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2017 Guralp Affinity Digitizer Evaluation

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Prepared by
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2017 Guralp Affinity Digitizer Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated two Guralp Affinity digitizers. The Affinity 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 Affinity 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 Guralp for providing the Affinity digitizers to evaluate and for their presence and support in conducting the evaluation.

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NOMENCLATURE

BB	Broadband
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
dB	Decibel
DOE	Department of Energy
GPS	Global Position System
GNSS	Global Navigation Satellite System
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 two Affinity digitizers, developed by Guralp.

Figure 1 Guralp Affinity Digitizers

The Guralp Affinity 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 Affinity 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 Guralp Affinity digitizers, serial numbers DAS-40565A and DAS-40565B shown in the figure above, was performed to compare their performance to the manufacturer's specifications and CTBTO requirements.

The two digitizers were both operating with the Guralp firmware "ctbto-prerelease build 15398" installed. The digitizers were configured to record continuously on all 4 channels at sample rates of 100 Hz, 40 Hz, and 20 Hz and streaming the data over ethernet to a local computer using Scream, Guralp's data collection system. The digitizers were configured to time synchronize to their internal GPS module and maintain an active GPS lock continuously. In addition, the digitizers are equipped with an internal Spyrus card for authentication of the CD1.1 data transmission.

Affinity

güralp

SPECIFICATIONS

SENSOR INPUTS	
Primary digitisation channels	Eight at 24 bits. Differential input: 40 V peak-to-peak (± 20 V). Also compatible with single-ended inputs: 20 V peak-to-peak (± 10 V)
Optional environmental channels	Sixteen multiplexed channels, ±10 V single-ended
Input impedence	113 kΩ
PERFORMANCE	
ADC converter type	4th-order, single-bit, low-pass Σ-Δ
Output format	32-bit
Dynamic Range	>138 dB at 100 samples per second
Absolute accuracy	0.5 %
Common-mode rejection	>80 dB
DATA PROCESSING	
Output rates available	1 to 4000 samples per second
Highest output capability	20,000 samples per second aggregate
Decimation filters	2, 4, 5, 2x4, 2x5
Anti-alias filters	3-pole
Low pass filters	FIR (other options available)
Out-of-band rejection	140 dB
Data transmission modes	Continuous and triggered
Trigger modes	STA/LTA, level, external, software
TIMING AND CALIBRATION	
Timing source precision	<42 µs drift per hour when unsynchronised (without GPS)
Timing sources	GPS, NTP and PTP
Calibration signal generator	Amplitude/frequency adjustable, sine, step or broadband noise
OPERATION AND POWER USAGE	
Operating temperature	-25 to +60 °C
Relative humidity range	zero to 100 %
Power supply	9 - 36 V DC (9 V will power digitiser only)
Power consumption at 12 V DC	
4 channel	1.2 W (no GPS or ethernet)
	1.55 W (GPS with 10 Mb/s Ethernet output)
8 channel	1.5 W (no GPS or ethernet)
	1.85 W (GPS with 10 Mb/s Ethernet output)
SOFTWARE PROTOCOLS	
Operating system	Linux
Communication technologies supported	RS232, USB, Ethernet (10BASE-T / 100BASE-T) with POE
Internet technologies supported	TCP/IP, PPP, SSH, HTTP, HTTPS (others on request)
	Firewall and routing capabilities
DATA COMMUNICATION	
Data recording formats	GCF, GDI and miniSEED
Seismic network protocols	Scream (Antelope/Earthworm), CD1.0/1.1, SEEDlink and others
Flash memory and storage	512 MB system Flash memory. Option of 16 GB or 32 GB internal Flash storage.

PHYSICAL CHARACTERISTICS	
Casing type	Stainless steel cylinder
System weight	5.5 Kg (excluding GPS and cables)
Weight with mounting and carry bracket	6.1 Kg (excluding GPS and cables)
Dimensions - cylinder alone	274 mm × 114 Ø, excluding connectors and cables
Dimensions with mounting/ carrying bracket	304 mm × 160 mm × 130 mm, excluding connectors and cables
Standard accessories pack comprises	GPS antenna; 20 m GPS cable; 5 m power cable; 3 m general purpose input/output cable; 5 m ethernet cable

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In the interests of continual improvement with respect to design, reliability, function or otherwise, all product specifications and data are subject to change without prior notice.

DAS-AFT-0001 Issue A

Figure 2 Guralp Affinity Specification (Guralp Datasheet)

2 TEST PLAN

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

2.1 Test Facility

Testing of the 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 possible, instrumentation calibrations are traceable to the National Institute for Standards Technology (NIST).

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

Figure 3 FACT Site Bunker

The digitizers were powered using two BK Precision Laboratory Power Supplies providing a nominal 12 Volts.

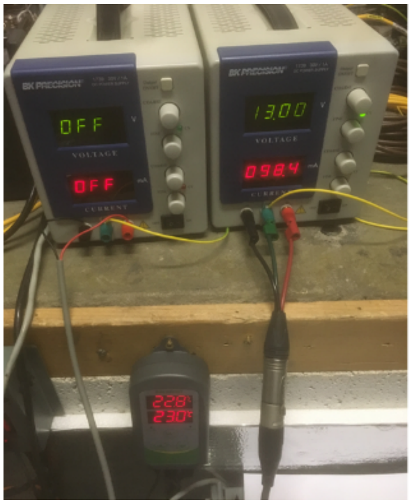

Figure 4 Power Supplies and Temperature Controller

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

Figure 5 Vaisala Temperature Monitor within FACT Bunker

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

Figure 6 GPS Re-broadcaster

2.2 Scope

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

Table 1 Tests performed

Power Consumption
Input Impedance
DC Accuracy
AC Accuracy
AC Full Scale
AC Over Scale
Input Shorted Offset
Self-Noise
Dynamic Range
System Noise
Temperature Self-Noise
Response Verification
Relative Transfer Function
Analog Bandwidth
Incoherence Noise
Total Harmonic Distortion
Modified Noise Power Ratio
Common Mode Rejection
Crosstalk
GPS Time Tag Accuracy
GPS Time Tag Drift
PTP Time Tag Accuracy
PTP Time Tag Drift
Calibrator
Sensor Compatibility Verification
CD1 Status Flag Verification
CD1 Frame Alignment Verification

2.3 Timeline

The majority of the digitizer testing was performed at Sandia National Laboratories between May 22 – 26, 2017. Testing was performed using two digitizers, so that different tests could be performed on each digitizer simultaneously. Additional testing of the Auxiliary channels and the CD1 functionality were performed in October and November, 2017. The following schedule of testing was followed:

Table 2 Timeline of Testing

Day	Time	DAS-40565A	DAS-40565B
Monday May 22, 2017	Morning	Equipment setup and checkout 20 Hz, 40 Hz, and 100 Hz at gain 1 Power Consumption Input Impedance Common Mode Crosstalk DC Accuracy AC Accuracy AC Full Scale AC Clip	Equipment setup and checkout 20 Hz, 40 Hz, and 100 Hz at gain 1 Power Consumption Input Impedance Common Mode Crosstalk DC Accuracy AC Accuracy AC Full Scale AC Clip
	Lunch	20 Hz, 40 Hz, and 100 Hz at gain 1 Analog Bandwidth Relative Transfer Function Response Incoherent Noise	20 Hz, 40 Hz, and 100 Hz at gain 1 Analog Bandwidth Relative Transfer Function Response Incoherent Noise
	Afternoon	20 Hz, 40 Hz, and 100 Hz at gain 1 Total Harmonic Distortion 20 Hz, 40 Hz, and 100 Hz at gain 2 Power Consumption Input Impedance Common Mode Crosstalk	20 Hz, 40 Hz, and 100 Hz at gain 1 Total Harmonic Distortion 20 Hz, 40 Hz, and 100 Hz at gain 2 Power Consumption Input Impedance Common Mode Crosstalk
	Overnight	20 Hz, 40 Hz, 100 Hz at gains of 1, 2, 4, and 8 Input Terminated Noise	20 Hz, 40 Hz, 100 Hz at gains of 1, 2, 4, and 8 Input Terminated Noise
Tuesday May 23, 2017	Morning	20 Hz, 40 Hz, and 100 Hz at gain 2 DC Accuracy AC Accuracy AC Full Scale AC Clip Analog Bandwidth Relative Transfer Function Response Incoherent Noise Total Harmonic Distortion 20 Hz, 40 Hz, and 100 Hz at gain 4 Power Consumption Input Impedance Common Mode Crosstalk	20 Hz, 40 Hz, and 100 Hz at gain 2 DC Accuracy AC Accuracy AC Full Scale AC Clip Analog Bandwidth Relative Transfer Function Response Incoherent Noise Total Harmonic Distortion 20 Hz, 40 Hz, and 100 Hz at gain 4 Power Consumption Input Impedance Common Mode Crosstalk
	Lunch	20 Hz, 40 Hz, and 100 Hz at gain 4 DC Accuracy AC Accuracy AC Full Scale AC Clip	20 Hz, 40 Hz, and 100 Hz at gain 4 DC Accuracy AC Accuracy AC Full Scale AC Clip

		Analog Bandwidth Relative Transfer Function Response Incoherent Noise	Analog Bandwidth Relative Transfer Function Response Incoherent Noise
	Afternoon	20 Hz, 40 Hz, and 100 Hz at gain 4 Total Harmonic Distortion 20, 40, 100 Hz at gain 1 GPS Timing Accuracy	20 Hz, 40 Hz, and 100 Hz at gain 4 Total Harmonic Distortion 20, 40, 100 Hz at gain 1 GPS Timing Accuracy
	Overnight	20, 40, 100 Hz at gain 1 GPS Timing Drift	20, 40, 100 Hz at gain 1 GPS Timing Drift
Wednesday May 24, 2017	Morning	20, 40, 100 Hz at gain 1 GPS Timing Recovery 20, 40, 100 Hz at gain 8 DC Accuracy AC Accuracy AC Full Scale AC Clip Analog Bandwidth Relative Transfer Function Response	20, 40, 100 Hz at gain 1 GPS Timing Recovery 20, 40, 100 Hz at gain 8 DC Accuracy AC Accuracy AC Full Scale AC Clip Analog Bandwidth Relative Transfer Function Response
	Lunch	20, 40, 100 Hz at gain 8 Total Harmonic Distortion	20, 40, 100 Hz at gain 8 Total Harmonic Distortion
	Afternoon	20, 40, 100 Hz at gain 8 Power Consumption Input Impedance Common Mode Crosstalk	20, 40, 100 Hz at gain 8 Power Consumption Input Impedance Common Mode Crosstalk
	Overnight	20, 40, 100 Hz at gain 1 MB3a calibrations.	20, 40, 100 Hz at gain 1 GS13 (40x) calibrations.
Thursday May 25, 2017	Morning	20, 40, 100 Hz at gain 1 Continued MB3a calibrations. Setup meteorological sensor on auxiliary port.	20, 40, 100 Hz at gain 1, 2, 4, and 8 Temperature chamber terminated noise for 24 hrs
	Lunch		
	Afternoon	20, 40, 100 Hz at gain 1 PTP Timing Accuracy	
	Overnight	20, 40, 100 Hz at gain 1 PTP Timing Drift	
Friday May 26, 2017	Morning	20, 40, 100 Hz at gain 1 PTP Timing Recovery	
	Lunch		
	Afternoon	20, 40, 100 Hz at gain 1 PTP Timing Evaluation	20, 40, 100 Hz at gain 1 STS-2 calibrations
	Overnight	long-term operation with MB3a	long-term operation with STS-2

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.

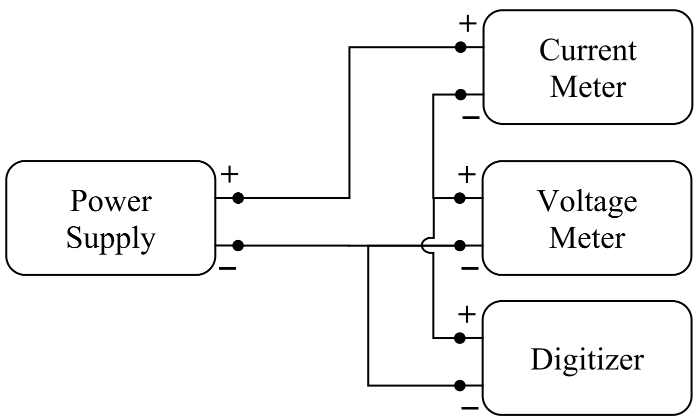

Figure 7 Power Consumption Configuration Diagram

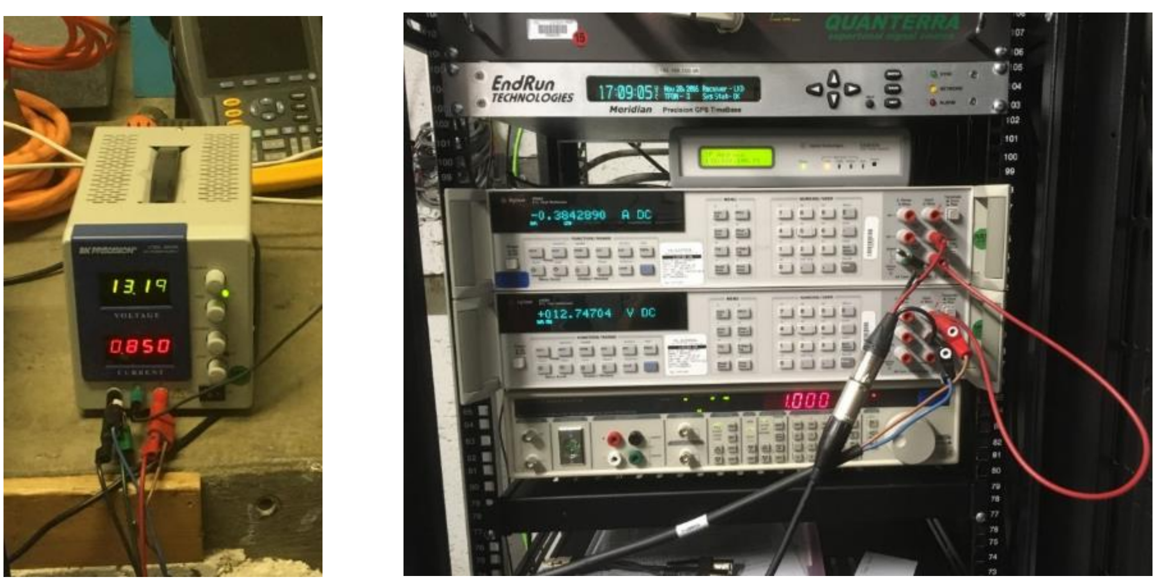

Figure 8 Power Consumption Configuration Picture

Table 3 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal

			Configuration
Power Supply	BK Precision 1735A DC Power Supply	204F13116	12 V
Voltage Meter	Agilent 3458A	MY45048371	DC Voltage Mode
Current Meter	Agilent 3458A	MY45048372	DC Current 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 figure below shows a representative waveform time series for the recordings of voltage and current made on the reference meters. The window regions bounded by the red lines indicate the segments of data used to evaluate the voltage and current.

