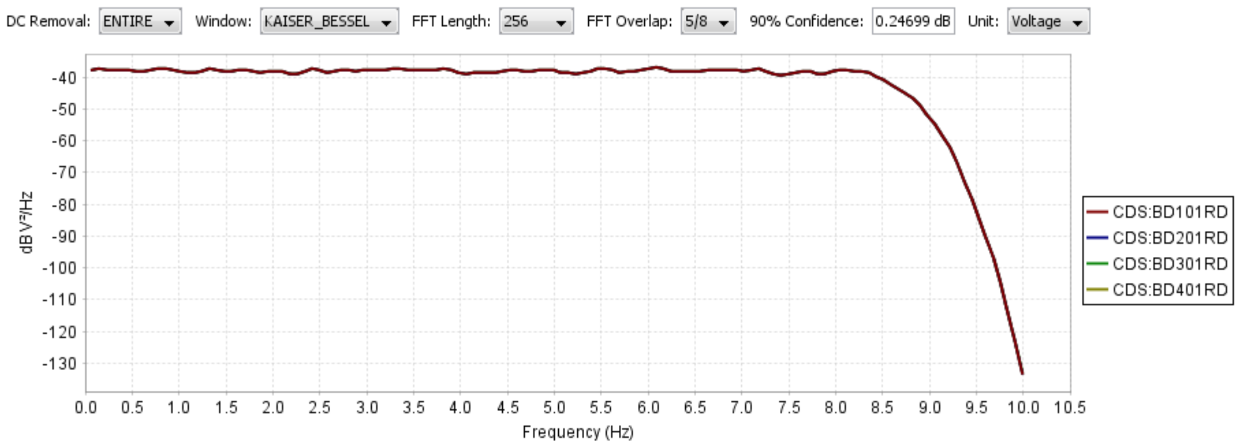

Figure 62 Analog Bandwidth 20 Hz, Gain 1

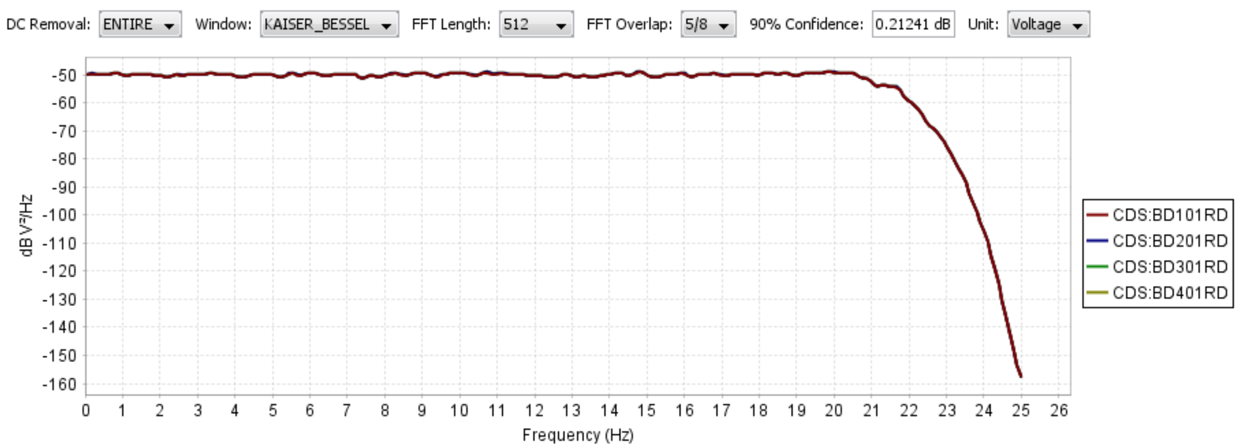

Figure 63 Analog Bandwidth 50 Hz, Gain 8

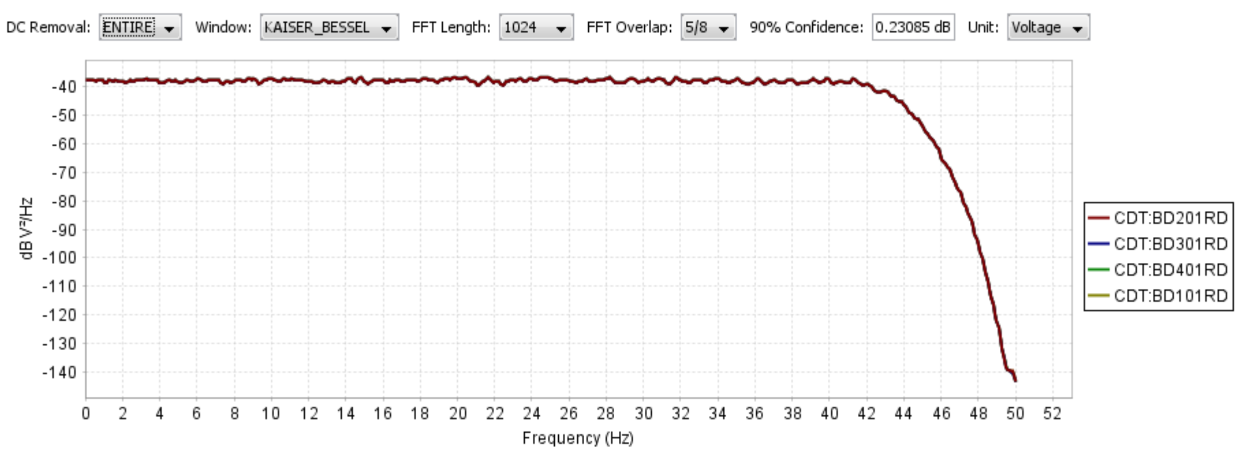

Figure 64 Analog Bandwidth 100 Hz, Gain 1

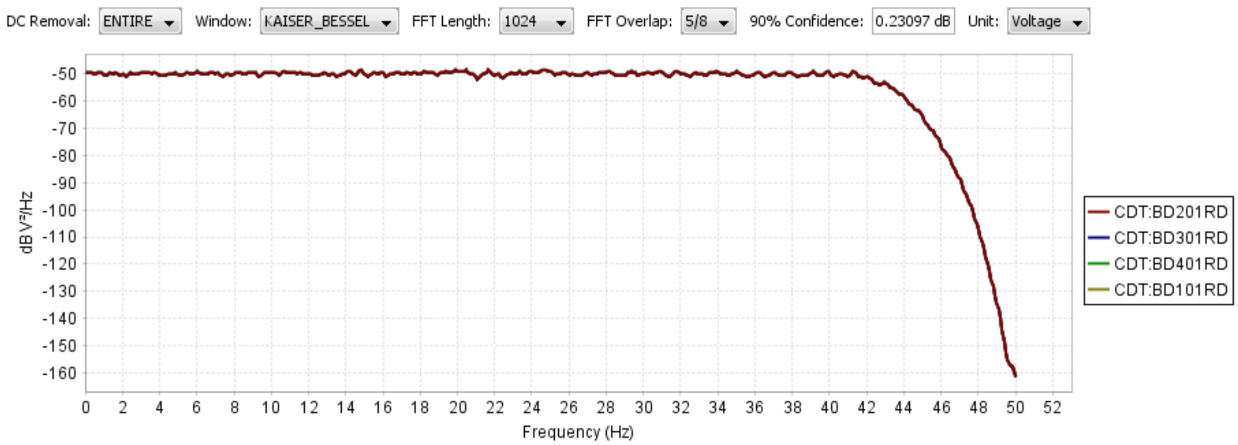

Figure 65 Analog Bandwidth 100 Hz, Gain 8

Table 34 Analog Bandwidth

	BD1	BD2	BD3	BD4	Percent of Nyquist
#137, 20 Hz, gain 1	8.516 Hz	8.516 Hz	8.516 Hz	8.516 Hz	85.16%
#137, 50 Hz, gain 8	21.289 Hz	21.289 Hz	21.289 Hz	21.289 Hz	85.16%
#138, 100 Hz, gain 1	42.285 Hz	42.285 Hz	42.285 Hz	42.285 Hz	84.57%
#138, 100 Hz, gain 8	42.285 Hz	42.285 Hz	42.285 Hz	42.285 Hz	84.57%

All of the SMAD channels were observed to have the same high frequency pass-band limit for a common sample rate and gain setting. It does not appear that there is any change in bandwidth as a fraction of the Nyquist rate, approximately 85%, when the sample rate was changed from 20 to 50 Hz or the gain was changed from 1 to 8. There does appear to be a slight difference in bandwidth between SMAD #137 and #138. However, the difference is very minor.

3.15 Incoherent Noise

The Incoherent Noise test measures the amount of noise present on a digitizer by collecting waveform data from input channels that are recording a common broad-band signal. The incoherent portion of the power spectra is mathematically extracted for each individual channel and compared against the noise obtained from the digitizer self-noise.

3.15.1 Measurand

The quantity being measured is the digitizer input channels self-noise power spectral density in dB relative to 1 V^2/Hz versus frequency.

3.15.2 Configuration

Three or more digitizer channels are connected to a white noise signal source as shown in the diagram below.

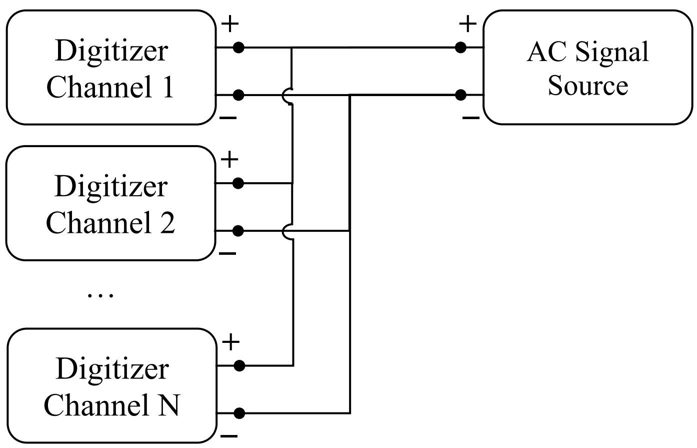

Figure 66 Incoherent Noise Configuration Diagram

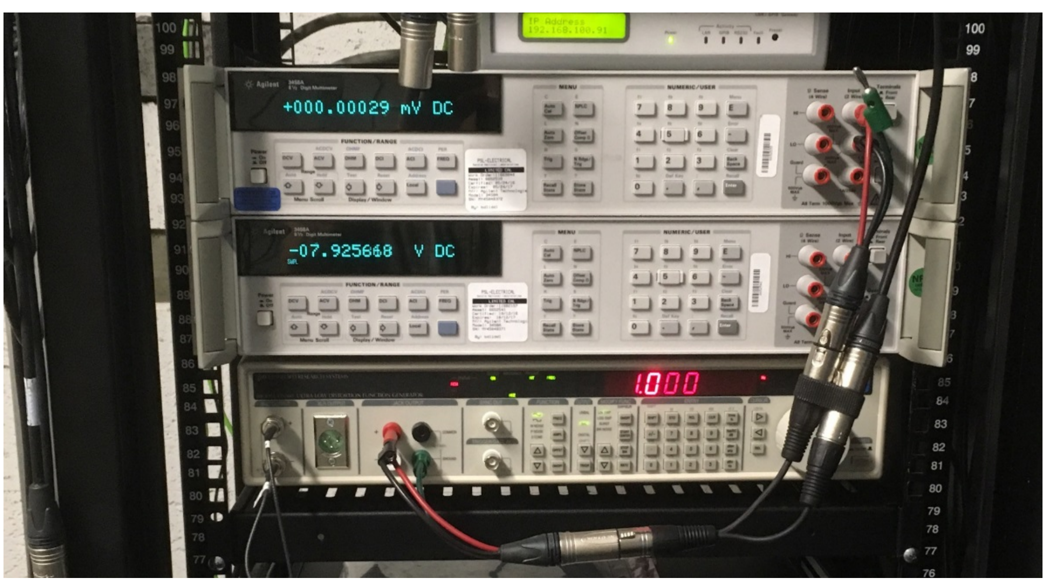

Figure 67 Incoherent Noise Configuration Picture

Table 35 Incoherent Noise Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	123669	Bandlimited white noise

The White Noise Source is configured to generate a band-width limited white noise voltage with an amplitude equal to approximately 10% of the digitizer input channel's full scale. One hour of data is recorded.

3.15.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$$x[n],\ 0 \le n \le N-1$$

The incoherent self-noise is then extracted using the waveform time-series and the derived set of auto and cross power spectral densities (Sleeman, 2007; Merchant, 2011).

3.15.4 Result

An example power spectra recorded by the SMAD digitizer is shown in the plot below.

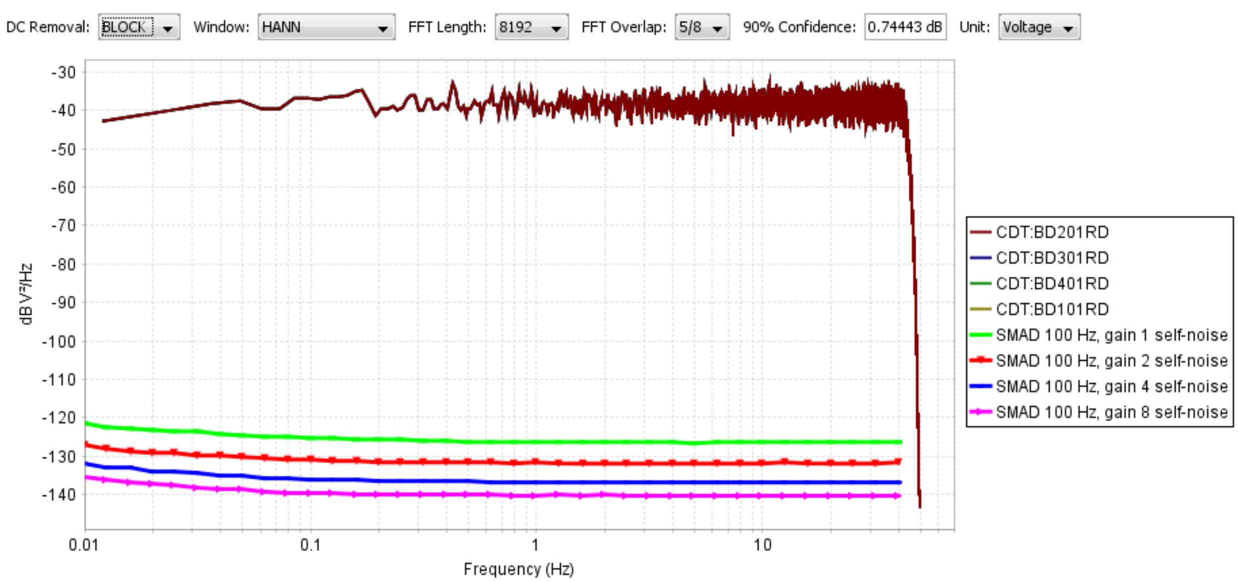

Figure 68 Incoherent Noise Raw Power Spectra, 100 Hz.

The resulting incoherent noise levels are shown in the plots below along with the corresponding terminated self-noise levels.

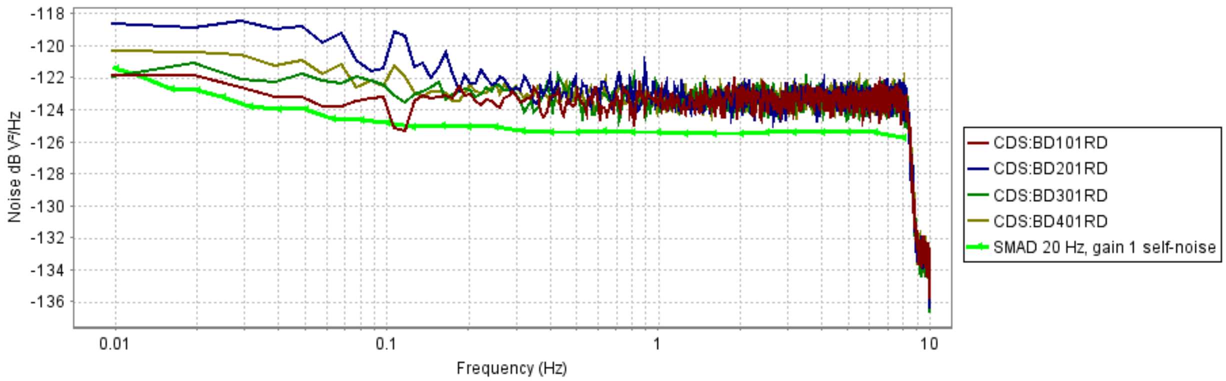

Figure 69 Relative Amplitude and Phase 20 Hz, Gain 1

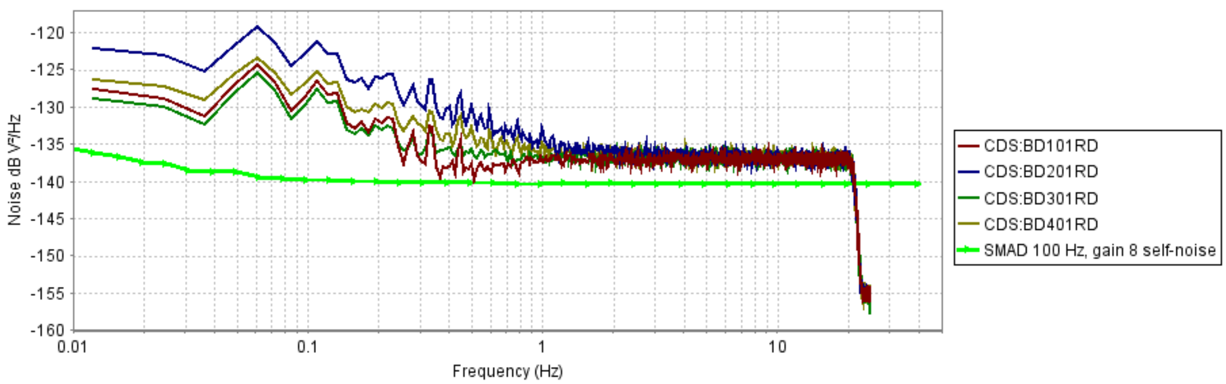

Figure 70 Relative Amplitude and Phase 50 Hz, Gain 8

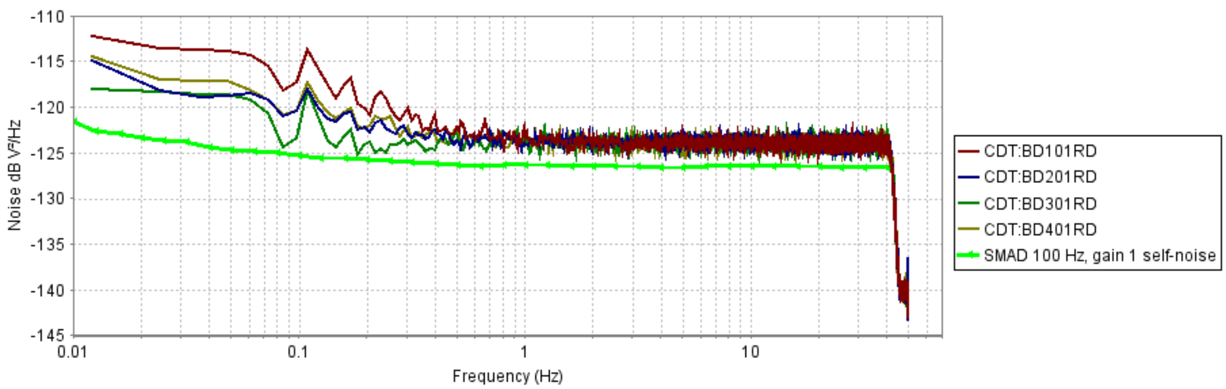

Figure 71 Relative Amplitude and Phase 100 Hz, Gain 1

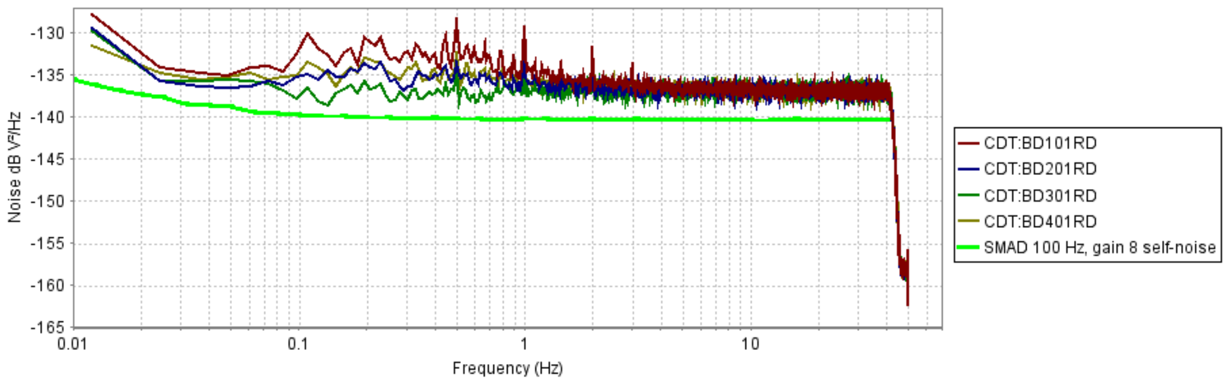

Figure 72 Relative Amplitude and Phase 100 Hz, Gain 8

In all cases, the incoherence noise present while the digitizer channels were being actively driven by a broad-band signal was slightly elevated, between 2 and 3 dB higher, than the self-noise while terminated. Note, however, that the generated signal was between 80 and 90 dB greater than the estimated self-noise levels.