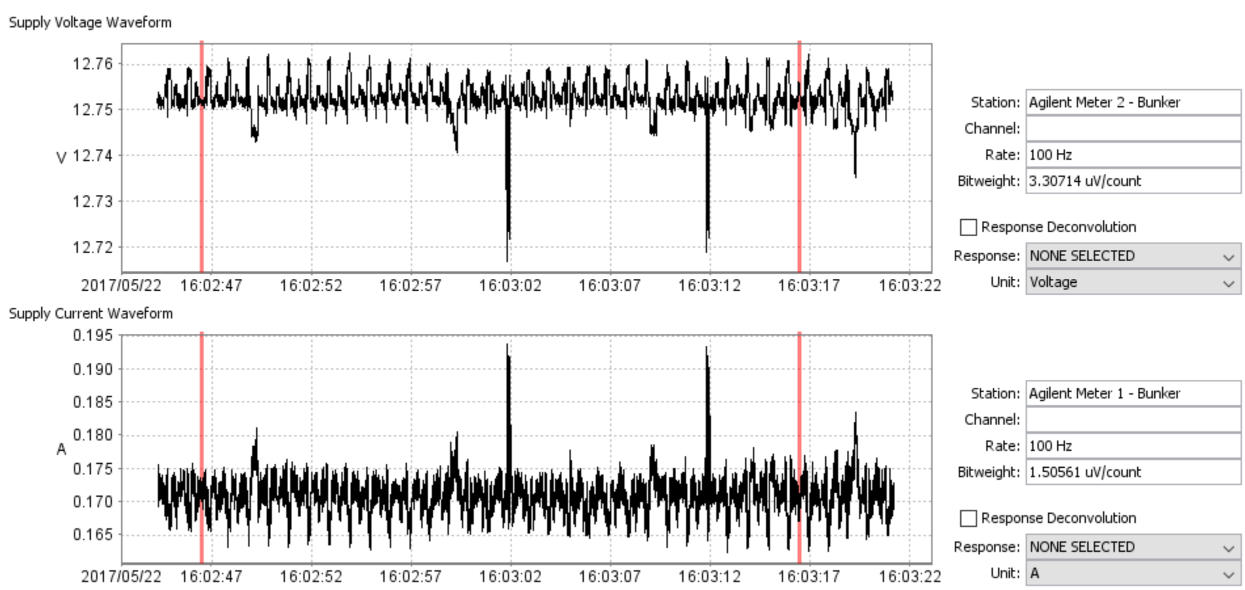

Figure 9 Power Consumption Voltage and Current Time Series

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

Table 4 Power Consumption Results: DAS-40565A

	Supply Voltage	Supply Voltage SD	Supply Current	Supply Current SD	Power Consumption	Power Consumption SD
Gain 1x	12.75 V	3.946 mV	0.171 A	3.026 mA	2.179 W	39.21 mW
Gain 2x	12.56 V	38.325 mV	0.176 A	3.960 mA	2.210 W	56.71 mW
Gain 4x	12.76 V	4.709 mV	0.173 A	4.002 mA	2.212 W	51.91 mW
Gain 8x	12.70 V	5.077 mV	0.171 A	3.281 mA	2.174 W	42.56 mW

Table 5 Power Consumption Results: DAS-40565B

	Supply Voltage	Supply Voltage SD	Supply Current	Supply Current SD	Power Consumption	Power Consumption SD
Gain 1x	12.62 V	6.350 mV	0.173 A	3.635 mA	2.186 W	46.99 mW
Gain 2x	12.64 V	14.821 mV	0.174 A	3.734 mA	2.203 W	49.78 mW
Gain 4x	12.76 V	4.426 mV	0.174 A	3.578 mA	2.217 W	46.39 mW
Gain 8x	12.70 V	4.992 mV	0.172 A	3.536 mA	2.184 W	45.76 mW

The Affinity digitizers were observed to consume 2.2 watts of power during operation with a standard deviation of approximately 50 mW. There does not appear to be any significant change in power consumption levels between the two units or with respect to the gain level setting.

Note that the observed 2.2 W of power consumption is greater than the datasheet specification of 1.55 W for a 4 channels digitizer with both Ethernet and GPS active. The digitizers were actively streaming 4 channels of data sampled at 100 Hz, 40 Hz, and 20 Hz on a 100 Mbit Ethernet connection to the local network. The Affinity digitizers under test were equipped with Spyrus cards for performing authentication of the CD1.1 data streams, which is expected to increase the power consumption of the digitizer.

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.

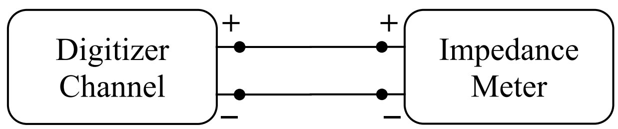

Figure 10 Input Impedance Configuration Diagram

Table 6 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Impedance Meter	Agilent 3458A	MY45048371	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 figure below shows a representative waveform time series for the recording of input impedance made on the reference meter. The window regions bounded by the red lines indicate the segment of data used to evaluate the average impedance.

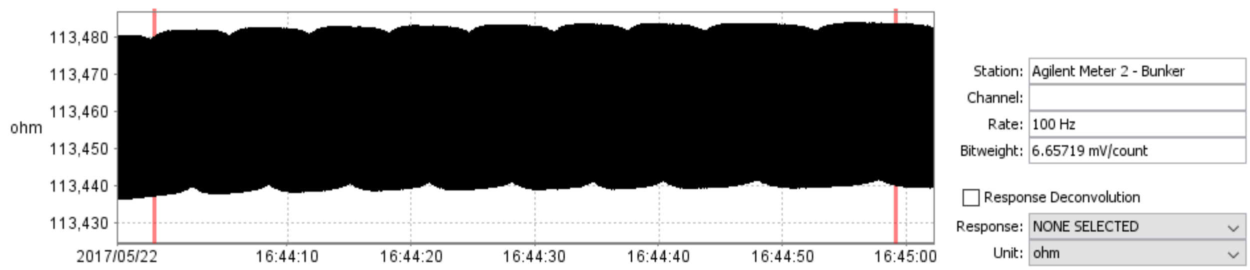

Figure 11 Input Impedance Time Series

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

Table 7 Input Impedance Results: DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z)	113.46 kOhm	113.46 kOhm	113.46 kOhm	113.46 kOhm
Channel 2 (N)	113.49 kOhm	113.49 kOhm	113.49 kOhm	113.48 kOhm
Channel 3 (E)	113.48 kOhm	113.48 kOhm	113.48 kOhm	113.48 kOhm
Channel 4 (X/C)	113.48 kOhm	113.48 kOhm	113.48 kOhm	113.48 kOhm

Table 8 Input Impedance Results: DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z)	113.45 kOhm	113.45 kOhm	113.45 kOhm	113.45 kOhm
Channel 2 (N)	113.45 kOhm	113.46 kOhm	113.46 kOhm	113.45 kOhm
Channel 3 (E)	113.48 kOhm	113.48 kOhm	113.48 kOhm	113.48 kOhm
Channel 4 (X/C)	113.49 kOhm	113.49 kOhm	113.49 kOhm	113.49 kOhm

The measured input impedance of the Affinity digitizer channels were all approximately 113.5 kOhm, within 0.4% of the nominal 113 kOhm datasheet specification. Any variation in measured impedance appears to be unique to the physical recording channel and does not change significantly with gain setting.

3.3 DC Accuracy

The DC Accuracy test is used to measure the 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 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.