3.16 Total Harmonic Distortion

The Total Harmonic Distortion test is used to measure the linearity of a digitizer channel by recording a known AC signal at a reference voltage from an ultra-low distortion oscillator.

3.16.1 Measurand

The quantity being measured is the digitizer input channel's linearity expressed in decibels.

3.16.2 Configuration

The digitizer is connected to an ultra-low distortion oscillator and a meter configured to measure voltage as shown in the diagram below.

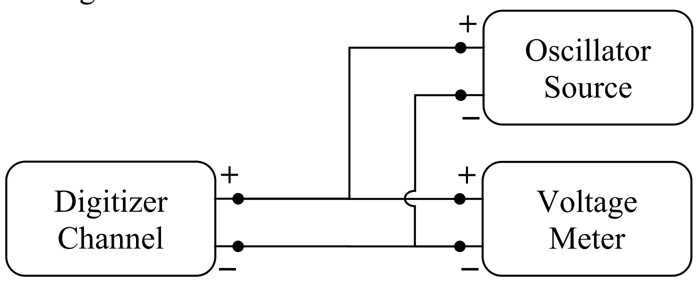

Figure 73 Total Harmonic Distortion Configuration Diagram

Table 36 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Oscillator	Quanterra Supertonal	123669	1.41 Hz, 50% Full Scale
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage

The Oscillator is configured to generate an AC signal with an amplitude of approximately 50% of the digitizer input channel's full scale and a frequency equal to 1.41 Hz. This frequency was chosen as it is near the calibration frequency of 1 Hz and neither this frequency or any of its nearby harmonics coincide with integer valued frequencies which are typically are often corrupted with

The meter and the digitizer channel record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz, which is a minimum of 100 times the frequency of the signal of interest in order to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.01 %.

Both the chosen oscillator and reference meter have signal characteristics that exceed that of the digitizer under test. Therefore, any distortion observed in the signal recorded on the digitizer channel may be inferred to be due to the digitizer.

A minimum of 1 hour of data is recorded.

The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.16.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n],\ 0 \leq n \leq N - 1$

The PSD is computed from the time series (Merchant, 2011) from the time series using a 4k-sample Kaiser-Bessel window. A Kaiser-Bessel window is used to minimize the width of the main lobe and the amplitude of side-lobes. The window length and data duration were chosen to provide sufficient frequency resolution around the primary harmonic.

$P_{xx}[k], 0 \leq k \leq N - 1$

Over frequencies (in Hertz):
$f[k], 0 \leq k \leq N - 1$

A peak-detection algorithm is applied to identify peaks that occur at the location of expected harmonics within the power spectra and the RMS power is computed for each of the peaks that are present (Merchant, 2011).

The THD is then computed as the ratio power in the harmonics to the power in the fundamental:

$$THD_{dB} = 10\log_{10}\left(\frac{\sqrt{\sum_{l=1}^{M-1}(rms[l])^2}}{rms[0]}\right)^2$$

The THD of the signal recorded on the reference meter is computed as well. The reference meter THD provides a baseline for the quality of the signal that was introduced to the digitizer. Any increase in signal distortion may be inferred to be due to the digitizer.

3.16.4 Result

The figure below shows a short segment of a representative waveform time series recorded on both the reference meter and a digitizer channel under test of the 2 hr, 1.41 Hz, 10 V peak sinusoid that was used to measure harmonic distortion.

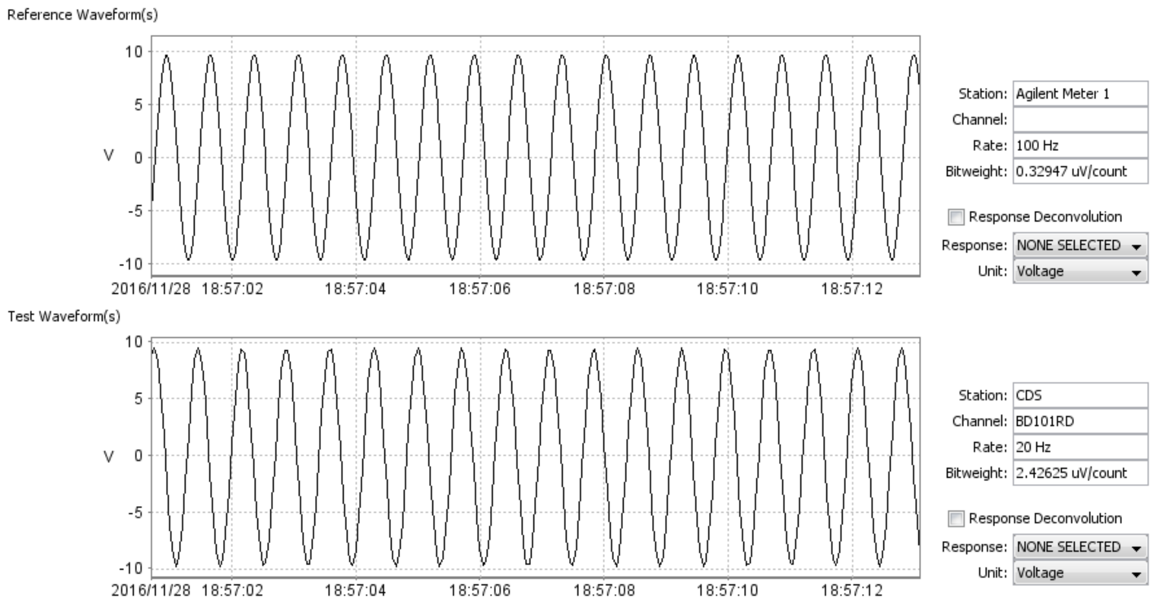

Figure 74 THD Waveform Time Series

The figures below show the power spectra of the THD for each of the sample rates evaluated.

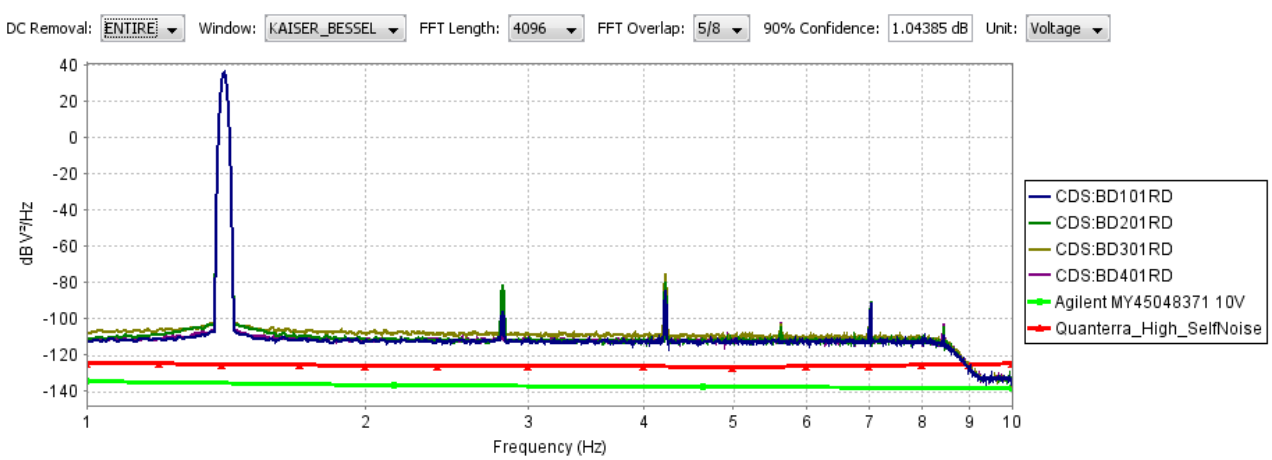

Figure 75 THD Power Spectra 20 Hz, Gain 1

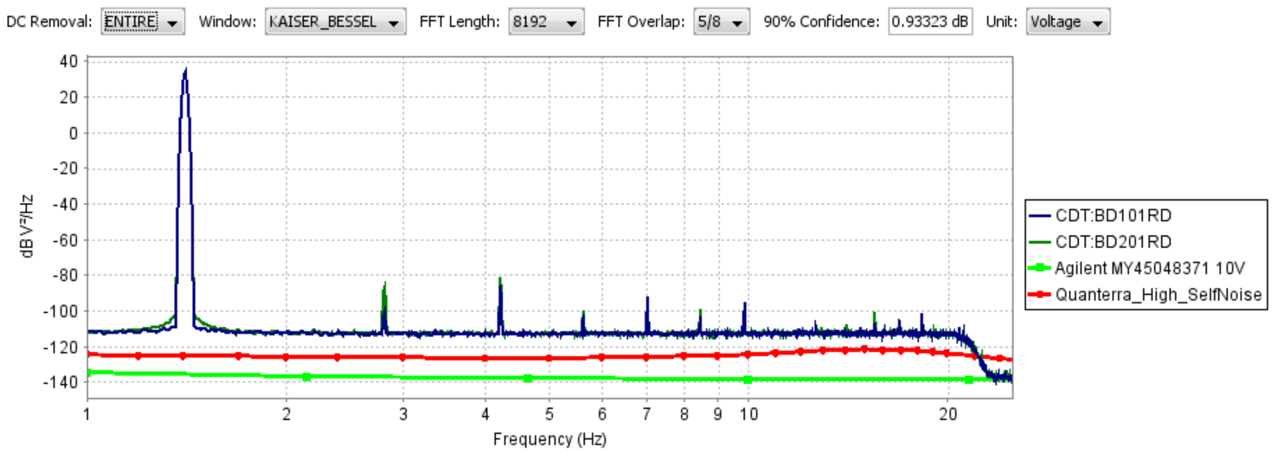

Figure 76 THD Power Spectra, 50 Hz, Gain 1

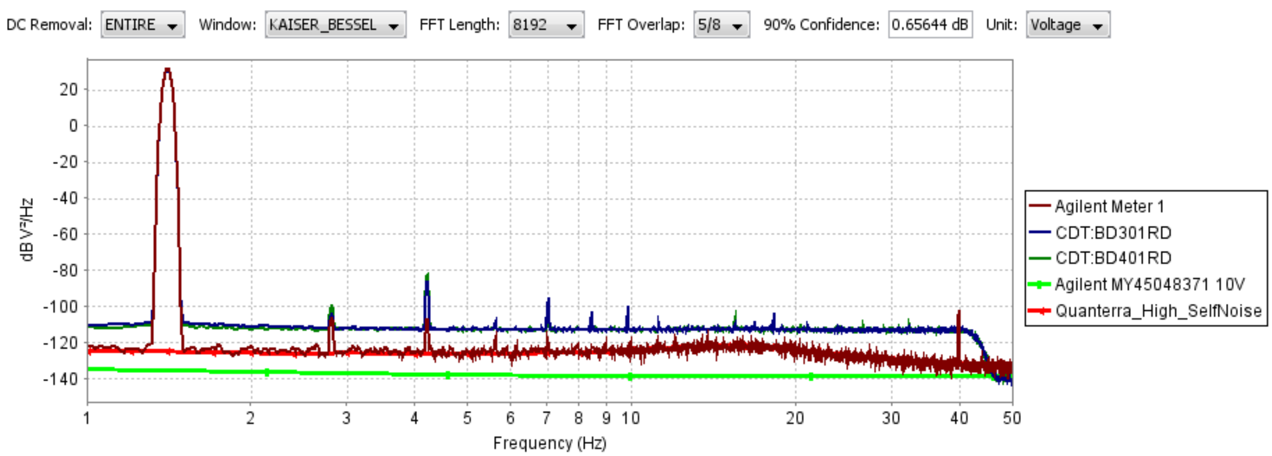

Figure 77 THD Power Spectra 100 Hz, Gain 1

Table 37 Total Harmonic Distortion

	Reference	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	-133.76 dB	-119.16 dB	-113.12 dB	-110.59 dB	-122.11 dB
#138, 50 Hz, gain 1	-134.96 dB	-118.96 dB	-114.73 dB		
#138, 100 Hz, gain 1	-134.96 dB			-116.42 dB	-114.21 dB

In all cases, the reference measurement of the signal generated by the low distortion oscillator exceeded the measurement made on the digitizer channel indicating that the distortion observed is due to the SMAD digitizer.

The observed harmonic distortion ranged between -110 and -122 dB with no significant change in linearity at different sample rates.

3.17 Common Mode Rejection

The Common Mode Rejection test measures the ability of a digitizer to reject a common mode signal on a differential input channel.

3.17.1 Measurand

The quantity being measured is the ratio of the common mode signal amplitude to the observed amplitude on the digitizer input channels in dB.

3.17.2 Configuration

The digitizer is connected to a AC signal source and a meter configured to measure voltage as shown in the diagram below.

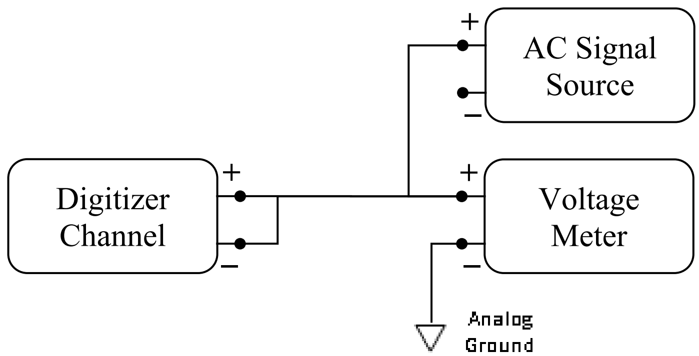

Figure 78 Common Mode Rejection Configuration Diagram

Since the digitizer input channels are differential and are shorted together, the digitizer should not be recording any signal. However, some amount of common mode signal will still be present on the digitizer input channel.

Table 38 Common Mode Rejection Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 10% Full Scale
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage

The AC Signal Source is configured to generate an AC voltage with an amplitude of approximately 10% of the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. One minute of data is recorded.

The meter and the digitizer channel record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz, which is a minimum of 100 times the frequency of the signal of interest in order to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.01 %.

The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.17.3 Analysis

A 10 cycle, or 10 seconds at 1 Hz, window is defined on the data for the recorded signal segment.

A four parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference meter in Volts in order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

$$V_{ref}\sin\left(2\pi f_0 t_n + \theta\right) + V_{dc}$$

A similar sine-fit is performed on the data recorded on the digitizer:

$$V_{meas}\sin\left(2\pi f_0 t_n + \theta\right) + V_{dc}$$

The Common Mode Rejection is then computed as the ratio between the reference and measured amplitudes:

$$CMR_{dB} = 10 * \log_{10}\left(\frac{V_{ref}}{V_{meas}}\right)^2$$

3.17.4 Result

The figures below show the waveform time series for the recording made on the digitizer channels under test. The window regions bounded by the red lines indicate the segment of data used for analysis.

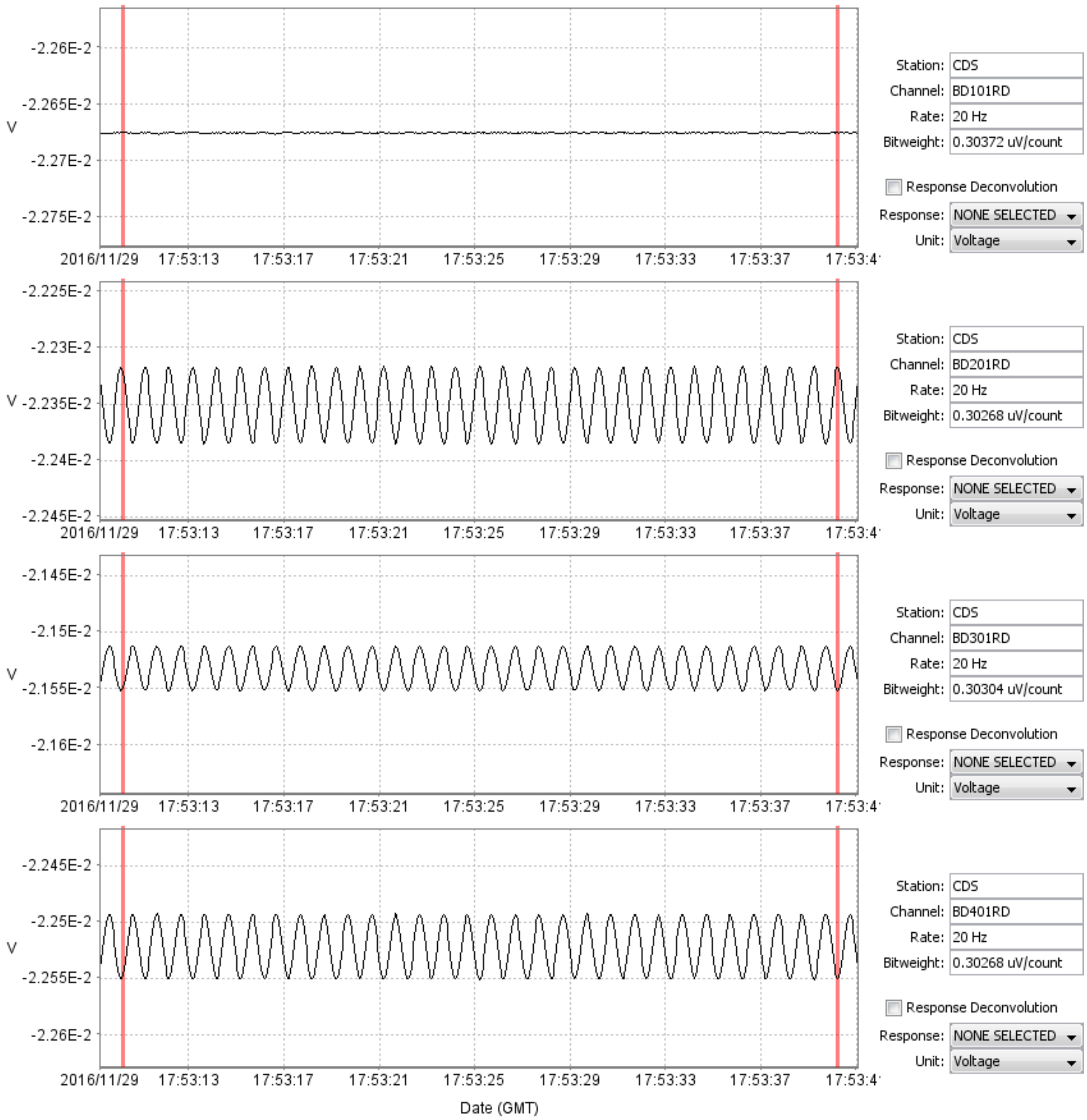

Figure 79 Common Mode Rejection Time Series, 20 Hz, Gain 8

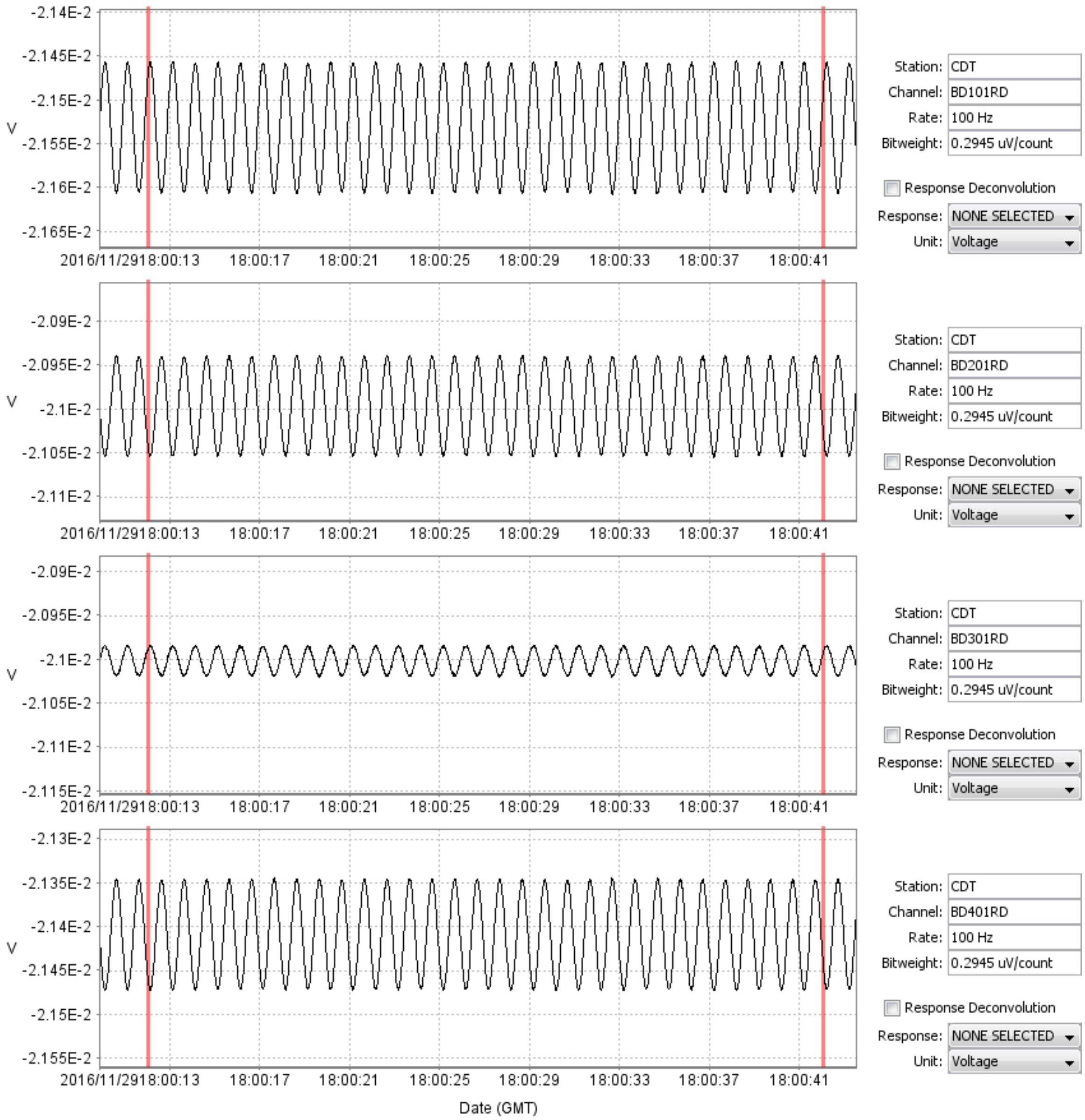

Figure 80 Common Mode Rejection Time Series, 100 Hz, Gain 8

The following table contains the computed common mode noise and rejection ratio.

Table 39 Common Mode Rejection Ratio

		BD1	BD2	BD3	BD4
#137, 20 Hz, gain 8	Amplitude	0.33 uV	33.76 uV	19.61 uV	28.41 uV
	Rejection	117.53 dB	77.39 dB	82.11 dB	78.89 dB
#138, 100 Hz, Gain 8	Amplitude	73.61 uV	56.10 uV	16.68 uV	62.08 uV
	Rejection	70.62 dB	72.98 dB	83.52 dB	72.10 dB

The observed common mode rejection was typically between 70 and 83 dB. However, in one instance for SMAD #137 on channel BD1 the common mode rejection was in excess of 117 dB.

3.18 Crosstalk

The Crosstalk test measures how much of a signal recorded on one channel of a digitizer is also present on another channel as noise.

3.18.1 Measurand

The quantity being measured is the ratio of the signal power present in one or more other channels to the observed signal power on another channel in dB.

3.18.2 Configuration

The digitizer is connected to a AC signal source and a meter configured to measure voltage as shown in the diagram below.

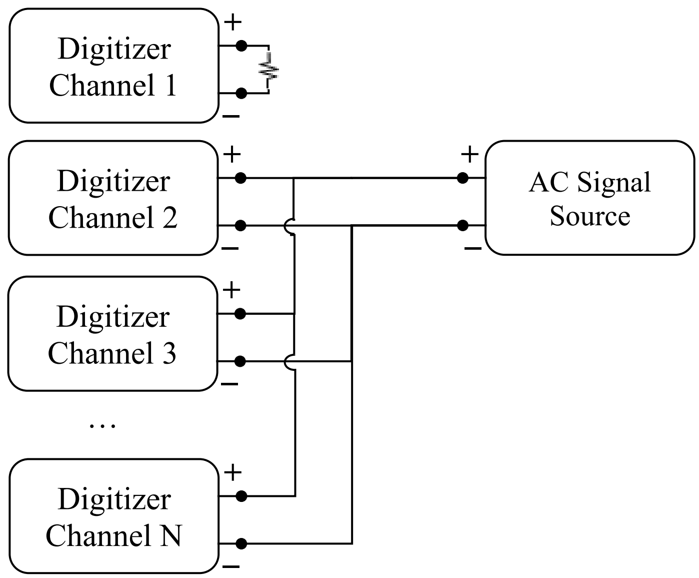

Figure 81 Crosstalk Configuration Diagram

Table 40 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 50% Full Scale

The AC Signal Source is configured to generate a AC voltage with an amplitude of approximately 50% of the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. Approximately 10 minutes of data is recorded.

3.18.3 Analysis

The measured bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

$x[n]$

The PSD is computed from the time series (Merchant, 2011) from the time series using a 1k-sample Hann window and 5/8 overlap of the input terminated channel and all of the tonal channels:

$P_i[k],\ 1 \le i \le N$

For the purposes of convention, the input terminated channel is assumed to be the first channel and the tonal channels are 2 through N. The RMS value of the maximum peak in each of the power spectra are identified and computed:

$V_{rms\ i},\ 1 \le i \le N$

The mean crosstalk value is also computed between the terminated channel and each of the tonal channels is computed:

$$Mean\ Crosstalk = 10\log_{10}\left[\frac{1}{N-1}\sum_{i=2}^{N}\frac{V_{rms\ 1}}{V_{rms\ i}}\right]^2$$

3.18.4 Result

The figure below shows a representative waveform time series for the recording made on the digitizer channels under test. All of the results were similar to the waveforms shown below. The window regions bounded by the red lines indicate the segment of data used for analysis.

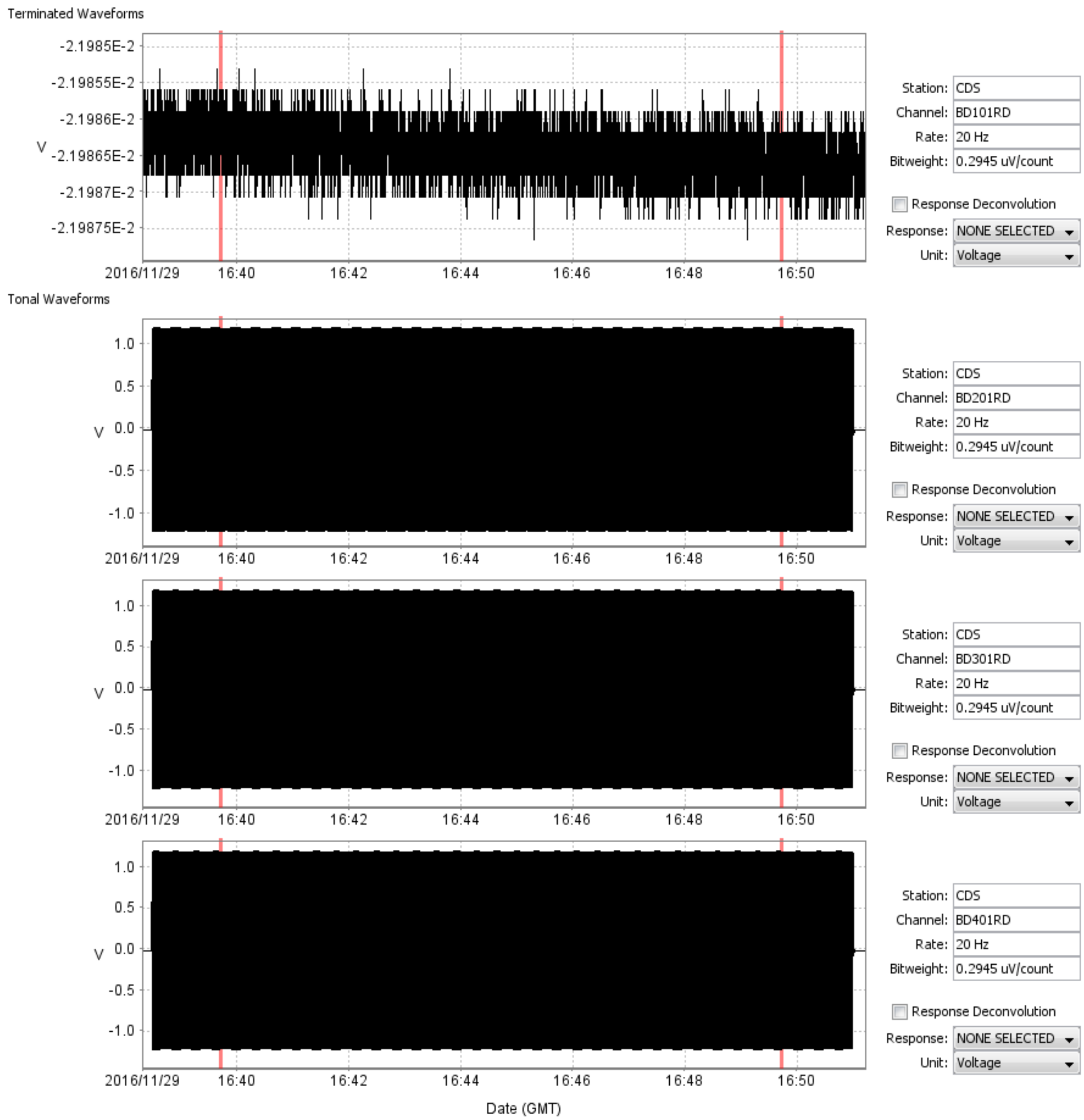

Figure 82 Crosstalk Representative Waveform Time Series

The figures below show a representative power spectra of the terminated and tonal channels for each of the two sample rates for which crosstalk was evaluated. All of the results were similar to the power spectra shown below.

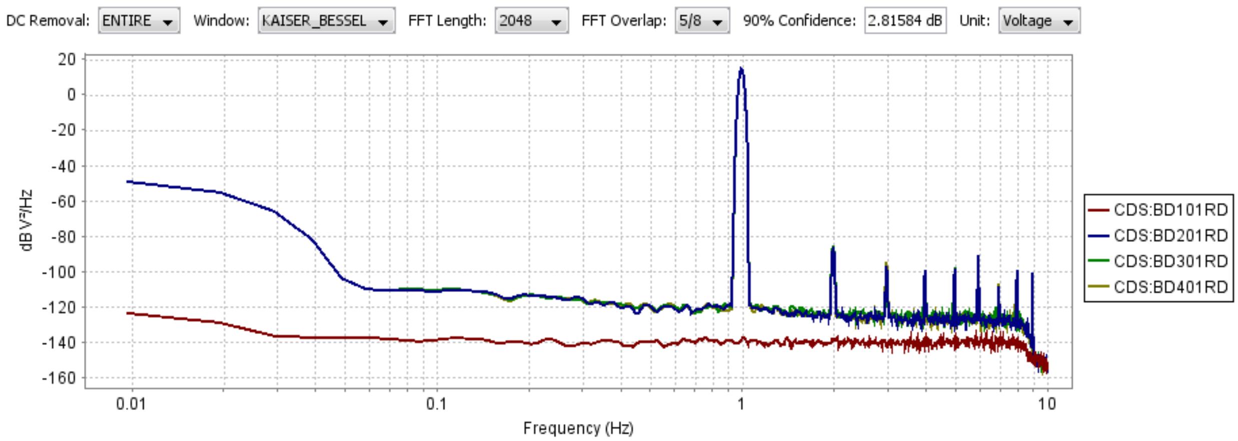

Figure 83 Crosstalk Power Spectra, 20 Hz, Gain 8

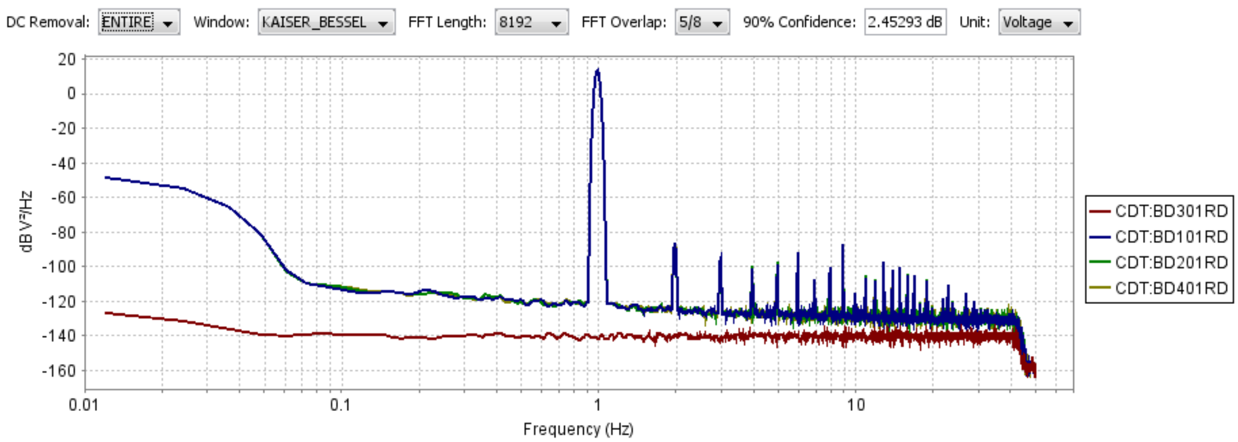

Figure 84 Crosstalk Power Spectra, 100 Hz, Gain 8

The following table contains the computed crosstalk ratios.

Table 41 Crosstalk

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 8	-151.26 dB	-152.99 dB	-153.84 dB	-152.68 dB
#138, 100 Hz, gain 8	-149.52 dB	-147.43 dB	-149.52 dB	-146.41 dB

The computed levels of crosstalk were all between -146 and -154 dB with no significant difference between the two units at sample rates of 20 Hz and 100 Hz. Note that the spectra of the terminated channel do not contain any peak indicating the presence of crosstalk. Therefore, the calculated values represent the maximum possible level of crosstalk that may be present.

3.19 Time Tag Accuracy

The Time Tag Accuracy test measures the digitizer's timing accuracy under stable conditions in which the digitizer is clock is locked and stable.

3.19.1 Measurand

The quantity being measured is the error in the time tag of specific time-series sample in seconds. Error is defined to be the observed time-stamp minus the expected time-stamp.

3.19.2 Configuration

The digitizer is connected to a timing source as shown in the diagram below.

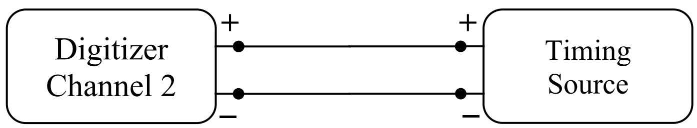

Figure 85 Time Tag Accuracy Configuration Diagram

Table 42 Time Tag Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Geotech Smart24	S1043	GPS PPM Output

The Timing Source may be configured to generate a time-synchronized pulse-per-minute, pulse-per-hour, or sinusoid. In each case, there is an observable signal characteristic

3.19.3 Analysis

The difference between the digitizers actual and expected time stamps are measured by evaluating the unique characteristics of the signal being recorded (Merchant, 2011). The average time tag error is computed over a minimum of an hour.

3.19.4 Result

The figure below shows a representative waveform time series of a Pulse-per-minute (PPM) for the recording made on a digitizer channel under test.

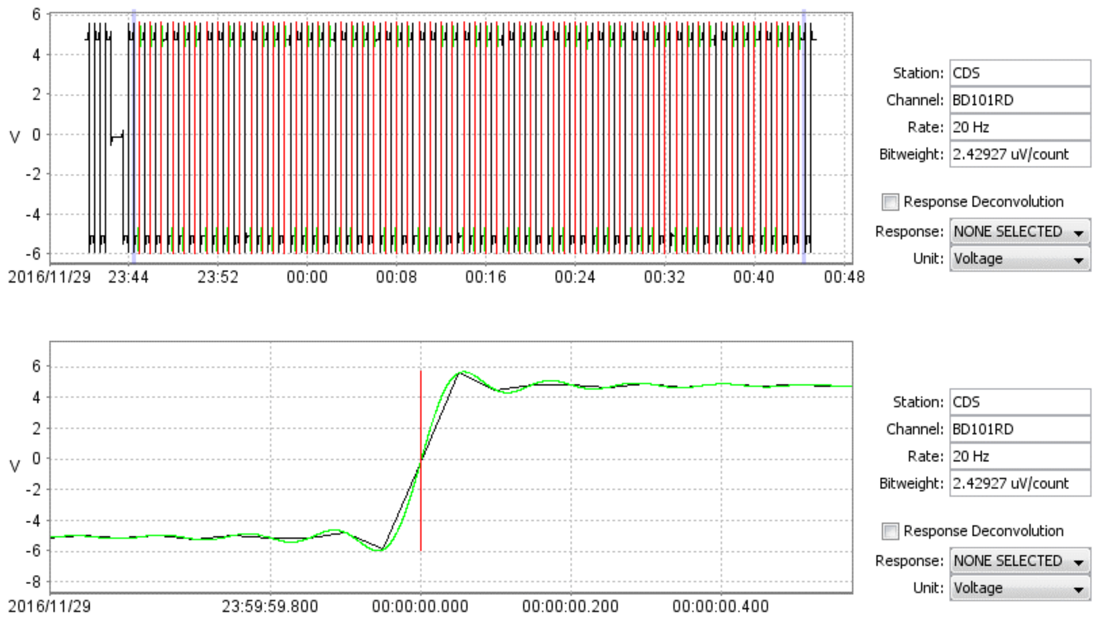

Figure 86 Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets.