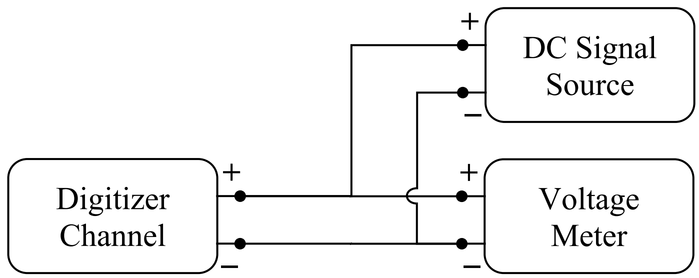

Figure 12 DC Accuracy Configuration Diagram

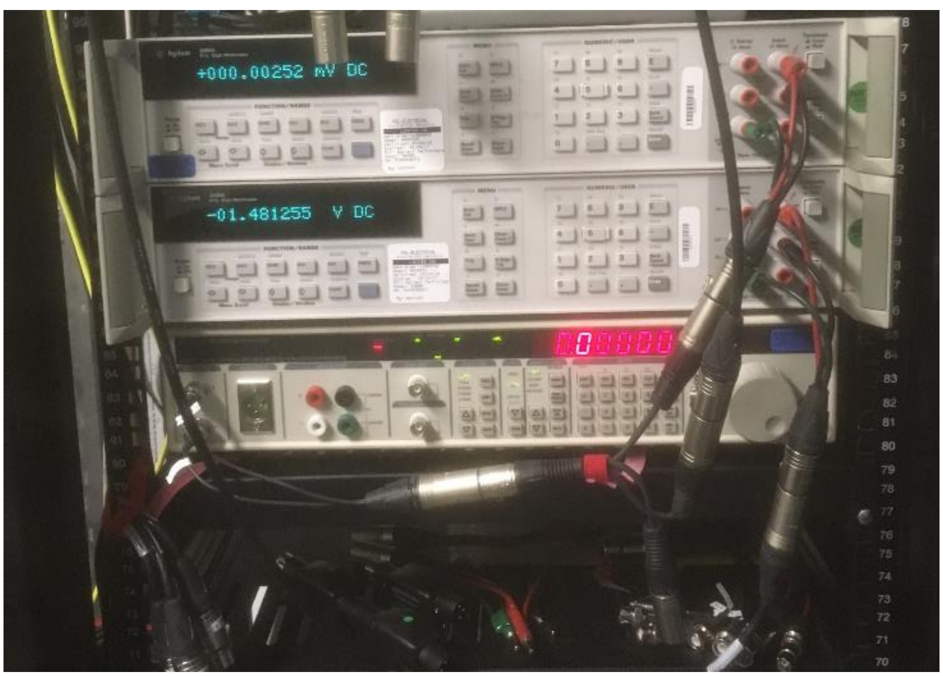

Figure 13 DC Accuracy Configuration Picture

Table 9 DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	SRS DS360	123669	DC Voltage, 10% FS
Voltage Meter	Agilent 3458A	MY45048371	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 digitizer is configured to record simultaneously at 20 Hz, 40 Hz, and 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:

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

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 segments of data used to evaluate the positive and negative values, respectively.

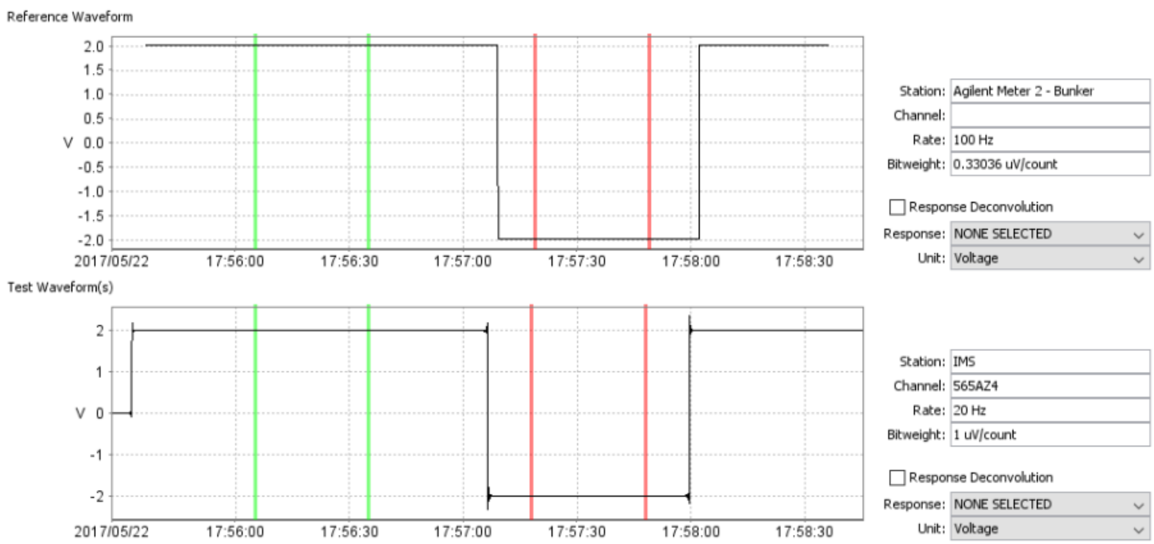

Figure 14 DC Accuracy Time Series

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

Table 10 DC Accuracy Bit-weight: DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Peak Voltage (input)	1.9956 V	0.9968 V	0.4983 V	0.2494 V
Channel 1 (Z) - 20 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 1 (Z) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 1 (Z) - 100 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 2 (N) - 20 Hz	1.0001 uV/count	0.5002 uV/count	0.2501 uV/count	0.1248 uV/count
Channel 2 (N) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2501 uV/count	0.1248 uV/count
Channel 2 (N) - 100 Hz	1.0001 uV/count	0.5002 uV/count	0.2501 uV/count	0.1248 uV/count
Channel 3 (E) - 20 Hz	1.0001 uV/count	0.5001 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 3 (E) - 40 Hz	1.0001 uV/count	0.5001 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 3 (E) - 100 Hz	1.0001 uV/count	0.5001 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 4 (X/C) - 20 Hz	1.0001 uV/count	0.5002 uV/count	0.2500 uV/count	0.1249 uV/count
Channel 4 (X/C) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2500 uV/count	0.1249 uV/count
Channel 4 (X/C) - 100 Hz	1.0001 uV/count	0.5002 uV/count	0.2500 uV/count	0.1249 uV/count
Nominal Bitweight:	1.0000 uV/count	0.5000 uV/count	0.2500 uV/count	0.1250 uV/count
Maximum difference:	0.0070%	0.0420%	0.0760%	0.1360%

Table 11 DC Accuracy Bit-weight: DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Peak Voltage (input)	1.9956 V	0.9968 V	0.4983 V	0.2494 V
Channel 1 (Z) - 20 Hz	1.0001 uV/count	0.5003 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 1 (Z) - 40 Hz	1.0001 uV/count	0.5003 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 1 (Z) - 100 Hz	1.0001 uV/count	0.5003 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 2 (N) - 20 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 2 (N) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 2 (N) - 100 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 3 (E) - 20 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 3 (E) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 3 (E) - 100 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 4 (X/C) - 20 Hz	1.0001 uV/count	0.5003 uV/count	0.2503 uV/count	0.1251 uV/count
Channel 4 (X/C) - 40 Hz	1.0001 uV/count	0.5003 uV/count	0.2503 uV/count	0.1251 uV/count
Channel 4 (X/C) - 100 Hz	1.0001 uV/count	0.5003 uV/count	0.2503 uV/count	0.1251 uV/count
Nominal Bitweight:	1.0000 uV/count	0.5000 uV/count	0.2500 uV/count	0.1250 uV/count
Maximum difference:	0.0090%	0.0620%	0.1000%	0.1040%

The nominal bit-weights provided by Guralp were specified to be 1 uV/count, 0.5 uV/count, and 0.125 uV/count for gains of 1, 2, 4, and 8, respectively. The measured DC bit-weights were found to be most consistent with the nominal values at a gain of 1x to within less than 0.01 %. This is consistent with Guralp documentation which describes the digitizer channels as having a factory calibration for the amplifier at a gain of 1x. The bit-weights at the gains of 2x, 4x, and 8x were found to match the nominal values to within less than 0.136 %.