Table 43 Time Tag Accuracy

	BD1	BD2	BD3	BD4
#137, 20 Hz, gain 1	224.77 us	223.96 us	224.76 us	223.97 us
#137, 20 Hz, gain 8	226.15 us	225.15 us	226.10 us	225.46 us
#138, 50 Hz, gain 1	170.97 us	170.74 us	171.62 us	171.23 us
#138, 100 Hz, gain 1	161.48 us	161.24 us	162.07 us	161.72 us

The measured time tag accuracy values were consistent for all of the recording channels on each digitizer. There appears to be a slight difference between the time tag accuracy at different sample rates where it was measured to be 225 us at 20 Hz, 170 us at 50 Hz, and 160 us at 100 Hz.

3.20 Timing Drift

The Time Tag Drift test measures how the digitizer's timing accuracy drifts when the digitizer's clock is not locked and recovers once lock is restored.

3.20.1 Measurand

The quantity being measured is the error in the time tag of specific time-series sample in seconds and the rate at which the error changes with time. Error is defined to be the observed time-stamp minus the expected time-stamp.

3.20.2 Configuration

The digitizer is connected to a timing source as shown in the diagram below.

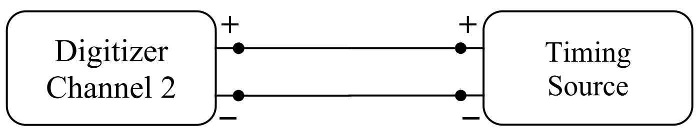

Figure 87 Timing Drift Configuration Diagram

Table 44 Timing Drift Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Geotech Smart24	S1043	GPS PPM Output

The Timing Source may be configured to generate a time-synchronized pulse-per-minute, pulse-per-hour, or sinusoid. In each case, there is an observable signal characteristic

The digitizer clock is allowed to stabilize before the GPS antenna is disconnected resulting in the digitizer to lose timing lock. The digitizer is allowed to drift over-night for a minimum of 12 hours before it is re-connected to the GPS antenna and allowed to regain its timing lock.

3.20.3 Analysis

The difference between the digitizers actual and expected time stamps are measured by evaluating the unique characteristics of the signal being recorded (Merchant, 2011).

The levels of timing error and rates of change are observed while the digitizer has GPS lock, while it is drifting without GPS lock, and while it is recovering once GPS lock is resumed.

3.20.4 Result

The figures below show the timing offsets over time as the digitizer channels drift and recover at sample rates of 20 Hz and 100 Hz.

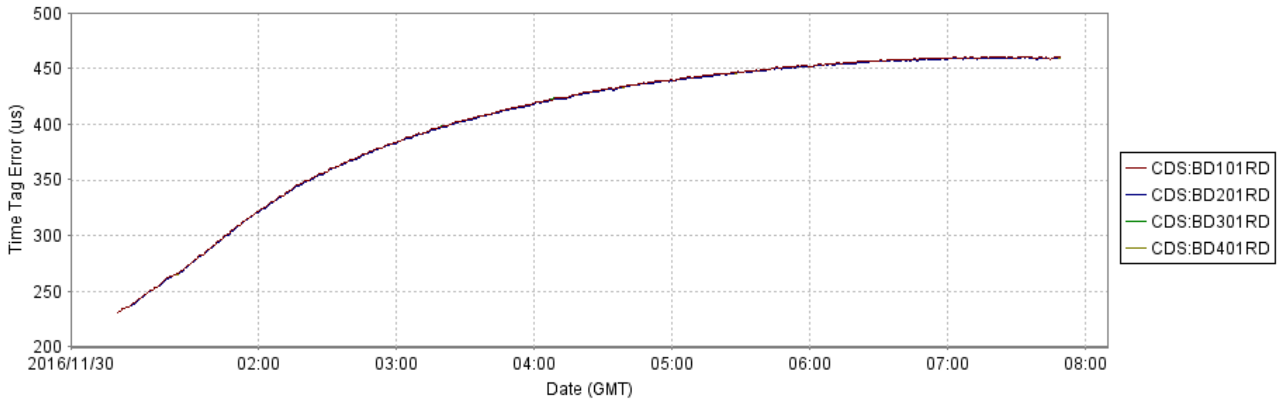

Figure 88 Time Tag Drift, 20 Hz

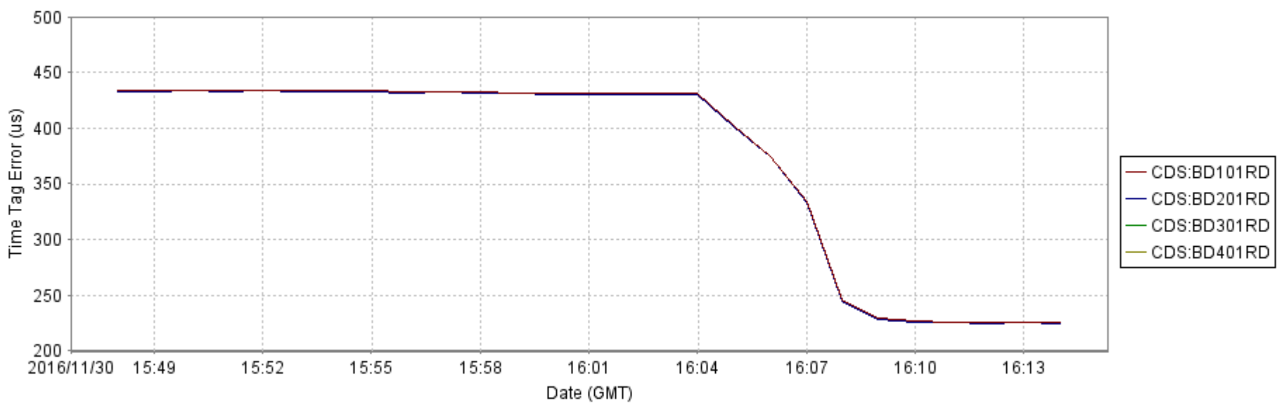

Figure 89 Time Tag Recovery, 20 Hz

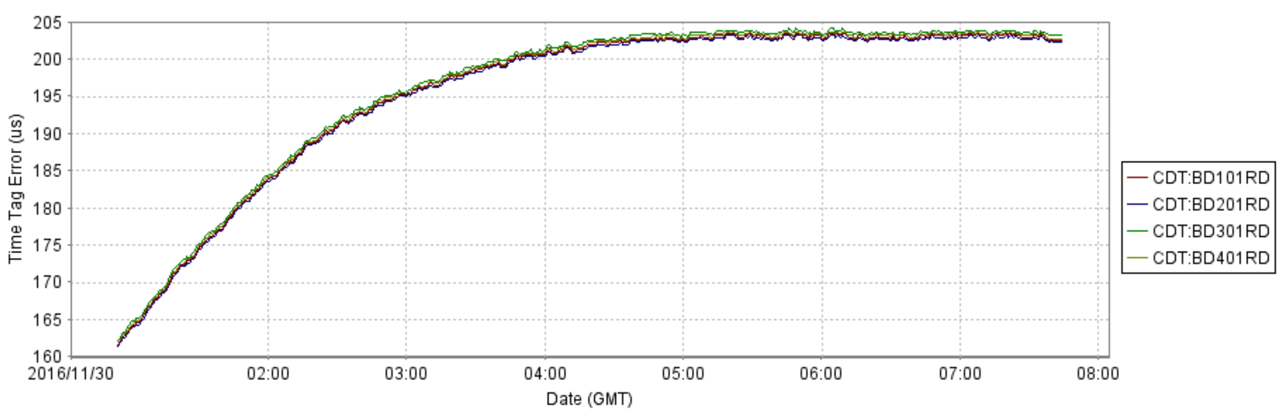

Figure 90 Time Tag Drift, 100 Hz

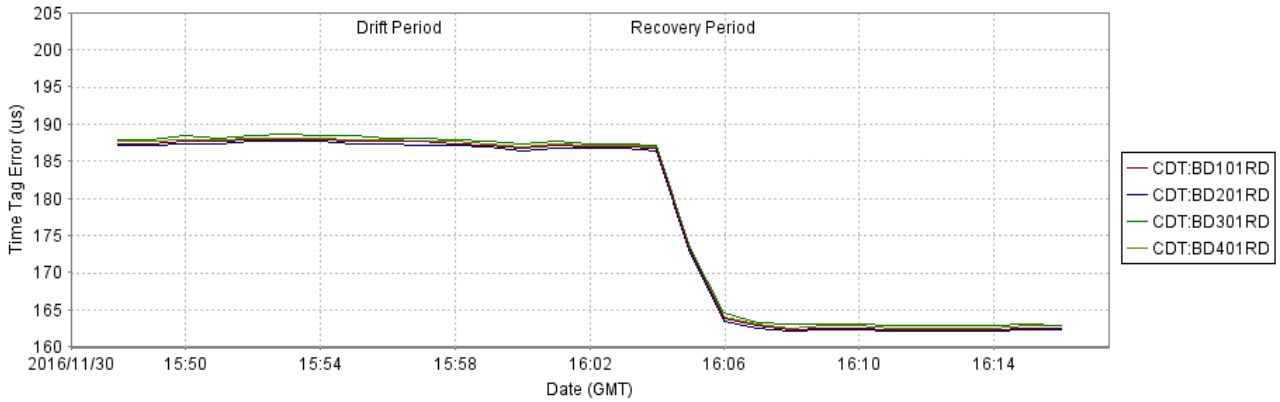

Figure 91 Time Tag Recovery, 100 Hz

The following table contains the computed timing offsets when locked, drifting, and recovering and the estimated rate at which the digitizer was observed to drift and recover.

Table 45 Time Tag Drift and Recovery

	#137, 20 Hz, gain 1	#138, 100 Hz, gain 1
Lock Level	235 us	163 us
Initial Drift Rate	90 us/hr	20 us/hr
Stabilized Drift Level	433 us	188 us
Recovery Rate	2628 us/hr	830 us/hr
Stabilized Recovery Level	225 us	163 us

SMAD digitizers #137 and #138 both started with an initial time tag accuracy of 235 and 163 microseconds, respectively. They both drifted fairly slowly once timing lock was lost and eventually stabilized at 433 and 188 microseconds, respectively. This stabilized level was maintained for more than 16 hours after GPS lock was lost. Once timing lock was regained, they both recovered very quickly over the course of several minutes back to levels of 225 and 163 microseconds, respectively.

3.21 Calibrator

The purpose of the calibrator amplitude test is to determine and verify if the digitizer accurately programs the correct signal characteristics for sensor calibrations.

3.21.1 Measurand

The quantity being measured is the amplitude, frequency, or power spectra of the calibration signal being generated.

3.21.2 Configuration

The digitizer calibrator output is connected to a voltage meter as shown in the diagram below.

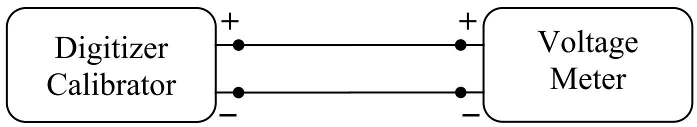

Figure 92 Calibrator Configuration Diagram

Table 46 Calibrator Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage

The calibrator is configured to generate sinusoids across a range of amplitude and frequencies. In addition, several random binary signals were generated with different pulse widths.

The meter is configured to record the described calibration signals. The recording made on the meter is used as the reference for determining the signal characteristics. The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.21.3 Analysis

For the sinusoid calibration signals, a minimum of a 10 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment.

A four parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference meter in Volts in order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

$V_{meas}\sin(2\,pi\,f\,t + \ ) + V_{dc}$

The measured signal characteristics are then compared against what was programmed into the digitizers calibrator.

For the random binary signals, the PSD is computed from the time series (Merchant, 2011) from the time series using a 1k-sample Hann window.

3.21.4 Result

The figures and tables below show the reference meter recording of the SMAD calibrator output.

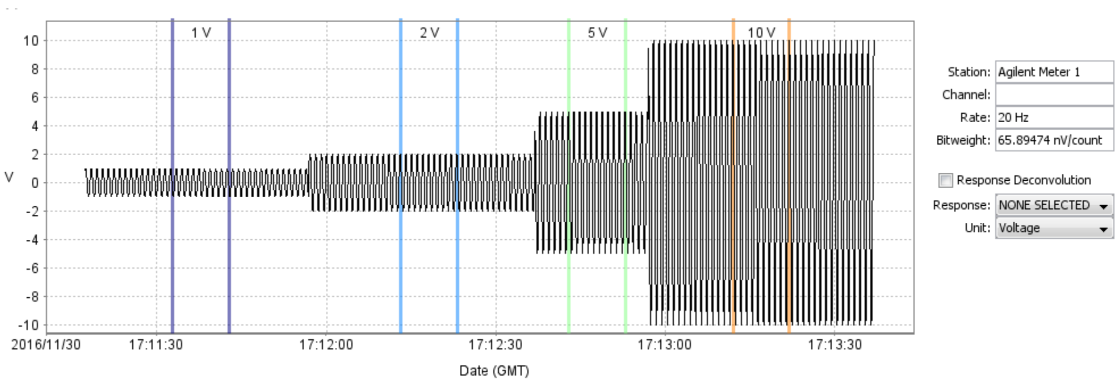

Figure 93 Calibrator Sine Amplitude at 1 Hz

Table 47 Calibrator Sine Amplitude at 1 Hz

Programmed Amplitude	Measured Amplitude
1 V	0.99811 V
2 V	1.99624 V
5 V	4.98391 V
10 V	9.98278 V

The calibrator sinusoid amplitudes were all consistent with the programmed amplitudes.

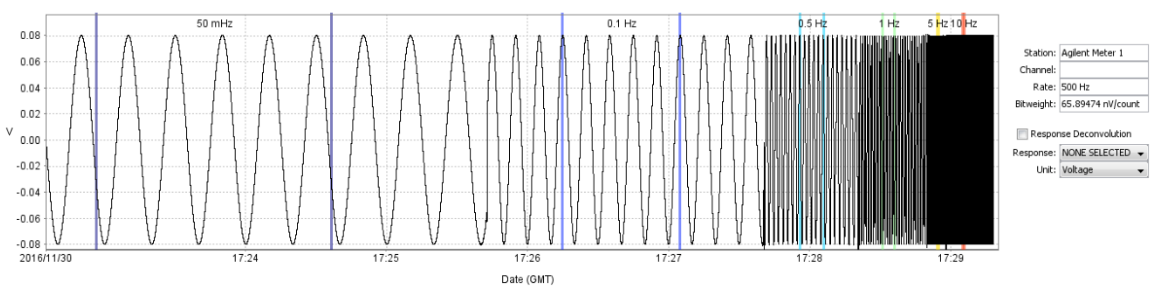

Figure 94 Calibrator Sine Frequency at 2 V

Table 48 Calibrator Sine Frequency at 2 V

Programmed Frequency	Measured Frequency
0.05 Hz	0.050001 Hz
0.1 Hz	0.10000 Hz
0.5 Hz	0.50000 Hz
1.0 Hz	1.0000 Hz
5 Hz	5.0196 Hz
10 Hz	10.039 Hz

The calibrator sinusoid frequencies were all consistent with the programmed frequencies.

The figures below show the power spectra of the random binary calibration signal generated by the SMAD digitizer for a null point and 20 Hz and 50 Hz.

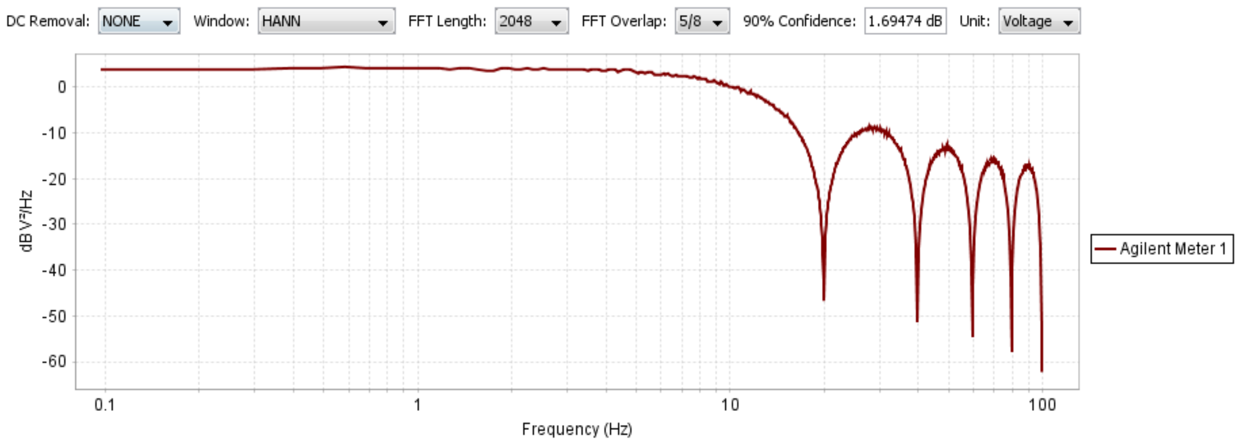

Figure 95 Random Binary, 20 Hz

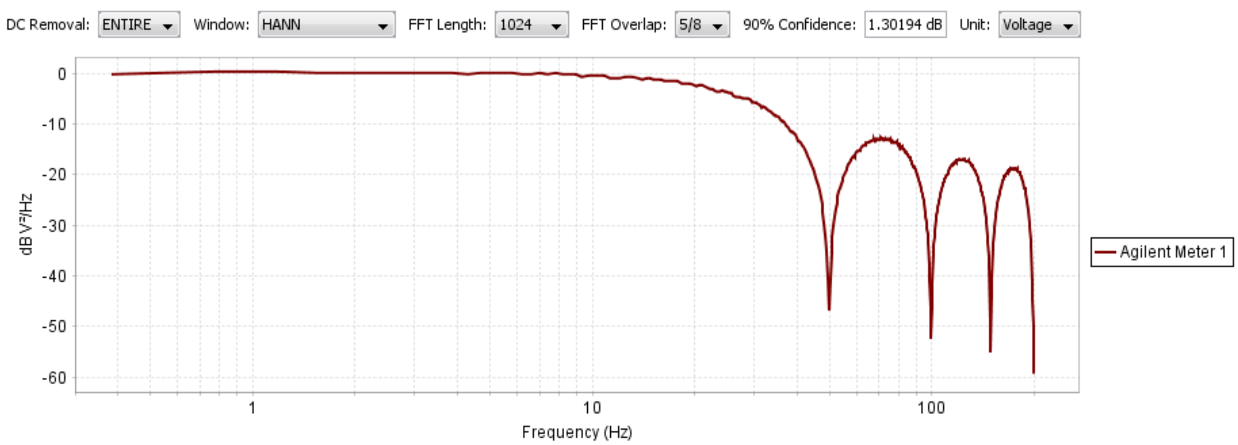

Figure 96 Random Binary, 50 Hz

The measured random binary power spectral densities were all consistent with what had been programmed.

3.22 CD1 Status Flags

During the evaluation of the SMAD digitizer, the status flags on the CD1 stream were examined to verify whether they were passing status flags for events such as the vault door intrusion detection, the digitizer case being opened, and calibration underway. The following sections document the transmission of those status flags.

3.22.1 Intrusion Detection Vault Door Open

The SMAD digitizer provides an input port which may be attached to an intrusion detection door switch. During the evaluation, the door switch provided by CEA was toggled and the CD1 status flag was displayed.

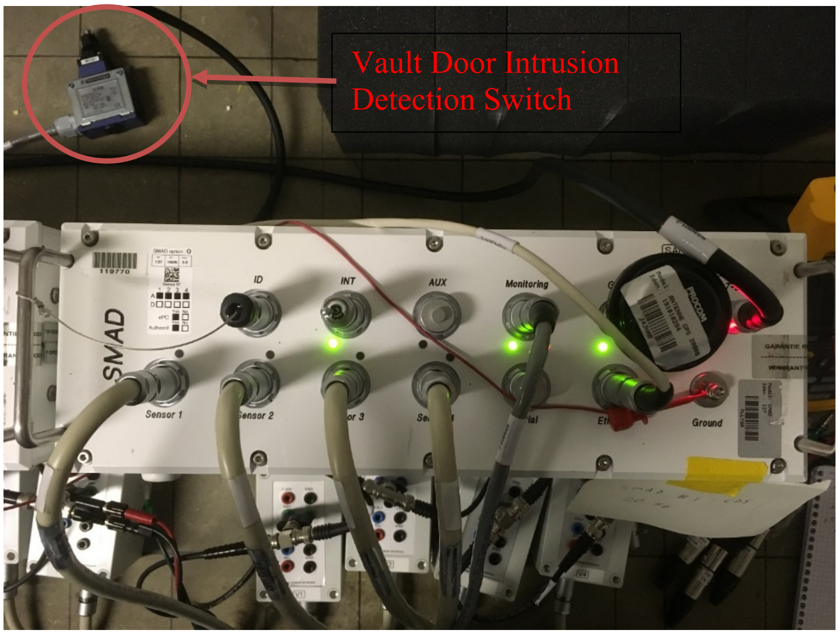

Figure 97 SMAD Digitizer with Intrusion Detection

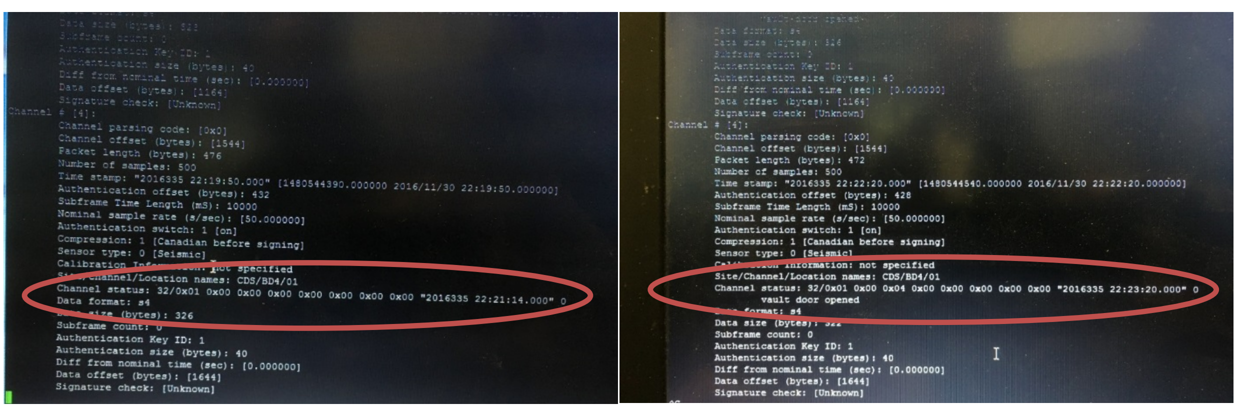

Figure 98 CD1 Stream with and without Intrusion Detection Flag

As may be seen in the CD1 stream in the figure above, the status flag indicating that the vault door opened was set.

3.22.2 Digitizer Case Open

The SMAD digitizer contains an internal switch on the case to provide indication of when the case is opened.

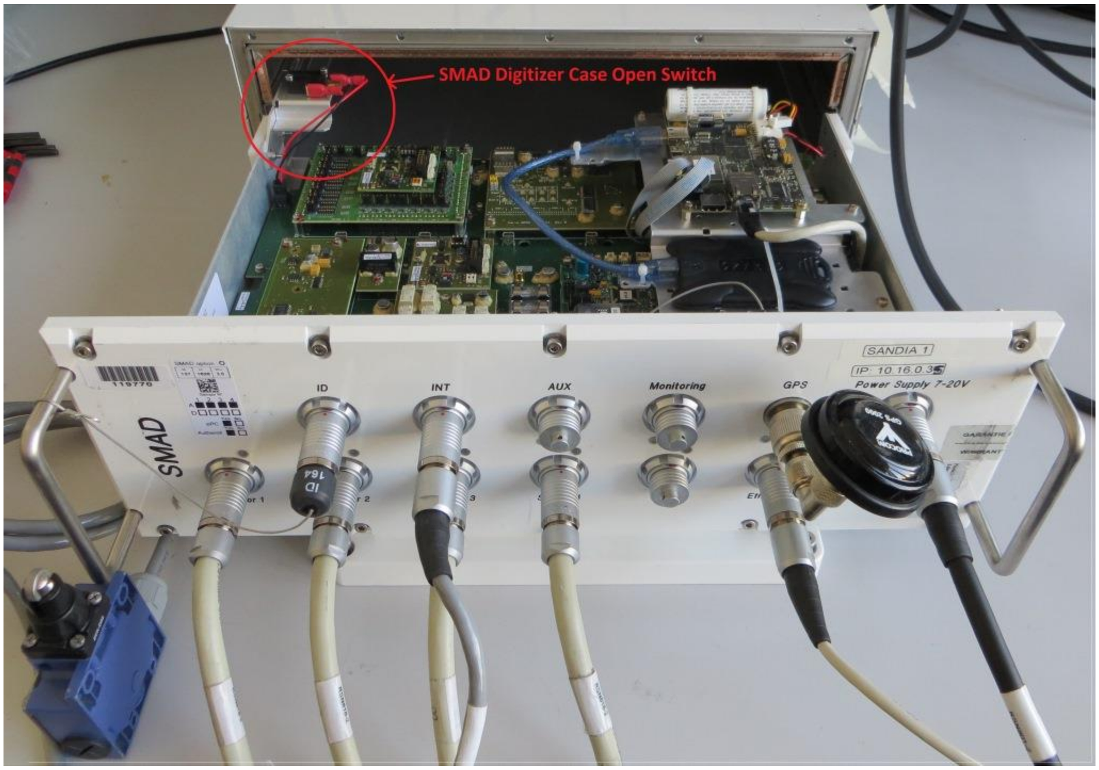

Figure 99 SMAD Digitizer Case Open Switch

For the purpose of this evaluation, CEA connected the switch to an external toggle so that it could be activated without actually opening the case. During the evaluation, the case switch was toggled and the CD1 status flag was displayed.

Figure 100 SMAD Digitizer Case Open Switch

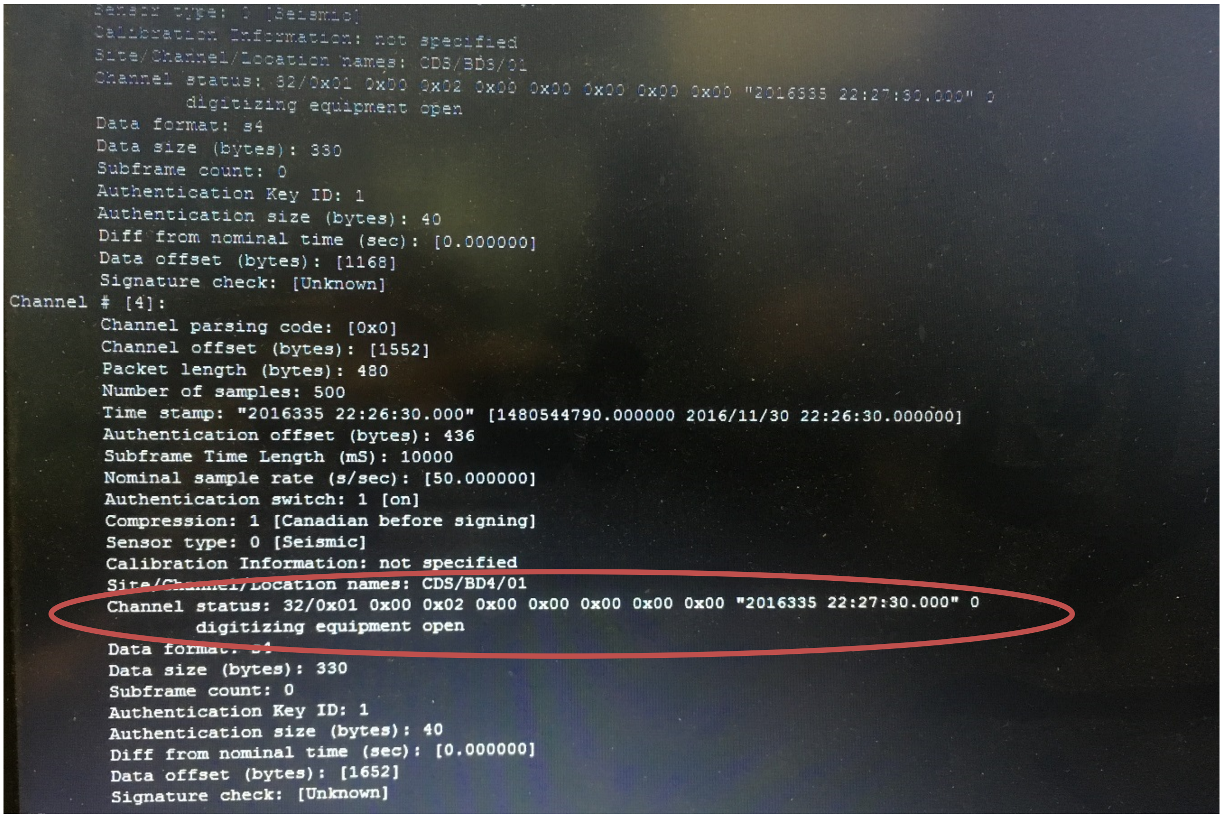

Figure 101 CD1 Stream with Case Open Flag

As may be seen in the CD1 stream in the figure above, the status flag indicating that the digitizer case was opened was set.

3.22.3 Calibration Underway

The SMAD digitizer reports a CD1 status flag when a calibration is underway.

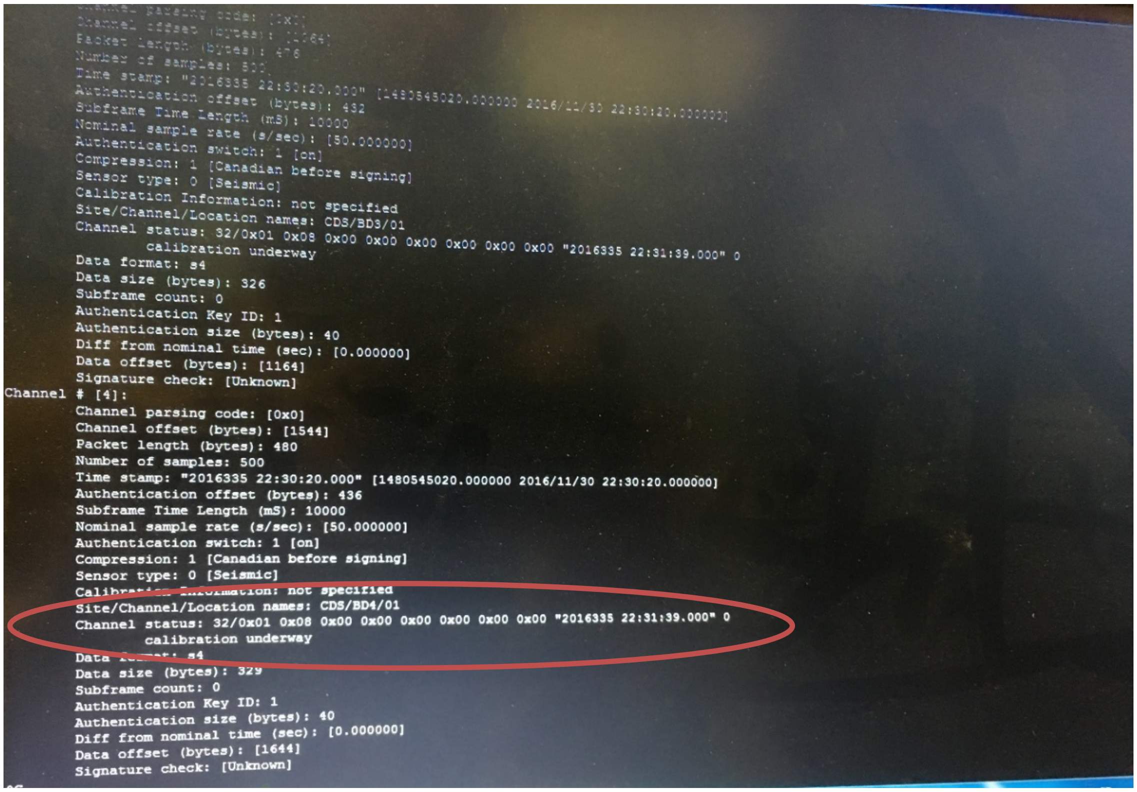

Figure 102 CD1 Stream with Calibration Underway Flag

As may be seen in the CD1 stream in the figure above, the status flag indicating that a calibration was underway was set.

4 SUMMARY

Power Consumption
The SMAD digitizer was found to consume between 4 and 7 watt of power in general operation. Power consumption increased most notably with increased sample rate. Very minor improvements in power consumption may be obtained by de-activating recording channels.

Input Impedance
The SMAD digitizer channels were found to have an input impedance that was within 0.05 % of the nominal 32 kOhm across 20, 50, and 100 Hz sample rates and gains of 1, 2, 4, and 8.

DC Accuracy
The SMAD digitizer channels were found to have consistent bit-weights at 20, 50, and 100 Hz sample rates of approximately 2.42 uV/count, 1.21 uV/count, 0.605 uV/count, and 0.303 uV/count at gains settings of 1, 2, 4, and 8, respectively. These values were between 2.7 % and 3.3 % greater than the nominal SMAD bit-weights.

AC Accuracy
The SMAD digitizer channels were found to have consistent bit-weights at 20, 50, and 100 Hz sample rates of approximately 2.42 uV/count, 1.21 uV/count, 0.606 uV/count, and 0.303 uV/count Hz at gains settings of 1, 2, 4, and 8, respectively. These values were between 3.0 % and 3.1 % greater than the nominal SMAD bit-weights.

Input Shorted Offset
The SMAD digitizer channels were found to have a DC offset that was approximately 0.45 % of full-scale across the 20 and 100 Hz sample rates and gains settings of 1, 2, 4, and 8.

AC Full Scale
The SMAD digitizer channels were able to fully resolve peak-to-peak amplitudes at or about their full scale of 39.53 V, 19.765 V, 9.8825 V, and 4.9413 V at gains settings of 1, 2, 4, and 8, respectively, at sample rates of 20, 50, and 100 Hz.

AC Over Scale
The SMAD digitizer channels all exhibited evidence of clipping at peak-to-peak amplitudes that met or exceeded the nominally specified full scale at gains settings of 1, 2, 4, and 8 and sample rates of 20, 50, and 100 Hz.

Self-Noise
The SMAD digitizer channels exhibited self-noise levels that were consistent at 20 and 100 Hz sample rates and gains settings of 1, 2, 4, and 8. The self-noise performance was consistent with what is expected from a 24-bit digitizer.

Temperature Self-Noise
The SMAD digitizer channels exhibited minimal change in self-noise levels at temperatures of -20 C, 40 C, 50 C, and 60 C. There was a very slight change in DC offset as a function of temperature. Both SMAD digitizers were unable to record at gains of 4 and 8 at temperatures near 60 C.

Dynamic Range
The SMAD digitizer channels exhibited dynamic range values between 133 and 142 dB at 20 and 100 Hz sample rates and gains settings of 1, 2, 4, and 8.

System Noise
System noise plots are provided to demonstrate the impact of the digitizer self-noise for a variety of seismometer and infrasound sensor applications.

Response Verification
The SMAD digitizer channels were found to all have an amplitude and phase response that was consistent from channel to channel.

Relative Transfer Function
The SMAD digitizer channels exhibited less than 1 microsecond of timing skew from channel to channel.

Analog Bandwidth
The SMAD digitizer channels exhibited a bandwidth of approximately 85% of the Nyquist rate at sample rates of 20 Hz, 50 Hz, and 100 Hz.

Total Harmonic Distortion
The SMAD digitizer channels exhibited total harmonic distortion that ranged between -110 and -122 dB with no significant change in linearity across sample rates of 20 Hz, 50 Hz, and 100 Hz.

Common Mode Rejection
The SMAD digitizer channels exhibited common mode rejection ratios of between 70 and 83 dB with one exception of a channel having greater than 117 dB.

Crosstalk
The SMAD digitizer channels exhibited crosstalk better than what was measured at between -146 and -154 dB which was limited by no observable crosstalk about the channel self-noise.

Time Tag Accuracy
The SMAD digitizers exhibited time tag accuracy values that changed with sample rate. The measured time accuracies were 225 us at 20 Hz, 170 us at 50 Hz, and 160 us at 100 Hz.

Time Tag Drift
The SMAD digitizers exhibited a slight amount of timing drift when GPS lock was lost over a period of 12 hours and stabilized at 433 microseconds and 188 microseconds for SN 137 and SN 138, respectively. Both digitizers were able to recover back to their original time tag accuracy within minutes of regaining GPS lock.

Calibrator Demonstration
The SMAD calibrator was able to demonstrate the ability to accurately generate sinusoids at amplitudes of 1, 2, 5, and 10 Volts and frequencies of 0.05, 0.1, 0.5, 1.0, 5.0, and 10.0 Hz. The

SMAD calibrator was also able to demonstrate the ability to generate random binary signals with a first null point at 20 Hz and 50 Hz.

CD1 Status Flags
The SMAD digitizer was able to demonstrate the transmission of CD1 status flags for a vault door intrusion detection, a digitizer case being opened, and calibration underway.

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APPENDIX A: SELF-NOISE

Digitizer self-noise values are reported in units of dB relative to 1 V^2/Hz at the defined octave-band frequencies. The 90% uncertainty of the provided estimates are less than +/- 0.5 dB based upon the number of windows and spectral averaging that was performed when computing the power spectral densities.