In addition to the primary recording channels, the multiplexed channels on the auxiliary port were configured to record at 10 Hz. The bit-weights on those channels were measured and shown in the table below:

Table 12 DC Accuracy Bit-weight: Multiplexed Channels

Channel	DAS-40565A	DAS-40565B
M60	1.0003 uV/count	1.0008 uV/count
M70	1.0004 uV/count	1.0007 uV/count
M80	1.0003 uV/count	1.0007 uV/count
M90	1.0003 uV/count	1.0007 uV/count
MA0	1.0003 uV/count	1.0006 uV/count
MB0	1.0003 uV/count	1.0007 uV/count
MC0	1.0003 uV/count	1.0006 uV/count
MD0	1.0003 uV/count	1.0006 uV/count
ME0	1.0003 uV/count	1.0008 uV/count
MF0	1.0003 uV/count	1.0006 uV/count
Nominal Bitweight:	1.0000 uV/count	1.0000 uV/count
Maximum difference:	0.0360%	0.0750%

The multiplexed channels are all configured to have a nominal bit-weight of 1 uV/count. The observed DC bit-weights were all within less than 0.075 % of this nominal.

3.4 AC Accuracy
The AC Accuracy test is used to measure the bit-weight 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.

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.

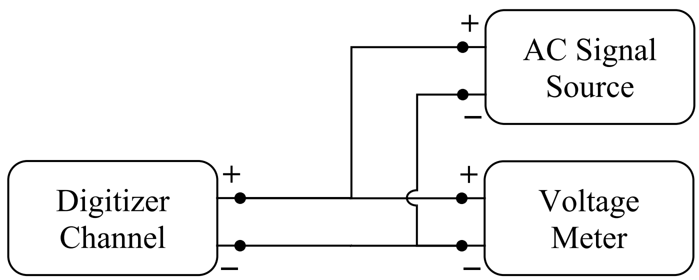

Figure 15 AC Accuracy Configuration Diagram

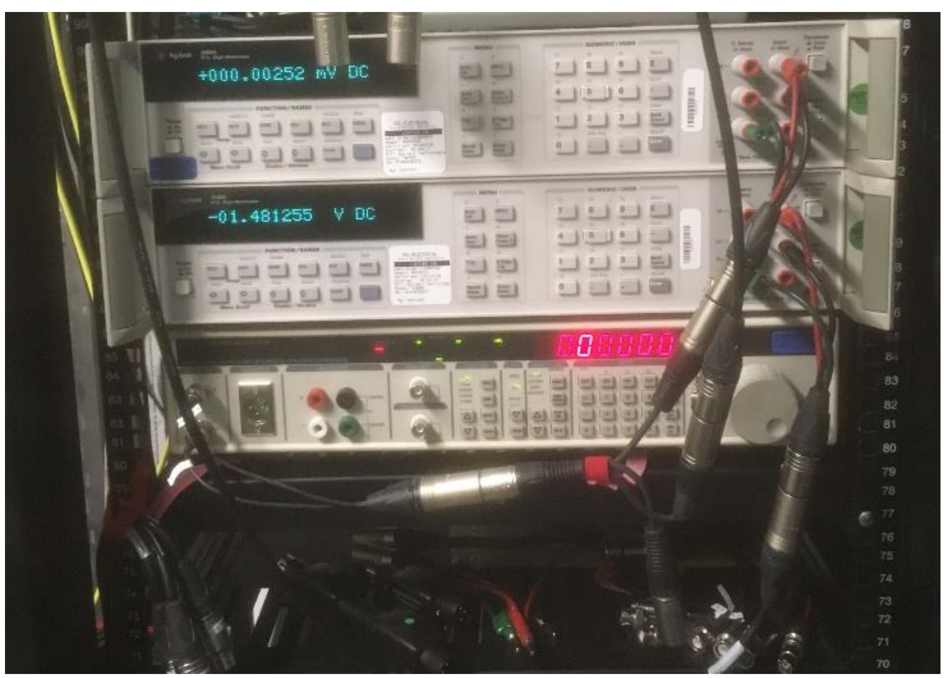

Figure 16 AC Accuracy Configuration Picture

Table 13 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	MY45048371	10 V full scale

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 digitizer is configured to record simultaneously at 20 Hz, 40 Hz, and 100 Hz.

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 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 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 segments of data used for analysis.