SMAD #137, 20 Hz

Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-121.42	-128.01	-132.45	-134.85
0.0125	-121.98	-128.61	-132.89	-135.84
0.0160	-122.74	-129.02	-133.78	-136.11
0.0200	-122.84	-129.58	-134.00	-136.53
0.0250	-123.21	-129.84	-134.50	-137.23
0.0315	-123.80	-129.84	-135.03	-137.77
0.0400	-123.98	-129.89	-135.21	-138.63
0.0500	-123.98	-130.39	-135.59	-138.76
0.0630	-124.56	-130.52	-135.81	-139.05
0.0800	-124.69	-130.62	-135.81	-139.27
0.1000	-124.84	-130.62	-135.87	-139.51
0.1250	-125.11	-130.63	-135.96	-139.55
0.1600	-125.06	-130.75	-135.86	-139.73
0.2000	-125.08	-130.86	-136.05	-139.77
0.2500	-125.09	-130.95	-136.15	-139.73
0.3150	-125.40	-131.06	-136.14	-139.72
0.4000	-125.43	-131.01	-136.17	-139.84
0.5000	-125.41	-131.01	-136.18	-139.84
0.6300	-125.39	-131.08	-136.22	-139.87
0.8000	-125.42	-131.04	-136.24	-139.91
1.0000	-125.47	-131.06	-136.25	-139.88
1.2500	-125.50	-131.06	-136.28	-139.86
1.6000	-125.49	-131.12	-136.27	-139.88
2.0000	-125.50	-131.14	-136.27	-139.93
2.5000	-125.48	-131.15	-136.28	-139.95
3.1500	-125.47	-131.15	-136.31	-139.96
4.0000	-125.48	-131.15	-136.32	-139.96
5.0000	-125.47	-131.14	-136.29	-139.94
6.3000	-125.48	-131.12	-136.31	-139.92
8.0000	-125.81	-131.43	-136.68	-140.25

SMAD #138, 100 Hz

Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-121.62	-127.16	-132.04	-135.65
0.0125	-122.73	-128.24	-133.00	-136.29
0.0160	-123.01	-128.88	-133.20	-136.86
0.0200	-123.43	-129.32	-134.13	-137.44
0.0250	-123.78	-129.37	-134.28	-137.70
0.0315	-123.87	-130.06	-134.54	-138.57
0.0400	-124.43	-130.13	-135.10	-138.75
0.0500	-124.79	-130.44	-135.38	-138.87
0.0630	-124.97	-130.81	-135.84	-139.55
0.0800	-125.07	-130.93	-135.99	-139.66
0.1000	-125.39	-131.07	-136.23	-139.82
0.1250	-125.60	-131.23	-136.30	-139.92
0.1600	-125.70	-131.41	-136.37	-139.99
0.2000	-125.87	-131.61	-136.48	-140.15
0.2500	-125.98	-131.65	-136.54	-140.20
0.3150	-126.15	-131.77	-136.69	-140.22
0.4000	-126.21	-131.74	-136.76	-140.18
0.5000	-126.38	-131.79	-136.82	-140.23
0.6300	-126.51	-131.86	-136.89	-140.28
0.8000	-126.44	-131.95	-136.95	-140.38
1.0000	-126.43	-131.88	-136.91	-140.37
1.2500	-126.45	-131.98	-137.02	-140.29
1.6000	-126.53	-131.99	-137.02	-140.43
2.0000	-126.51	-131.96	-136.98	-140.28
2.5000	-126.53	-131.97	-137.02	-140.41
3.1500	-126.53	-132.10	-137.01	-140.36
4.0000	-126.65	-132.04	-137.07	-140.39
5.0000	-126.71	-132.04	-137.03	-140.38
6.3000	-126.56	-131.97	-137.10	-140.46
8.0000	-126.56	-132.00	-137.10	-140.38
10.0000	-126.60	-132.04	-137.08	-140.44
12.5000	-126.54	-131.91	-137.09	-140.40
16.0000	-126.53	-132.04	-137.13	-140.36
20.0000	-126.57	-132.01	-137.14	-140.40
25.0000	-126.63	-131.95	-136.99	-140.41
31.5000	-126.63	-132.01	-137.16	-140.41
40.0000	-126.64	-131.93	-137.04	-140.46

APPENDIX B: SYSTEM NOISE

Digitizer system noise values are reported in units of dB relative to either 1 $(m/s)^2/Hz$ or 1 $(m/s)^2/Hz$ at the defined octave-band frequencies depending on whether an seismic or infrasonic response was applied to the self-noise data. The 90% uncertainty of the provided estimates are less than +/- 0.5 dB based upon the number of windows and spectral averaging that was performed when computing the power spectral densities.

SMAD #137, 20 Hz, MB2005 Response

Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-84.28	-90.92	-95.42	-97.98
0.0125	-85.71	-92.56	-96.78	-99.77
0.0160	-87.54	-93.81	-98.48	-100.98
0.0200	-87.78	-94.88	-99.05	-101.50
0.0250	-88.69	-95.31	-99.78	-102.53
0.0315	-89.20	-95.43	-100.67	-103.19
0.0400	-89.69	-95.69	-100.83	-104.30
0.0500	-89.87	-96.17	-101.33	-104.55
0.0630	-90.47	-96.39	-101.58	-104.92
0.0800	-90.61	-96.59	-101.77	-105.21
0.1000	-90.88	-96.63	-101.81	-105.38
0.1250	-90.90	-96.71	-101.82	-105.61
0.1600	-91.13	-96.82	-101.96	-105.71
0.2000	-91.09	-96.88	-101.99	-105.81
0.2500	-91.13	-96.99	-102.13	-105.75
0.3150	-91.40	-97.08	-102.12	-105.74
0.4000	-91.44	-96.98	-102.15	-105.83
0.5000	-91.44	-97.03	-102.27	-105.86
0.6300	-91.48	-97.15	-102.26	-105.98
0.8000	-91.41	-97.09	-102.20	-105.88
1.0000	-91.38	-97.22	-102.27	-105.99
1.2500	-91.50	-97.07	-102.44	-105.97
1.6000	-91.54	-97.04	-102.35	-105.99
2.0000	-91.53	-97.07	-102.38	-105.87
2.5000	-91.66	-97.16	-102.23	-105.86
3.1500	-91.44	-97.17	-102.28	-105.84
4.0000	-91.65	-97.14	-102.28	-105.77
5.0000	-91.33	-97.18	-102.24	-105.79
6.3000	-91.27	-97.05	-102.37	-105.72
8.0000	-91.26	-96.96	-102.26	-105.85

SMAD #137, 20 Hz, MB3a Response

Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-84.28	-90.92	-95.43	-97.98
0.0125	-85.71	-92.56	-96.78	-99.78
0.0160	-87.54	-93.81	-98.48	-100.98
0.0200	-87.78	-94.88	-99.06	-101.50
0.0250	-88.70	-95.31	-99.78	-102.54
0.0315	-89.21	-95.43	-100.67	-103.20
0.0400	-89.69	-95.70	-100.83	-104.30
0.0500	-89.87	-96.17	-101.33	-104.55
0.0630	-90.47	-96.39	-101.59	-104.92
0.0800	-90.61	-96.60	-101.77	-105.22
0.1000	-90.88	-96.63	-101.82	-105.39
0.1250	-90.90	-96.72	-101.82	-105.61
0.1600	-91.13	-96.82	-101.96	-105.71
0.2000	-91.10	-96.88	-101.99	-105.81
0.2500	-91.13	-96.99	-102.13	-105.75
0.3150	-91.40	-97.08	-102.12	-105.74
0.4000	-91.44	-96.99	-102.15	-105.84
0.5000	-91.44	-97.03	-102.27	-105.86
0.6300	-91.48	-97.15	-102.27	-105.98
0.8000	-91.41	-97.09	-102.20	-105.88
1.0000	-91.38	-97.22	-102.27	-105.99
1.2500	-91.49	-97.07	-102.44	-105.97
1.6000	-91.53	-97.04	-102.34	-105.99
2.0000	-91.52	-97.06	-102.37	-105.87
2.5000	-91.64	-97.15	-102.22	-105.84
3.1500	-91.41	-97.14	-102.26	-105.81
4.0000	-91.61	-97.10	-102.24	-105.73
5.0000	-91.27	-97.11	-102.17	-105.72
6.3000	-91.16	-96.94	-102.26	-105.60
8.0000	-91.09	-96.79	-102.09	-105.67

SMAD #137, 20 Hz, MB3a Derivative Response

Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-43.15	-49.79	-54.29	-56.85
0.0125	-45.63	-52.48	-56.70	-59.70
0.0160	-49.43	-55.70	-60.37	-62.87
0.0200	-50.57	-57.66	-61.84	-64.28
0.0250	-53.08	-59.73	-64.17	-66.92
0.0315	-55.84	-61.71	-67.17	-69.60
0.0400	-57.87	-63.76	-69.21	-72.61
0.0500	-59.81	-66.02	-71.49	-74.17
0.0630	-62.99	-68.87	-73.95	-77.02
0.0800	-64.91	-70.67	-75.57	-79.26
0.1000	-66.57	-72.87	-77.96	-81.85
0.1250	-69.24	-74.89	-79.95	-83.74
0.1600	-71.05	-77.15	-82.05	-86.10
0.2000	-73.09	-79.04	-83.85	-87.58
0.2500	-75.02	-80.92	-86.11	-89.58
0.3150	-77.44	-82.87	-88.07	-91.89
0.4000	-79.63	-84.93	-90.00	-93.80
0.5000	-81.42	-86.87	-92.31	-95.76
0.6300	-83.38	-89.17	-94.24	-97.89
0.8000	-85.40	-90.96	-96.27	-99.95
1.0000	-87.28	-93.09	-98.19	-101.93
1.2500	-89.45	-95.06	-100.28	-103.97
1.6000	-91.58	-97.05	-102.41	-106.01
2.0000	-93.50	-99.10	-104.32	-107.86
2.5000	-95.52	-101.13	-106.20	-109.80
3.1500	-97.38	-103.08	-108.22	-111.84
4.0000	-99.69	-105.25	-110.34	-113.85
5.0000	-101.32	-107.18	-112.23	-115.83
6.3000	-103.32	-109.11	-114.45	-117.83
8.0000	-105.48	-111.21	-116.49	-120.06

SMAD #138, 100 Hz, STS-2 Response

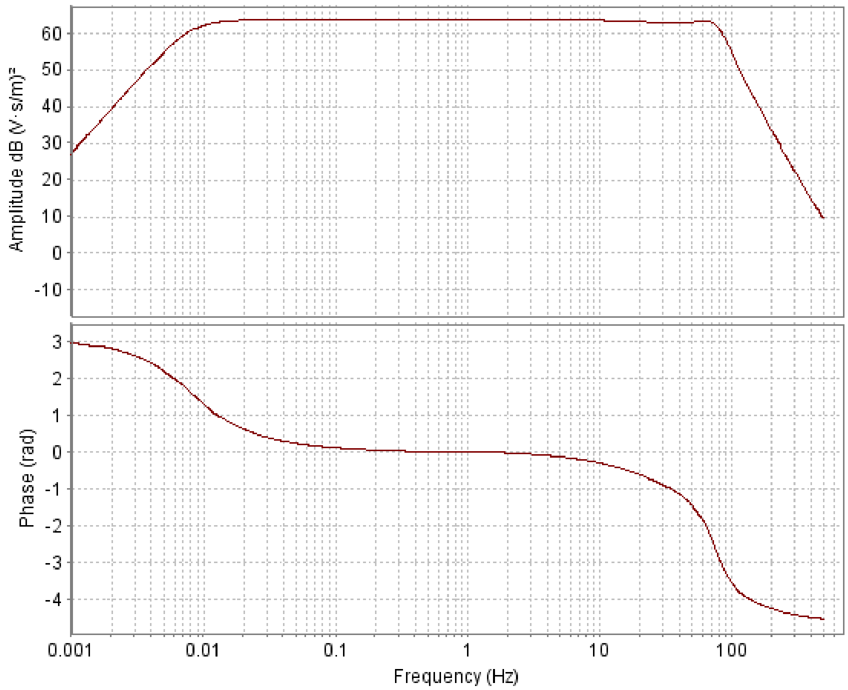
Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-182.80	-188.46	-193.30	-196.92
0.0125	-185.44	-190.91	-195.74	-198.93
0.0160	-186.10	-192.00	-196.35	-199.99
0.0200	-186.78	-192.31	-197.87	-200.87
0.0250	-187.20	-192.80	-197.54	-201.09
0.0315	-187.36	-193.56	-197.63	-201.38
0.0400	-187.93	-193.58	-198.63	-202.35
0.0500	-188.36	-193.93	-198.94	-202.35
0.0630	-188.67	-194.49	-199.43	-203.24
0.0800	-188.50	-194.31	-199.47	-203.40
0.1000	-188.86	-194.60	-199.81	-203.41
0.1250	-189.18	-194.87	-199.98	-203.27
0.1600	-189.21	-194.90	-199.78	-203.51
0.2000	-189.37	-195.27	-200.04	-203.78
0.2500	-189.51	-195.35	-200.21	-203.64
0.3150	-189.64	-195.21	-200.26	-203.82
0.4000	-189.73	-195.24	-200.42	-203.62
0.5000	-189.89	-195.27	-200.50	-203.82
0.6300	-190.08	-195.39	-200.55	-203.84
0.8000	-189.87	-195.43	-200.58	-203.80
1.0000	-189.94	-195.36	-200.40	-203.92
1.2500	-189.88	-195.52	-200.53	-203.80
1.6000	-190.04	-195.50	-200.54	-203.97
2.0000	-190.02	-195.50	-200.52	-203.81
2.5000	-190.04	-195.49	-200.47	-203.86
3.1500	-190.02	-195.56	-200.52	-203.85
4.0000	-190.07	-195.55	-200.51	-203.86
5.0000	-190.04	-195.49	-200.46	-203.85
6.3000	-190.01	-195.41	-200.48	-203.90
8.0000	-189.98	-195.37	-200.41	-203.85
10.0000	-189.98	-195.34	-200.41	-203.81
12.5000	-189.83	-195.30	-200.35	-203.74
16.0000	-189.78	-195.20	-200.24	-203.59
20.0000	-189.65	-195.06	-200.12	-203.48
25.0000	-189.46	-194.87	-199.91	-203.27
31.5000	-189.30	-194.71	-199.72	-203.12
40.0000	-189.37	-194.76	-199.77	-203.15

SMAD #138, 100 Hz, ZM500 Response

Frequency (Hz)	BD1 (gain 1)	BD2 (gain 2)	BD3 (gain 4)	BD4 (gain 8)
0.0100	-119.36	-124.97	-129.90	-133.54
0.0125	-125.52	-131.07	-135.82	-139.09
0.0160	-129.72	-135.59	-139.93	-143.59
0.0200	-135.85	-141.44	-146.92	-150.00
0.0250	-138.66	-144.23	-148.96	-152.54
0.0315	-142.61	-148.84	-153.27	-157.37
0.0400	-147.68	-153.39	-158.57	-162.07
0.0500	-151.67	-157.40	-162.29	-165.68
0.0630	-156.73	-162.55	-167.54	-171.23
0.0800	-160.33	-165.87	-171.39	-175.09
0.1000	-165.20	-170.51	-175.73	-179.32
0.1250	-168.72	-174.59	-179.69	-182.79
0.1600	-173.10	-178.67	-183.60	-187.55
0.2000	-177.07	-183.11	-187.93	-191.76
0.2500	-181.28	-186.61	-191.21	-195.07
0.3150	-184.78	-190.40	-195.38	-198.85
0.4000	-188.26	-193.85	-198.71	-201.96
0.5000	-190.78	-196.21	-201.26	-204.59
0.6300	-192.37	-197.78	-202.83	-206.17
0.8000	-193.04	-198.65	-203.70	-207.07
1.0000	-193.46	-198.87	-203.92	-207.33
1.2500	-193.57	-199.18	-204.18	-207.53
1.6000	-193.80	-199.26	-204.25	-207.70
2.0000	-193.84	-199.17	-204.34	-207.55
2.5000	-193.82	-199.37	-204.34	-207.69
3.1500	-193.79	-199.53	-204.36	-207.67
4.0000	-194.00	-199.36	-204.35	-207.71
5.0000	-193.96	-199.35	-204.36	-207.71
6.3000	-193.92	-199.30	-204.41	-207.76
8.0000	-193.89	-199.33	-204.34	-207.69
10.0000	-193.84	-199.37	-204.38	-207.72
12.5000	-193.88	-199.22	-204.43	-207.70
16.0000	-193.86	-199.33	-204.46	-207.62
20.0000	-193.86	-199.27	-204.45	-207.70
25.0000	-193.94	-199.33	-204.30	-207.70
31.5000	-193.90	-199.32	-204.44	-207.77
40.0000	-193.92	-199.28	-204.26	-207.76

APPENDIX C: RESPONSE MODELS

STS-2 Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

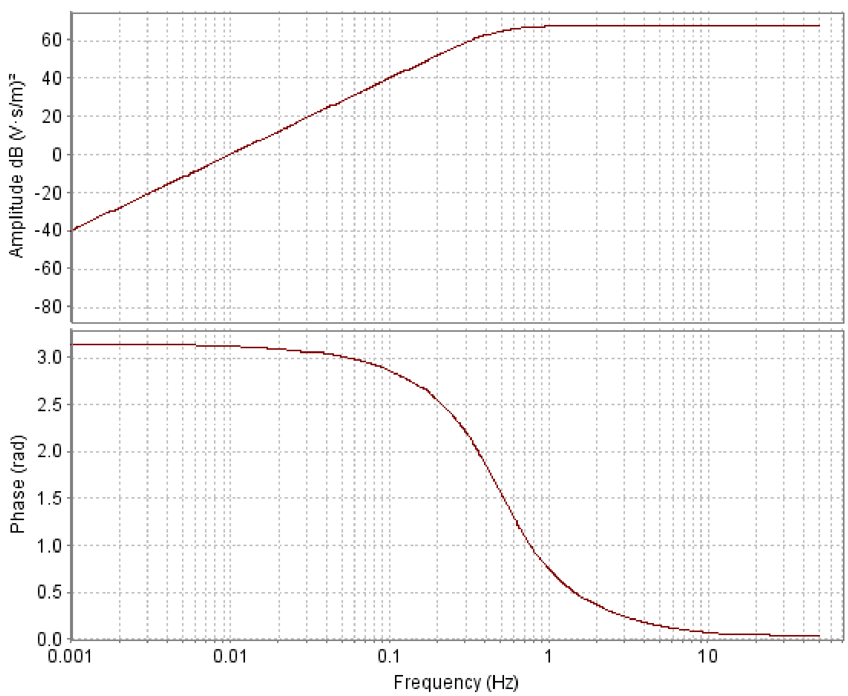
-251.0	0.0
-131.0	467.0
-131.0	-467.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
88,586.67303 MV·s/m

ZM500 Seismometer



Sensitivity:
2,250 V·s/m at 1.0 Hz

Poles:

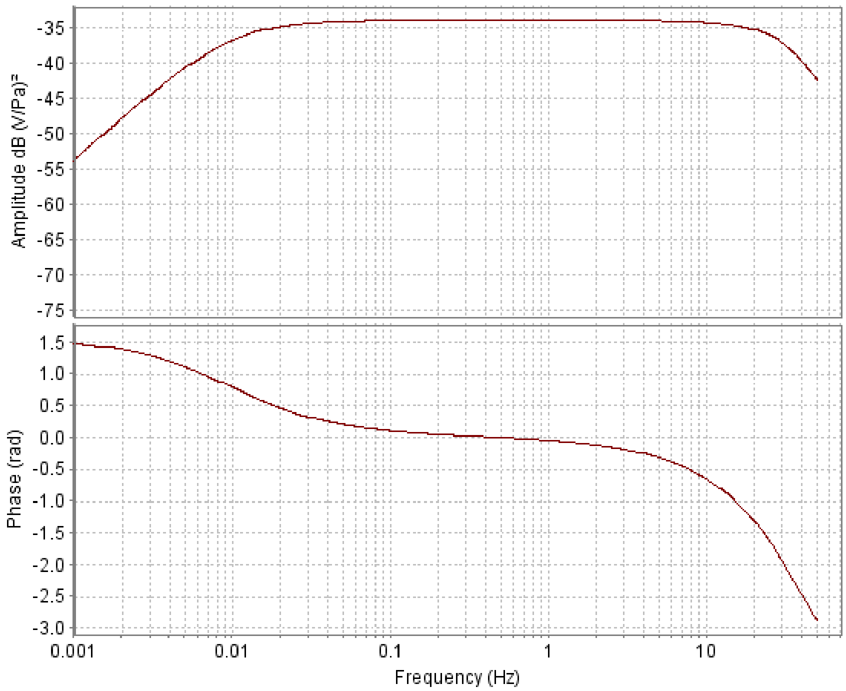
-2.22	2.22
-2.22	-2.22

Zeros:

0.0	0.0
0.0	0.0

A:
2,319.07003 V·s/m

MB2005 Infrasonic



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

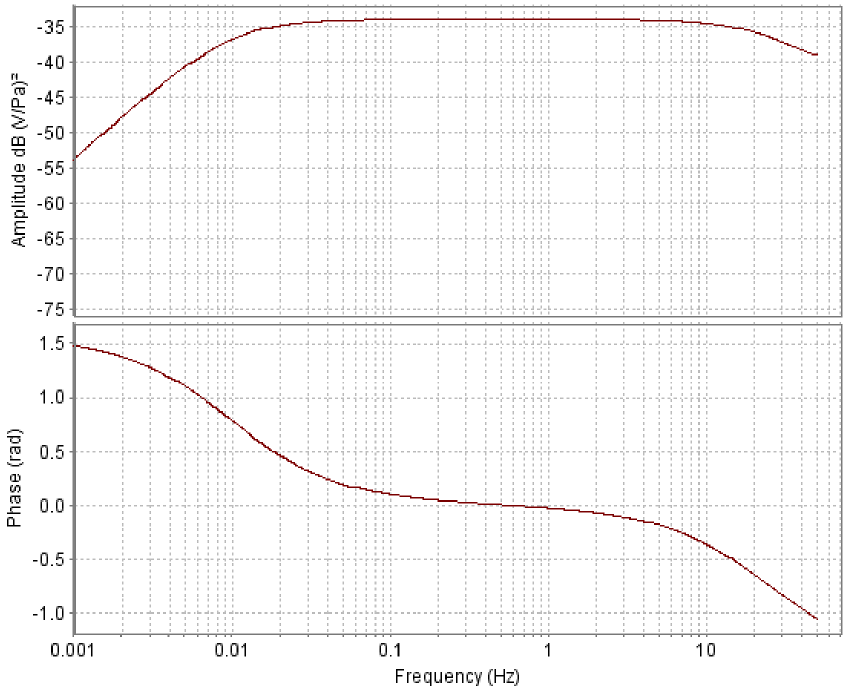
-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.06283	0.0

Zeros:

-468820.0	0.0
0.0	0.0

A:
466,949.57524 MV/Pa

MB3a Infrasonic



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

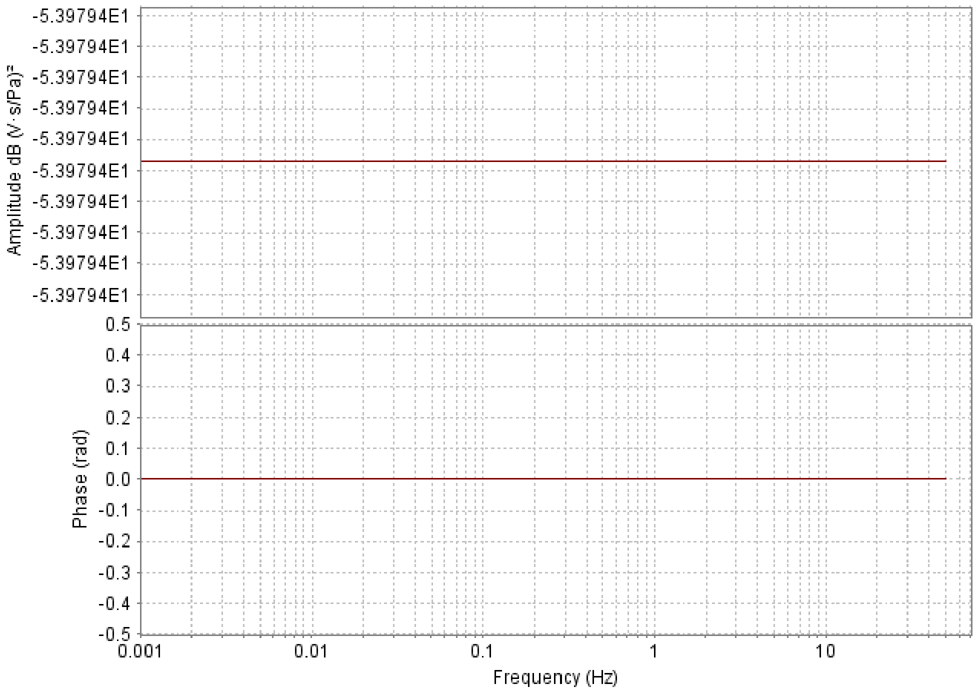
-156.25	0.0
-142.112	706.193
-142.112	-706.193
-0.062834	0.0

Zeros:

-1156.25	0.0
0.0	0.0

A:
1,403.52868 V/Pa

MB3a Derivative Infrasonic



Sensitivity:
2 mV·s/Pa at 1.0 Hz

Poles:
N/A

Zeros:
N/A

A:
2 mV·s/Pa

APPENDIX D: TESTBED CALIBRATIONS

Agilent 3458A # MY45048371

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 6652541_11682157

Item Identification

Asset Number	6652541
Description	Multimeter,Digital
Model	3458A
Serial #	MY45048371
Manufacturer	Agilent Technologies
Customer Asset Id	N/A
Purchase Order	N/A
Customer	Ground-Based Monitoring R&E 05752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1044
Date of Receipt	September 13, 2016
Dates Tested (Start – End)	September 30, 2016 - September 30, 2016
Date Approved	October 12, 2016
Calibration Expiration Date	October 12, 2017

Calibration Description

Calibration Lab	PSL-ELECTRICAL
Calibration Procedure, rev.	HP 3458A, 4.2
Temperature	23 deg C
Humidity	40 %RH
Barometric Pressure	N/A mmHg
As Found Condition	PASS
As Left Condition	PASS
Software Used	MET/CAL 8.3.2.37
Tamper Seal	None

Page **1** of **8**
6652541_11682157

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Specifications and Results

This instrument (Agilent/HP 3458A) was tested using the SNL Primary Standards Laboratory's Multimeter/ Multifunction Station MMS #9300 and is certified to be within the following LIMITED specifications:

DC Volts:
± (11 ppm of reading + 10 ppm of range) 100 mV range
± (10 ppm of reading + 1 ppm of range) 1 V range
± (10 ppm of reading + 0.2 ppm of range) 10 V range
± (12 ppm of reading + 0.3 ppm of range) 100 V range
± (12 ppm of reading + 0.1 ppm of range) 1000 V range

AC Volts:
10 Hz to 40 Hz ± (0.2% of reading + 0.002% of range) 10 mV to 100 V ranges
40 Hz to 20 kHz ± (0.045% of reading + 0.002% of range) 10 mV to 100 V ranges
40 Hz to 20 kHz ± (0.08% of reading + 0.002% of range) 1000 V range
20 kHz to 50 kHz ± (0.1% of reading + 0.011% of range) 10 mV range
20 kHz to 50 kHz ± (0.1% of reading + 0.002% of range) 100 mV to 100 V ranges
50 kHz to 100 kHz ± (0.5% of reading + 0.011% of range) 10 mV range
50 kHz to 100 kHz ± (0.2% of reading + 0.002% of range) 100 mV to 100 V ranges
100 kHz to 300 kHz ± (4% of reading + 0.02% of range) 10 mV range
100 kHz to 300 kHz ± (1% of reading + 0.01% of range) 100 mV to 10 V ranges
100 kHz to 200 kHz ± (1% of reading + 0.01% of range) 100 V range

NOTE: 700 V RMS maximum on 1000 VAC range

4-wire Ohms:
± (100 ppm of reading + 10 ppm of range) 10 Ω range
± (50 ppm of reading + 5 ppm of range) 100 Ω range
± (50 ppm of reading + 1 ppm of range) 1 KΩ to 100 KΩ ranges
± (100 ppm of reading + 2 ppm of range) 1 MΩ range
± (200 ppm of reading + 10 ppm of range) 10 MΩ range
± (500 ppm of reading + 10 ppm of range) 100 MΩ range
± (2% of reading + 10 ppm of range) 1 GΩ range

DC Current
± (10% of reading + 0.01% of range) 100 nA range
± (3.0% of reading + 0.01% of range) 1 µA range
± (0.3% of reading + 0.001% of range) 10 µA
± (0.04% of reading + 0.01% of range) 100 µA and 1 A ranges
± (0.02% of reading + 0.005% of range) 1 mA, 10 mA, and 100 mA ranges

AC Current:
20 Hz to 1 kHz ± (0.15% of reading + 0.02% of range) 100 µA range
20 Hz to 5 kHz ± (0.15% of reading + 0.02% of range) 1 mA to 100 mA ranges
40 Hz to 5 kHz ± (0.15% of reading + 0.02% of range) 1 A range
5 kHz to 10 kHz ± (0.5% of reading + 0.02% of range) 1 mA to 100 mA ranges

Frequency:
10 Hz to 40 Hz ± 0.05% of reading
40 Hz to 10 MHz ± 0.01% of reading

Note 1: Measurement setup configuration is defined in manufacturer's accuracy statement footnotes.
Note 2: Additional errors due to deviations in setup configuration shall be added by the user to the specifications in this certificate.
Note 3: Contact the Primary Standards Laboratory for assistance with uncertainty calculations as needed.

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

Unit Under Test: Agilent 3458A Digital Multimeter	Test Result: **PASS**
Asset Number: 6652541	Test Type: FOUND-LEFT
Serial Number: MY45048371	Calibration Date: 9/30/2016
Procedure Name: HP 3458A	Temperature: 23 °C
Revision: 4.2	Humidity: 40 %
Calibrated By: Brian Liddle	

- Test Type is defined as follows:
  - AS-FOUND Data collected prior to adjustment and/or repair
  - AS-LEFT Data collected after adjustment and/or repair
  - FOUND-LEFT Data collected without adjustment and/or repair
- Test Uncertainty Ratio (TUR) is defined as:
  - TUR = Specification Limit / Uncertainty of the Measurement
- A hash (#) appended to the TUR indicates a guardbanded measurement
  - Guardbanded limits are smaller than the specification limits
  - Guardbanding performed according to the Primary Standards Laboratory Operations Procedure (PSL-PRO-001)
- An asterisk (*) appended to the TUR indicates use of a Test Accuracy Ratio (TAR) instead of a TUR
  - TAR = Specification Limit / Accuracy of the Standard

COMMENTS:

Standards Used

Asset #	Description	Due Date
11123	Keithley 5155-9 1 Gohm resistor	5/10/2018
20174	Fluke 5725A Amplifier	8/10/2017
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/17/2017
6664631	Fluke 5730A Multifunction Calibrator	5/9/2017
6668991	Fluke 5790B AC Measurement Standard	6/29/2017

Test Results

Test Description **True Value** **Lower Limit** **Measured Value** **Upper Limit** **Units** **TUR** **% Tol** **Status**

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

CALIBRATION MANUAL:
Agilent Technologies 3458A Multimeter
Calbration Manual, Edition 6, October 2013
PN 03458-90017

LIMITED CALIBRATION:
PSL specifications are larger than manufacturer's
specifications reported in Factory User Manual.
This is a limitation of the PSL.

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The internal temperature of the 3458A is 36.2 deg.C

DC Volts

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99820	100.00007	100.00180	mV	1.91#	4	
-100.00000 mV		-100.00180	-100.00000	-99.99820	mV	1.91#	0	
1.00000000 V		0.99999035	1.00000018	1.00000965	V	2.08#	2	
-1.00000000 V		-1.00000965	-1.00000044	-0.99999035	V	2.08#	5	
-10.0000000 V		-10.0000964	-10.0000107	-9.9999036	V	3.09#	11	
-5.0000000 V		-5.0000488	-5.0000059	-4.9999512	V	2.89#	12	
-2.0000000 V		-2.0000196	-2.0000012	-1.9999804	V	2.22#	6	
2.0000000 V		1.9999804	2.0000015	2.0000196	V	2.22#	7	

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
5.0000000 V		4.9999512	5.0000046	5.0000488	V	2.89#	10	
10.0000000 V		9.9999036	10.0000082	10.0000964	V	3.09#	8	
100.000000 V		99.998878	100.000131	100.001122	V	2.46#	12	
1000.00000 V		999.98987	1000.00176	1000.01013	V	1.83#	17	
DC Current								
100.000 nA		91.597	99.981	108.403	nA	1.85#	0	
1.000000 µA		0.969900	0.999973	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999795	10.030100	µA	5.2	1	
100.00000 µA		99.95000	99.99837	100.05000	µA	5.4	3	
1.0000000 mA		0.9997500	0.9999940	1.0002500	mA	6.8	2	
10.000000 mA		9.997500	9.999940	10.002500	mA	7.1	2	
100.00000 mA		99.97500	100.00013	100.02500	mA	5.6	1	
1.0000000 A		0.9995000	1.0000079	1.0005000	A	6.2	2	
Resistance								
10.00000 Ohm	10.000281	9.99918	10.00027	10.00138	Ohm	5.2	1	
100.00000 Ohm	100.003660	99.99816	100.00374	100.00916	Ohm	5.9	1	
1.0000000 kOhm	0.99998410	0.9999331	0.9999872	1.0000351	kOhm	8.2	6	
10.000000 kOhm	9.9998320	9.999322	9.999884	10.000342	kOhm	8.2	10	
100.00000 kOhm	100.000690	99.99559	100.00133	100.00579	kOhm	6.5	13	
1.0000000 MOhm	0.99996080	0.9998588	0.9999692	1.0000628	MOhm	8.5	8	
10.000000 MOhm	9.9982260	9.996126	9.998293	10.000326	MOhm	5.8	3	
100.00000 MOhm	100.010650	99.95964	99.99522	100.06166	MOhm	5.5	30	
1.00192000 GOhm		0.9818716	1.0005328	1.0219684	GOhm	>10	7	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9431	100.1700	µA	6.8	34	
100.0000 µA @ 45 Hz		99.8300	99.9865	100.1700	µA	10.0	8	
100.0000 µA @ 1 kHz		99.8300	99.9852	100.1700	µA	10.0	9	
1.000000 mA @ 20 Hz		0.998300	0.999530	1.001700	mA	8.9	28	
1.000000 mA @ 45 Hz		0.998300	0.999976	1.001700	mA	>10	1	
1.000000 mA @ 5 kHz		0.998300	1.000252	1.001700	mA	5.9	15	
1.000000 mA @ 10 kHz		0.995062	1.000536	1.004938	mA	3.25#	11	
10.00000 mA @ 20 Hz		9.98300	9.99535	10.01700	mA	8.9	27	
10.00000 mA @ 45 Hz		9.98300	9.99981	10.01700	mA	>10	1	
10.00000 mA @ 5 kHz		9.98300	10.00160	10.01700	mA	7.1	9	
10.00000 mA @ 10 kHz		9.95013	10.00277	10.04987	mA	3.47#	6	
100.0000 mA @ 20 Hz		99.8300	99.9560	100.1700	mA	8.9	26	
100.0000 mA @ 45 Hz		99.8300	100.0021	100.1700	mA	>10	1	
100.0000 mA @ 5 kHz		99.8300	100.0331	100.1700	mA	7.7	20	
100.0000 mA @ 10 kHz		99.4800	100.0596	100.5200	mA	4.7	12	
1.000000 A @ 40 Hz		0.998300	0.999931	1.001700	A	6.5	4	
1.000000 A @ 5 kHz		0.998365	1.001058	1.001635	A	3.62#	65	
AC Volts								
10.00000 mV @ 10 Hz	9.997600	9.97740	9.99811	10.01780	mV	7.2	3	
10.00000 mV @ 40 Hz	9.997700	9.99328	9.99840	10.00212	mV	2.94#	16	
10.00000 mV @ 20 kHz	9.998300	9.99388	9.99918	10.00272	mV	2.94#	20	
10.00000 mV @ 50 kHz	9.999000	9.98790	9.99777	10.01010	mV	4.1	11	
10.00000 mV @ 100 kHz	10.001400	9.95029	9.98886	10.05251	mV	>10	25	
10.00000 mV @ 300 kHz	9.998300	9.59637	9.88230	10.40023	mV	>10	29	
100.0000 mV @ 10 Hz	99.99500	99.7930	99.9984	100.1970	mV	>10	2	
100.0000 mV @ 40 Hz	99.99530	99.9483	99.9955	100.0423	mV	>10	1	
100.0000 mV @ 20 kHz	99.99520	99.9482	99.9907	100.0422	mV	>10	10	
100.0000 mV @ 50 kHz	99.99520	99.8932	99.9943	100.0972	mV	>10	1	
100.0000 mV @ 100 kHz	99.99690	99.7949	99.9842	100.1989	mV	>10	6	
100.0000 mV @ 300 kHz	99.99400	98.9841	99.9211	101.0039	mV	>10	7	
1.000000 V @ 10 Hz	1.0000237	0.998004	1.000022	1.002044	V	>10	0	
1.000000 V @ 40 Hz	1.0000196	0.999550	1.000034	1.000490	V	>10	3	
1.000000 V @ 20 kHz	1.0000224	0.999552	0.999957	1.000492	V	>10	14	
1.000000 V @ 50 kHz	1.0000291	0.999009	1.000049	1.001049	V	>10	2	
1.000000 V @ 100 kHz	1.0000269	0.998007	1.000153	1.002047	V	>10	6	
1.000000 V @ 300 kHz	1.0001011	0.990000	1.001503	1.010202	V	>10	14	
10.00000 V @ 10 Hz	10.000326	9.98013	10.00062	10.02053	V	>10	1	

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	10.000220	9.99552	10.00043	10.00492	V	>10	4	
10.00000 V @ 20 kHz	10.000190	9.99549	9.99959	10.00489	V	>10	13	
10.00000 V @ 50 kHz	10.000207	9.99001	10.00030	10.01041	V	>10	1	
10.00000 V @ 100 kHz	9.999795	9.97960	9.99935	10.01999	V	>10	2	
10.00000 V @ 300 kHz	10.001654	9.90064	9.99865	10.10267	V	>10	3	
100.0000 V @ 10 Hz	100.00266	99.8007	100.0055	100.2047	V	>10	1	
100.0000 V @ 40 Hz	100.00218	99.9552	100.0044	100.0492	V	>10	5	
100.0000 V @ 20 kHz	100.00295	99.9559	100.0003	100.0500	V	>10	6	
100.0000 V @ 50 kHz	100.00901	99.9070	100.0128	100.1110	V	>10	4	
100.0000 V @ 100 kHz	100.01336	99.8113	100.0096	100.2154	V	>10	2	
100.0000 V @ 200 kHz	100.06044	99.0498	100.0308	101.0710	V	>10	3	
700.0000 V @ 40 Hz	700.01590	699.4359	700.0061	700.5959	V	>10	2	
700.0000 V @ 20 kHz	700.02470	699.4447	699.7808	700.6047	V	>10	42	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000099	10.005000	Hz	>10	2	
40.00000 Hz @ 1 V		39.996000	40.000415	40.004000	Hz	>10	10	
100.00000 Hz @ 1 V		99.990000	100.000600	100.010000	Hz	>10	6	
1000.0000 Hz @ 1 V		999.90000	1000.00696	1000.10000	Hz	>10	7	
10000.0000 Hz @ 1 V		9999.00000	10000.06962	10001.00000	Hz	>10	7	
20000.0000 Hz @ 1 V		19998.00000	20000.13923	20002.00000	Hz	>10	7	
50000.0000 Hz @ 1 V		49995.00000	50000.35285	50005.00000	Hz	>10	7	
100.00000 kHz @ 1 V		99.990000	100.000696	100.010000	kHz	>10	7	
500.00000 kHz @ 1 V		499.950000	500.003481	500.050000	kHz	>10	7	
1.000000 MHz @ 1 V		0.9999000	1.0000071	1.0001000	MHz	>10	7	
2.000000 MHz @ 1 V		1.9998000	2.0000139	2.0002000	MHz	>10	7	
4.000000 MHz @ 1 V		3.9996000	4.0000278	4.0004000	MHz	>10	7	
6.000000 MHz @ 1 V		5.9994000	6.0000422	6.0006000	MHz	>10	7	
8.000000 MHz @ 1 V		7.9992000	8.0000566	8.0008000	MHz	>10	7	
10.000000 MHz @ 1 V		9.9990000	10.0000696	10.0010000	MHz	>10	7	

***** End of Test Results *****

PRIMARY STANDARDS
LABORATORY
Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limitations
PSL specifications are larger than manufacturer's specifications reported in Factory User Manual. This is a limitation of the PSL.