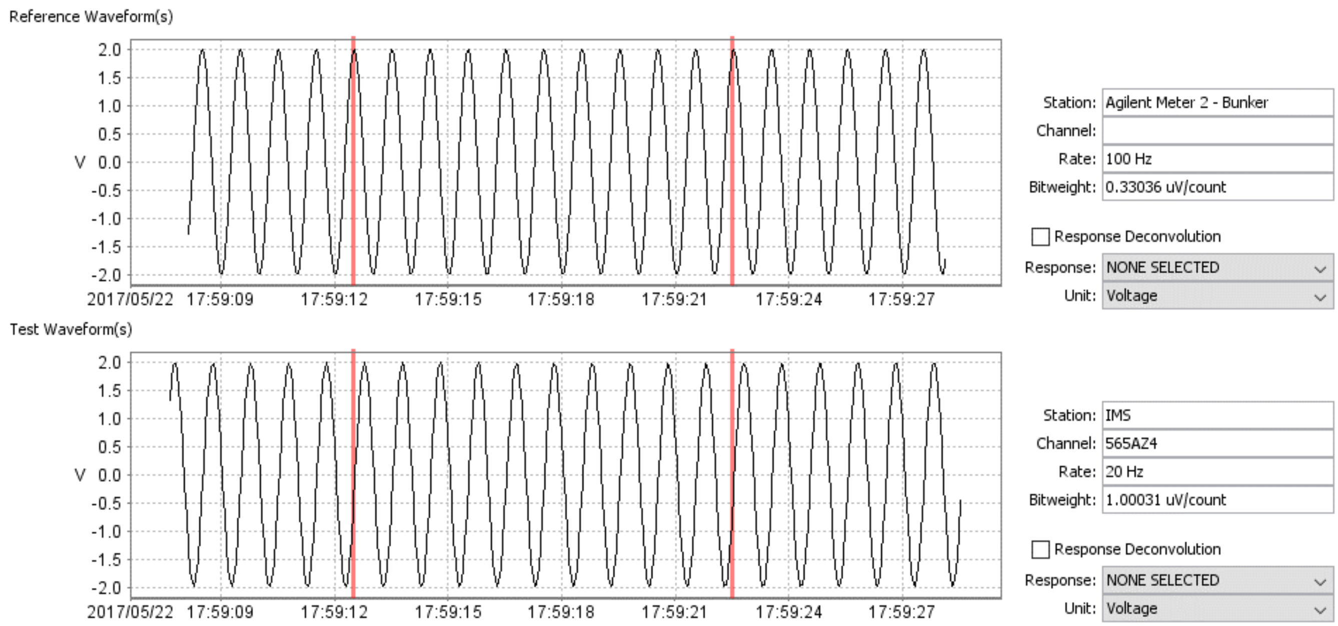

Figure 17 AC Accuracy Time Series

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

Table 14 AC Accuracy Bit-weight: DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Peak Voltage (input)	1.9946 V	0.9963 V	0.4981 V	0.2492 V
Channel 1 (Z) - 20 Hz	1.0003 uV/count	0.5003 uV/count	0.2503 uV/count	0.1250 uV/count
Channel 1 (Z) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 1 (Z) - 100 Hz	1.0001 uV/count	0.5003 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 2 (N) - 20 Hz	1.0003 uV/count	0.5003 uV/count	0.2501 uV/count	0.1249 uV/count
Channel 2 (N) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2501 uV/count	0.1248 uV/count
Channel 2 (N) - 100 Hz	1.0002 uV/count	0.5002 uV/count	0.2501 uV/count	0.1248 uV/count
Channel 3 (E) - 20 Hz	1.0003 uV/count	0.5002 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 3 (E) - 40 Hz	1.0001 uV/count	0.5001 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 3 (E) - 100 Hz	1.0002 uV/count	0.5001 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 4 (X/C) - 20 Hz	1.0003 uV/count	0.5003 uV/count	0.2501 uV/count	0.1249 uV/count
Channel 4 (X/C) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2501 uV/count	0.1249 uV/count
Channel 4 (X/C) - 100 Hz	1.0001 uV/count	0.5002 uV/count	0.2501 uV/count	0.1249 uV/count
Nominal Bitweight:	1.0000 uV/count	0.5000 uV/count	0.2500 uV/count	0.1250 uV/count
Maximum difference:	0.0330%	0.0680%	0.1000%	0.1280%

Table 15 AC Accuracy Bit-weight: DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Peak Voltage (input)	1.9946 V	0.9963 V	0.4981 V	0.2492 V
Channel 1 (Z) - 20 Hz	1.0003 uV/count	0.5004 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 1 (Z) - 40 Hz	1.0001 uV/count	0.5003 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 1 (Z) - 100 Hz	1.0002 uV/count	0.5003 uV/count	0.2502 uV/count	0.1249 uV/count
Channel 2 (N) - 20 Hz	1.0004 uV/count	0.5004 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 2 (N) - 40 Hz	1.0001 uV/count	0.5003 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 2 (N) - 100 Hz	1.0002 uV/count	0.5003 uV/count	0.2502 uV/count	0.1251 uV/count
Channel 3 (E) - 20 Hz	1.0004 uV/count	0.5003 uV/count	0.2503 uV/count	0.1251 uV/count
Channel 3 (E) - 40 Hz	1.0001 uV/count	0.5002 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 3 (E) - 100 Hz	1.0002 uV/count	0.5003 uV/count	0.2502 uV/count	0.1250 uV/count
Channel 4 (X/C) - 20 Hz	1.0003 uV/count	0.5004 uV/count	0.2503 uV/count	0.1252 uV/count
Channel 4 (X/C) - 40 Hz	1.0001 uV/count	0.5003 uV/count	0.2503 uV/count	0.1251 uV/count
Channel 4 (X/C) - 100 Hz	1.0002 uV/count	0.5004 uV/count	0.2503 uV/count	0.1251 uV/count
Nominal Bitweight:	1.0000 uV/count	0.5000 uV/count	0.2500 uV/count	0.1250 uV/count
Maximum difference:	0.0350%	0.0880%	0.1280%	0.1280%

The nominal bit-weights provided by Guralp were specified to be 1 uV/count, 0.5 uV/count, and 0.125 uV/count for gains of 1, 2, 4, and 8, respectively. The measured AC bit-weights were found to be most consistent with the nominal values at a gain of 1x to within 0.035 %. This is consistent with Guralp documentation which describes the digitizer channels as having a factory calibration for the amplifier at a gain of 1x. The bit-weights at the gains of 2x, 4x, and 8x were found to match the nominal values to within less than 0.128 %.

In addition to the primary recording channels, the multiplexed channels on the auxiliary port were configured to record at 10 Hz. The bit-weights on those channels were measured and shown in the table below:

Table 16 AC Accuracy Bit-weight: Multiplexed Channels

Channel	DAS-40565A	DAS-40565B
M60	1.0002 uV/count	0.9976 uV/count
M70	1.0003 uV/count	0.9982 uV/count
M80	1.0002 uV/count	0.9979 uV/count
M90	1.0002 uV/count	0.9977 uV/count
MA0	1.0002 uV/count	0.9975 uV/count
MB0	1.0002 uV/count	0.9983 uV/count
MC0	1.0002 uV/count	0.9983 uV/count
MD0	1.0002 uV/count	0.9973 uV/count
ME0	1.0002 uV/count	0.9979 uV/count
MF0	1.0003 uV/count	0.9978 uV/count
Nominal Bitweight	1.0000 uV/count	1.0000 uV/count
Maximum difference:	0.0270%	0.2740%

The multiplexed channels are all configured to have a nominal bit-weight of 1 uV/count. The observed AC bit-weight were all within less than 0.274 % of this nominal.

3.5 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.

3.5.1 Measurand

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

3.5.2 Configuration

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

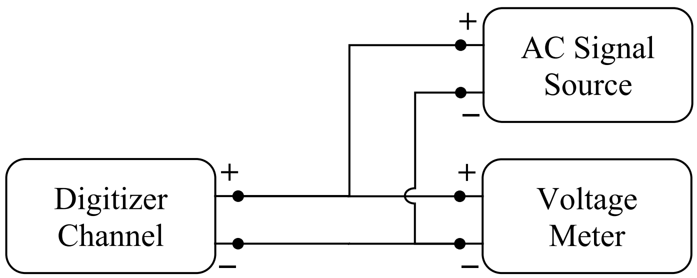

Figure 18 AC Full Scale Configuration Diagram

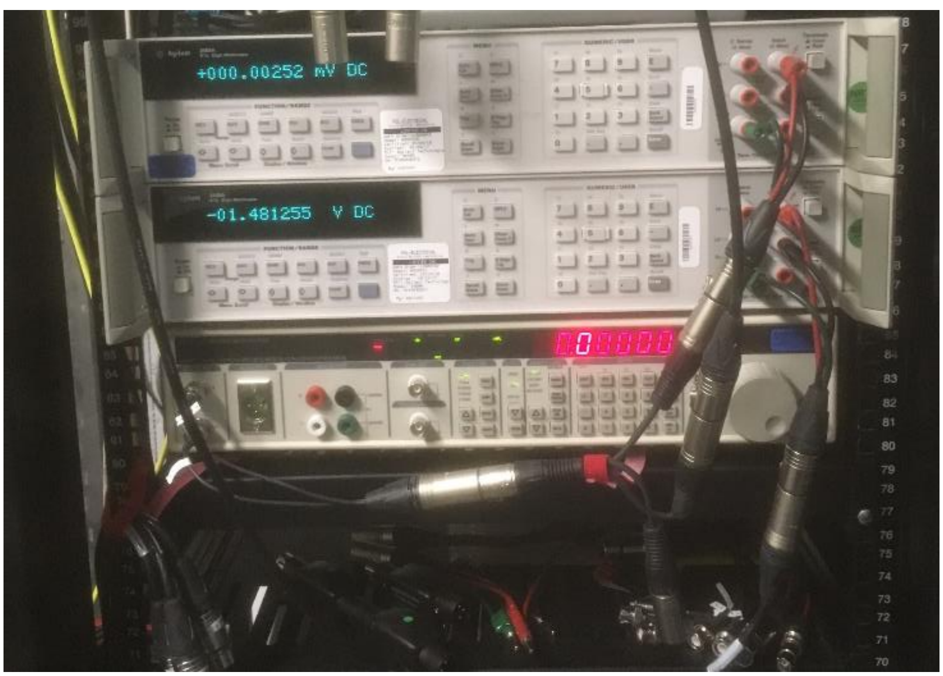

Figure 19 AC Full Scale Configuration Picture

Table 17 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	MY45048371	1 V full scale

The AC Signal Source is configured to generate an 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.