Equipment (Standard) Used

Asset #	Description	Model	Expires
6668991	Standard,Measurement	5790B	June 29, 2017
6664631	Calibrator,Multifunction	5730A	April 25, 2017
6651332	Generator,Function	33250A	February 18, 2017
20174	Amplifier	5725A	August 10, 2017
11123	Resistor,Standard	5155-9	May 10, 2018

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Traceability

Values and the associated uncertainties supplied by the Primary Standards Lab (PSL) are traceable to the SI through one or more of the following:

1. Reference standards whose values are disseminated by the National Institute of Standards and Technology (United States of America) or, where appropriate, to the national metrological institute of another nation participating in the CIPM MRA;
2. Reference standards whose values are disseminated by a laboratory that has demonstrated competence, measurement capability, and traceability for those values;
3. The accepted value(s) of fundamental physical phenomena (intrinsic standards);
4. Ratio(s) or other non-maintained standards established by either a self-calibration and/or a direct calibration technique;
5. Standards maintained and disseminated by the PSL in special cases and where warranted, such as consensus standards where no national or international standards exist;

Note 1: This certificate or report shall not be reproduced except in full, without the advance written approval of the Primary Standards Lab at Sandia National Laboratories.

Note 2: For National Voluntary Laboratory Accreditation Program (NVLAP) accredited capabilities, the PSL at Sandia National Laboratories is accredited by NVLAP for the specific scope of accreditation under Laboratory Code 105002-0. This certificate or report shall not be used by the customer to claim product endorsement by NVLAP, the Primary Standards Laboratory, Sandia National Laboratories or any agency of the U. S. Government.

Note 3: The as received condition of the standard, set of standards, or measurement equipment described herein was as expected, unless otherwise noted in the body of the certificate or report.

Note 4: The presence of names and titles under "Authorization" are properly authenticated electronic signatures conforming to the equivalent identification signatory requirements of ISO 17025:2005 5.10.2.j.

Authorization

Calibrated By:	Approved By:
Liddle, Brian David Metrologist	Aragon, Steven J. Metrologist

End-of-Document

Agilent 3458A # MY45048372

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 6652539_11669844

Item Identification

Asset Number	6652539
Description	Multimeter,Digital
Model	3458A
Serial #	MY45048372
Manufacturer	Agilent Technologies
Customer Asset Id	N/A
Purchase Order	N/A
Customer	Ground-Based Monitoring R&E 05752
Custodian	Merchant, Bion J.
Location	SNLNM/TA1/758/1042
Date of Receipt	May 05, 2016
Dates Tested (Start – End)	May 24, 2016 - May 24, 2016
Date Approved	May 24, 2016
Calibration Expiration Date	May 24, 2017

Calibration Description

Calibration Lab	PSL-ELECTRICAL
Calibration Procedure, rev.	HP 3458A, 4.1
Temperature	23 deg C
Humidity	40 %RH
Barometric Pressure	N/A mmHg
As Found Condition	PASS
As Left Condition	PASS
Software Used	MET/CAL 8.3.2.3
Tamper Seal	Yes

Page **1** of **8**
6652539_11669844

PRIMARY STANDARDS
LABORATORY
Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Specifications and Results

This instrument (Agilent/HP 3458A) was tested using the SNL Primary Standards Laboratory's Multimeter/ Multifunction Station MMS #9300 and is certified to be within the following LIMITED specifications:

DC Volts:
± (11 ppm of reading + 10 ppm of range) 100 mV range
± (10 ppm of reading + 1 ppm of range) 1 V range
± (10 ppm of reading + 0.2 ppm of range) 10 V range
± (12 ppm of reading + 0.3 ppm of range) 100 V range
± (12 ppm of reading + 0.1 ppm of range) 1000 V range

AC Volts:
10 Hz to 40 Hz ± (0.2% of reading + 0.002% of range) 10 mV to 100 V ranges
40 Hz to 20 kHz ± (0.045% of reading + 0.002% of range) 10 mV to 100 V ranges
40 Hz to 20 kHz ± (0.08% of reading + 0.002% of range) 1000 V range
20 kHz to 50 kHz ± (0.1% of reading + 0.011% of range) 10 mV range
20 kHz to 50 kHz ± (0.1% of reading + 0.002% of range) 100 mV to 100 V ranges
50 kHz to 100 kHz ± (0.5% of reading + 0.011% of range) 10 mV range
50 kHz to 100 kHz ± (0.2% of reading + 0.002% of range) 100 mV to 100 V ranges
100 kHz to 300 kHz ± (4% of reading + 0.02% of range) 10 mV range
100 kHz to 300 kHz ± (1% of reading + 0.01% of range) 100 mV to 10 V ranges
100 kHz to 200 kHz ± (1% of reading + 0.01% of range) 100 V range

NOTE: 700 V RMS maximum on 1000 VAC range

4-wire Ohms:
± (100 ppm of reading + 10 ppm of range) 10 Ω range
± (50 ppm of reading + 5 ppm of range) 100 Ω range
± (50 ppm of reading + 1 ppm of range) 1 KΩ to 100 KΩ ranges
± (100 ppm of reading + 2 ppm of range) 1 MΩ range
± (200 ppm of reading + 10 ppm of range) 10 MΩ range
± (500 ppm of reading + 10 ppm of range) 100 MΩ range
± (2% of reading + 10 ppm of range) 1 GΩ range

DC Current
± (10% of reading + 0.01% of range) 100 nA range
± (3.0% of reading + 0.01% of range) 1 μA range
± (0.3% of reading + 0.001% of range) 10 μA
± (0.04% of reading + 0.01% of range) 100 μA and 1 A ranges
± (0.02% of reading + 0.005% of range) 1 mA, 10 mA, and 100 mA ranges

AC Current:
20 Hz to 1 kHz ± (0.15% of reading + 0.02% of range) 100 µA range
20 Hz to 5 kHz ± (0.15% of reading + 0.02% of range) 1 mA to 100 mA ranges
40 Hz to 5 kHz ± (0.15% of reading + 0.02% of range) 1 A range
5 kHz to 10 kHz ± (0.5% of reading + 0.02% of range) 1 mA to 100 mA ranges

Frequency:
10 Hz to 40 Hz ± 0.05% of reading
40 Hz to 10 MHz ± 0.01% of reading

Note 1: Measurement setup configuration is defined in manufacturer's accuracy statement footnotes.
Note 2: Additional errors due to deviations in setup configuration shall be added by the user to the specifications in this certificate.
Note 3: Contact the Primary Standards Laboratory for assistance with uncertainty calculations as needed.

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Calibration Data Report

Primary Electrical Lab

Unit Under Test:	Agilent 3458A Digital Multimeter	Test Result:	**PASS**
Asset Number:	6652539	Test Type:	FOUND-LEFT
Serial Number:	MY45048372	Calibration Date:	5/24/2016
Procedure Name:	HP 3458A	Temperature:	23 °C
Revision:	4.1	Humidity:	40 %
Calibrated By:	Brian Liddle		

- Test Type is defined as follows:
  - AS-FOUND Data collected prior to adjustment and/or repair
  - AS-LEFT Data collected after adjustment and/or repair
  - FOUND-LEFT Data collected without adjustment and/or repair
- Test Uncertainty Ratio (TUR) is defined as:
  - TUR = Specification Limit / Uncertainty of the Measurement
- A hash (#) appended to the TUR indicates a guardbanded measurement
  - Guardbanded limits are smaller than the specification limits
  - Guardbanding performed according to the Primary Standards Laboratory Operations Procedure (PSL-PRO-001)
- An asterisk (*) appended to the TUR indicates use of a Test Accuracy Ratio (TAR) instead of a TUR
  - TAR = Specification Limit / Accuracy of the Standard

COMMENTS:

Standards Used

Asset #	Description	Due Date
11123	Keithley 5155-9 1 Gohm resistor	5/10/2018
20563	FLUKE 5790A CALIBRATOR	6/11/2016
44972	Fluke 5725A Amplifier	12/15/2016
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/17/2017
6664631	Fluke 5730A Multifunction Calibrator	4/25/2017

Test Results

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

CALIBRATION MANUAL:
   Agilent Technologies 3458A Multimeter
   Calbration Manual, Edition 6, October 2013
   PN 03458-90017

LIMITED CALIBRATION:
   PSL specifications are larger than manufacturer's
   specifications reported in Factory User Manual.
   This is a limitation of the PSL.
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The internal temperature of the 3458A is 36.2 deg.C
DC Volts
```

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99820	99.99965	100.00180	mV	1.91#	20	
-100.00000 mV		-100.00180	-99.99960	-99.99820	mV	1.91#	22	
1.00000000 V		0.99999035	0.99999661	1.00000965	V	2.08#	35	
-1.00000000 V		-1.00000965	-0.99999695	-0.99999035	V	2.08#	32	
-10.0000000 V		-10.0000964	-9.9999728	-9.9999036	V	3.09#	28	
-5.0000000 V		-5.0000488	-4.9999869	-4.9999512	V	2.89#	27	
-2.0000000 V		-2.0000196	-1.9999937	-1.9999804	V	2.22#	32	
2.0000000 V		1.9999804	1.9999937	2.0000196	V	2.22#	32	

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
5.0000000 V		4.9999512	4.9999871	5.0000488	V	2.89#	26	
10.0000000 V		9.9999036	9.9999715	10.0000964	V	3.09#	30	
100.000000 V		99.998878	99.999755	100.001122	V	2.46#	22	
1000.00000 V		999.98987	999.99754	1000.01013	V	1.83#	24	
DC Current								
100.000 nA		91.597	100.101	108.403	nA	1.85#	1	
1.000000 µA		0.969900	1.000068	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999933	10.030100	µA	5.2	0	
100.00000 µA		99.95000	99.99859	100.05000	µA	5.4	3	
1.0000000 mA		0.9997500	0.9999936	1.0002500	mA	6.8	3	
10.000000 mA		9.997500	9.999938	10.002500	mA	7.1	2	
100.00000 mA		99.97500	100.00034	100.02500	mA	5.6	1	
1.0000000 A		0.9995000	1.0000220	1.0005000	A	6.2	4	
Resistance								
10.00000 Ohm	10.000281	9.99918	10.00025	10.00138	Ohm	5.2	3	
100.00000 Ohm	100.003660	99.99816	100.00378	100.00916	Ohm	5.9	2	
1.0000000 kOhm	0.99998410	0.9999331	0.9999845	1.0000351	kOhm	8.2	1	
10.000000 kOhm	9.9998320	9.999322	9.999852	10.000342	kOhm	8.2	4	
100.00000 kOhm	100.000690	99.99559	100.00099	100.00579	kOhm	6.5	6	
1.0000000 MOhm	0.99996080	0.9998588	0.9999674	1.0000628	MOhm	8.5	7	
10.000000 MOhm	9.9982260	9.996126	9.998412	10.000326	MOhm	5.8	9	
100.00000 MOhm	100.010650	99.95964	100.02127	100.06166	MOhm	5.5	21	
1.00192000 GOhm		0.9818716	1.0025255	1.0219684	GOhm	>10	3	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9362	100.1700	µA	6.8	38	
100.0000 µA @ 45 Hz		99.8300	99.9819	100.1700	µA	10.0	11	
100.0000 µA @ 1 kHz		99.8300	99.9814	100.1700	µA	10.0	11	
1.000000 mA @ 20 Hz		0.998300	0.999483	1.001700	mA	8.9	30	
1.000000 mA @ 45 Hz		0.998300	0.999950	1.001700	mA	>10	3	
1.000000 mA @ 5 kHz		0.998300	1.000239	1.001700	mA	5.9	14	
1.000000 mA @ 10 kHz		0.995062	1.000505	1.004938	mA	3.25#	10	
10.00000 mA @ 20 Hz		9.98300	9.99484	10.01700	mA	8.9	30	
10.00000 mA @ 45 Hz		9.98300	9.99954	10.01700	mA	>10	3	
10.00000 mA @ 5 kHz		9.98300	10.00141	10.01700	mA	7.1	8	
10.00000 mA @ 10 kHz		9.95013	10.00250	10.04987	mA	3.47#	5	
100.0000 mA @ 20 Hz		99.8300	99.9517	100.1700	mA	8.9	28	
100.0000 mA @ 45 Hz		99.8300	99.9993	100.1700	mA	>10	0	
100.0000 mA @ 5 kHz		99.8300	100.0313	100.1700	mA	7.7	18	
100.0000 mA @ 10 kHz		99.4800	100.0569	100.5200	mA	4.7	11	
1.000000 A @ 40 Hz		0.998300	0.999882	1.001700	A	6.5	7	
1.000000 A @ 5 kHz		0.998365	1.000787	1.001635	A	3.62#	48	
AC Volts								
10.00000 mV @ 10 Hz	10.009400	9.98918	9.99806	10.02962	mV	7.2	56	
10.00000 mV @ 40 Hz	10.001600	9.99718	9.99822	10.00602	mV	2.94#	77	
10.00000 mV @ 20 kHz	10.000500	9.99608	9.99885	10.00492	mV	2.94#	37	
10.00000 mV @ 50 kHz	10.001000	9.98990	9.99627	10.01210	mV	4.1	43	
10.00000 mV @ 100 kHz	10.003500	9.95238	9.98557	10.05462	mV	>10	35	
10.00000 mV @ 300 kHz	9.999400	9.59742	9.85994	10.40138	mV	>10	35	
100.0000 mV @ 10 Hz	100.07420	99.8721	99.9986	100.2763	mV	>10	37	
100.0000 mV @ 40 Hz	99.99530	99.9483	99.9977	100.0423	mV	>10	5	
100.0000 mV @ 20 kHz	99.97920	99.9322	99.9906	100.0262	mV	>10	24	
100.0000 mV @ 50 kHz	99.98200	99.8800	99.9917	100.0840	mV	>10	10	
100.0000 mV @ 100 kHz	99.98440	99.7824	99.9790	100.1864	mV	>10	3	
100.0000 mV @ 300 kHz	99.96950	98.9598	99.9037	100.9792	mV	>10	7	
1.000000 V @ 10 Hz	0.9999851	0.997965	1.000062	1.002005	V	>10	4	
1.000000 V @ 40 Hz	0.9999934	0.999523	1.000040	1.000463	V	>10	10	
1.000000 V @ 20 kHz	0.9999986	0.999529	0.999954	1.000469	V	>10	9	
1.000000 V @ 50 kHz	1.0000081	0.998988	1.000033	1.001028	V	>10	2	
1.000000 V @ 100 kHz	1.0000056	0.997986	1.000094	1.002026	V	>10	4	
1.000000 V @ 300 kHz	1.0000952	0.989994	1.001301	1.010196	V	>10	12	
10.00000 V @ 10 Hz	9.999958	9.97976	10.00060	10.02016	V	>10	3	

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	9.999940	9.99524	10.00044	10.00464	V	>10	11	
10.00000 V @ 20 kHz	10.000035	9.99533	9.99981	10.00474	V	>10	5	
10.00000 V @ 50 kHz	10.000073	9.98987	10.00033	10.01027	V	>10	3	
10.00000 V @ 100 kHz	10.000197	9.98000	9.99859	10.02040	V	>10	8	
10.00000 V @ 300 kHz	10.000297	9.89929	9.99356	10.10130	V	>10	7	
100.0000 V @ 10 Hz	99.99889	99.7969	100.0082	100.2009	V	>10	5	
100.0000 V @ 40 Hz	99.99940	99.9524	100.0070	100.0464	V	>10	16	
100.0000 V @ 20 kHz	100.00103	99.9540	100.0023	100.0480	V	>10	3	
100.0000 V @ 50 kHz	100.00567	99.9037	100.0131	100.1077	V	>10	7	
100.0000 V @ 100 kHz	100.00786	99.8058	100.0083	100.2099	V	>10	0	
100.0000 V @ 200 kHz	100.04847	99.0380	100.0279	101.0590	V	>10	2	
700.0000 V @ 40 Hz	700.01380	699.4338	699.9477	700.5938	V	>10	11	
700.0000 V @ 20 kHz	700.03500	699.4550	699.6812	700.6150	V	>10	61	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000029	10.005000	Hz	>10	1	
40.00000 Hz @ 1 V		39.996000	40.000000	40.004000	Hz	>10	0	
100.00000 Hz @ 1 V		99.990000	100.000085	100.010000	Hz	>10	1	
1000.0000 Hz @ 1 V		999.90000	1000.00152	1000.10000	Hz	>10	2	
10000.0000 Hz @ 1 V		9999.00000	10000.01335	10001.00000	Hz	>10	1	
20000.0000 Hz @ 1 V		19998.00000	20000.02479	20002.00000	Hz	>10	1	
50000.0000 Hz @ 1 V		49995.00000	50000.06675	50005.00000	Hz	>10	1	
100.00000 kHz @ 1 V		99.990000	100.000133	100.010000	kHz	>10	1	
500.00000 kHz @ 1 V		499.950000	500.000668	500.050000	kHz	>10	1	
1.000000 MHz @ 1 V		0.9999000	1.0000012	1.0001000	MHz	>10	1	
2.000000 MHz @ 1 V		1.9998000	2.0000027	2.0002000	MHz	>10	1	
4.000000 MHz @ 1 V		3.9996000	4.0000053	4.0004000	MHz	>10	1	
6.000000 MHz @ 1 V		5.9994000	6.0000078	6.0006000	MHz	>10	1	
8.000000 MHz @ 1 V		7.9992000	8.0000101	8.0008000	MHz	>10	1	
10.000000 MHz @ 1 V		9.9990000	10.0000134	10.0010000	MHz	>10	1	

***** End of Test Results *****

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Limitations
PSL specifications are larger than manufacturer's specifications reported in Factory User Manual. This is a limitation of the PSL.

Equipment (Standard) Used

Asset #	Description	Model	Expires
6664631	Calibrator,Multifunction	5730A	April 25, 2017
6651332	Generator,Function	33250A	February 18, 2017
44972	Amplifier	5725A	December 15, 2016
20563	Standard,Measurement,AC	5790A	June 11, 2016
11123	Resistor,Standard	5155-9	May 10, 2018

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Authorization

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Metrologist

Approved By:

Diana Kothmann
QA Representative

End-of-Document

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