3.5.3 Analysis

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

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

A short window is defined on the data around one of each 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.

3.5.4 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.

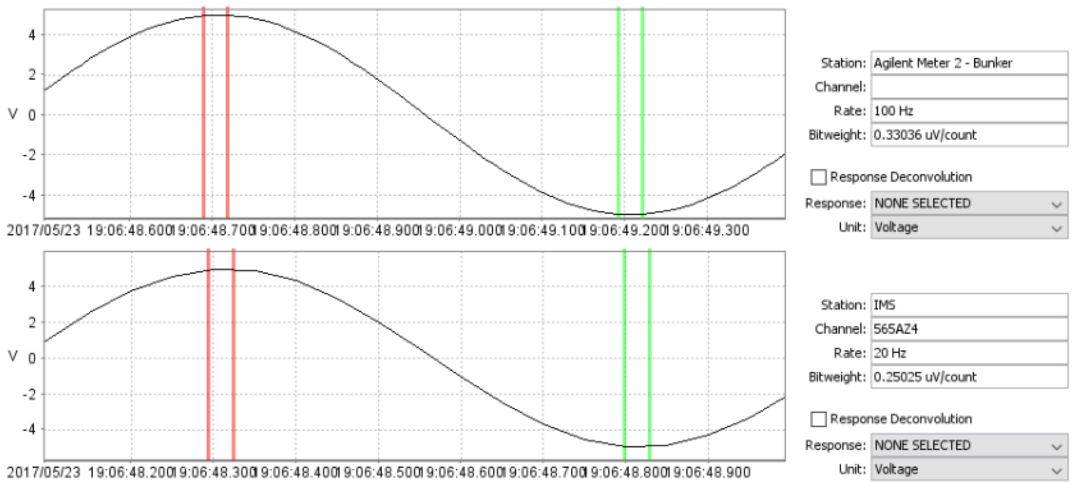

Figure 20 AC Full Scale Time Series

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

Table 18 AC Full Scale: DAS-40565A

	Gain 1x		Gain 2x		Gain 4x		Gain 8x	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
Reference	19.898 V	-19.945 V	9.951 V	-9.974 V	4.974 V	-4.987 V	2.489 V	-2.496 V
Channel 1 (Z) - 20 Hz	19.894 V	-19.938 V	9.898 V	-9.914 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 1 (Z) - 40 Hz	19.894 V	-19.938 V	9.937 V	-9.964 V	4.952 V	-4.981 V	2.489 V	-2.496 V
Channel 1 (Z) - 100 Hz	19.894 V	-19.938 V	9.948 V	-9.973 V	4.973 V	-4.987 V	2.489 V	-2.496 V
Channel 2 (N) - 20 Hz	19.894 V	-19.938 V	9.898 V	-9.914 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 2 (N) - 40 Hz	19.894 V	-19.938 V	9.937 V	-9.964 V	4.952 V	-4.981 V	2.489 V	-2.496 V
Channel 2 (N) - 100 Hz	19.894 V	-19.938 V	9.948 V	-9.973 V	4.973 V	-4.987 V	2.489 V	-2.496 V
Channel 3 (E) - 20 Hz	19.894 V	-19.938 V	9.898 V	-9.914 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 3 (E) - 40 Hz	19.894 V	-19.938 V	9.937 V	-9.964 V	4.952 V	-4.981 V	2.489 V	-2.496 V
Channel 3 (E) - 100 Hz	19.894 V	-19.938 V	9.948 V	-9.963 V	4.973 V	-4.987 V	2.489 V	-2.496 V
Channel 4 (X/C) - 20 Hz	19.894 V	-19.938 V	9.898 V	-9.914 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 4 (X/C) - 40 Hz	19.894 V	-19.938 V	9.937 V	-9.964 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 4 (X/C) - 100 Hz	19.894 V	-19.938 V	9.948 V	-9.973 V	4.973 V	-4.987 V	2.489 V	-2.496 V

Table 19 AC Full Scale: DAS-40565B

	Gain 1x		Gain 2x		Gain 4x		Gain 8x	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
Reference	19.899 V	-19.943 V	10.942 V	-10.967 V	4.974 V	-4.987 V	2.489 V	-2.496 V
Channel 1 (Z) - 20 Hz	19.886 V	-19.927 V	10.801 V	-10.636 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 1 (Z) - 40 Hz	19.886 V	-19.927 V	10.738 V	-10.564 V	4.967 V	-4.981 V	2.489 V	-2.496 V
Channel 1 (Z) - 100 Hz	19.891 V	-19.942 V	10.742 V	-10.583 V	4.973 V	-4.987 V	2.489 V	-2.496 V
Channel 2 (N) - 20 Hz	19.886 V	-19.927 V	10.797 V	-10.632 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 2 (N) - 40 Hz	19.886 V	-19.927 V	10.732 V	-10.561 V	4.967 V	-4.981 V	2.489 V	-2.496 V
Channel 2 (N) - 100 Hz	19.891 V	-19.942 V	10.737 V	-10.579 V	4.973 V	-4.987 V	2.489 V	-2.496 V
Channel 3 (E) - 20 Hz	19.886 V	-19.927 V	10.796 V	-10.631 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 3 (E) - 40 Hz	19.886 V	-19.927 V	10.732 V	-10.560 V	4.967 V	-4.981 V	2.489 V	-2.496 V
Channel 3 (E) - 100 Hz	19.891 V	-19.942 V	10.737 V	-10.579 V	4.973 V	-4.987 V	2.489 V	-2.496 V
Channel 4 (X/C) - 20 Hz	19.886 V	-19.927 V	10.791 V	-10.628 V	4.952 V	-4.960 V	2.489 V	-2.496 V
Channel 4 (X/C) - 40 Hz	19.885 V	-19.927 V	10.726 V	-10.557 V	4.967 V	-4.981 V	2.489 V	-2.496 V
Channel 4 (X/C) - 100 Hz	19.891 V	-19.942 V	10.731 V	-10.576 V	4.973 V	-4.987 V	2.489 V	-2.496 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.

3.6 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.

3.6.1 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.

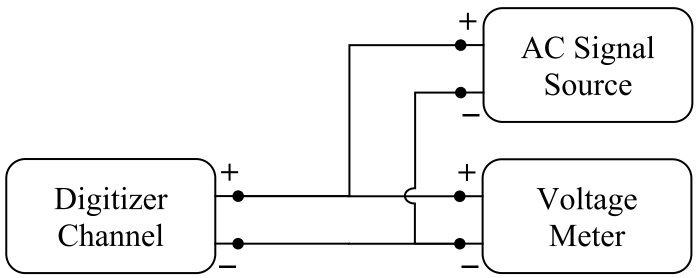

Figure 21 AC Over Scale Configuration Diagram

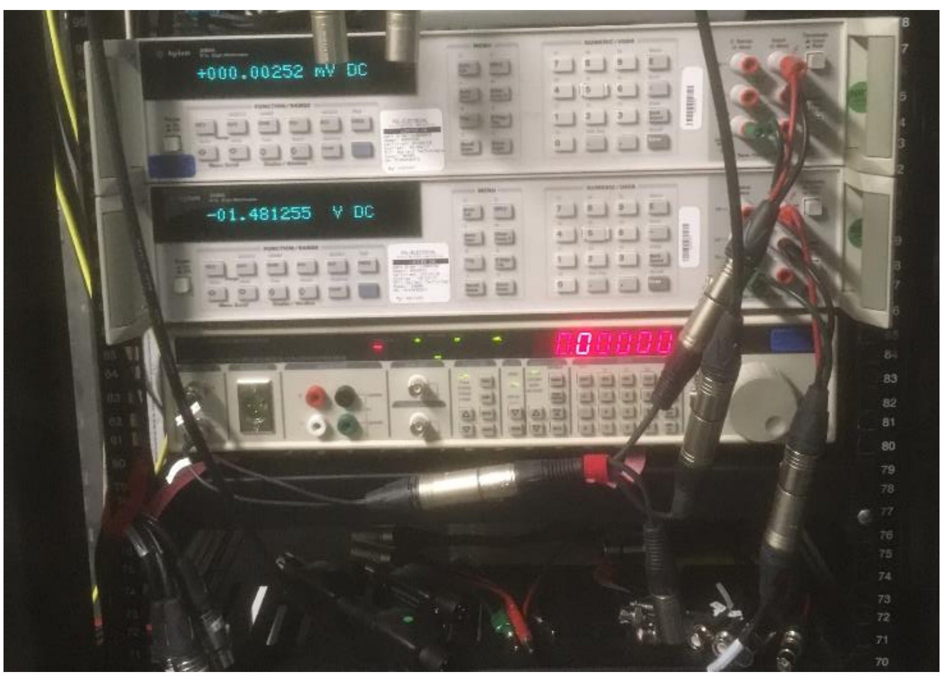

Figure 22 AC Over Scale Configuration Picture

Table 20 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.

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 bit-weight, 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 each 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 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 digitizer channels under test. The window regions bounded by the red and green lines indicate the segments of data used to evaluate the positive and negative regions, respectively.

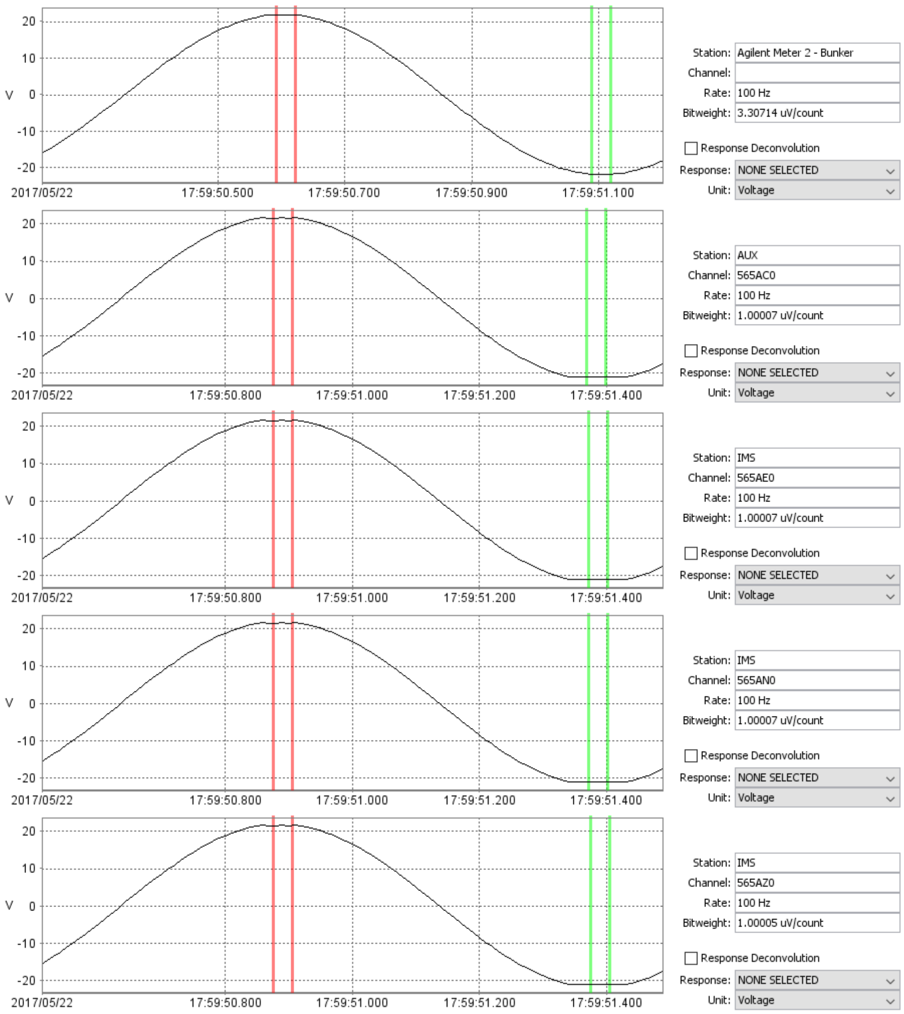

Figure 23 AC Over Scale Time Series

Note that in the figure above, signs of flattening in the time series are visible at each of the positive and negative peaks.

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

Table 21 AC Over Scale: DAS-40565A

	Gain 1x		Gain 2x		Gain 4x		Gain 8x	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
Reference	21.880 V	-21.933 V	10.941 V	-10.969 V	5.472 V	-5.486 V	2.739 V	-2.747 V
Channel 1 (Z) - 20 Hz	21.560 V	-21.256 V	10.813 V	-10.644 V	5.408 V	-5.324 V	2.688 V	-2.653 V
Channel 1 (Z) - 40 Hz	21.506 V	-21.166 V	10.748 V	-10.610 V	5.376 V	-5.286 V	2.687 V	-2.647 V
Channel 1 (Z) - 100 Hz	21.494 V	-21.172 V	10.753 V	-10.589 V	5.378 V	-5.297 V	2.685 V	-2.645 V
Channel 2 (N) - 20 Hz	21.559 V	-21.257 V	10.812 V	-10.644 V	5.406 V	-5.322 V	2.687 V	-2.651 V
Channel 2 (N) - 40 Hz	21.506 V	-21.168 V	10.747 V	-10.570 V	5.373 V	-5.284 V	2.686 V	-2.645 V
Channel 2 (N) - 100 Hz	21.493 V	-21.173 V	10.751 V	-10.591 V	5.375 V	-5.294 V	2.683 V	-2.643 V
Channel 3 (E) - 20 Hz	21.559 V	-21.255 V	10.810 V	-10.641 V	5.407 V	-5.323 V	2.690 V	-2.655 V
Channel 3 (E) - 40 Hz	21.505 V	-21.166 V	10.745 V	-10.567 V	5.375 V	-5.285 V	2.689 V	-2.650 V
Channel 3 (E) - 100 Hz	21.493 V	-21.171 V	10.749 V	-10.587 V	5.377 V	-5.296 V	2.687 V	-2.647 V
Channel 4 (X/C) - 20 Hz	21.554 V	-21.254 V	10.809 V	-10.643 V	5.404 V	-5.320 V	2.687 V	-2.652 V
Channel 4 (X/C) - 40 Hz	21.499 V	-21.165 V	10.743 V	-10.569 V	5.370 V	-5.283 V	2.686 V	-2.646 V
Channel 4 (X/C) - 100 Hz	21.486 V	-21.167 V	10.748 V	-10.589 V	5.373 V	-5.293 V	2.684 V	-2.644 V

Table 22 AC Over Scale: DAS-40565B

	Gain 1x		Gain 2x		Gain 4x		Gain 8x	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
Reference	21.888 V	-21.933 V	10.942 V	-10.967 V	5.473 V	-5.487 V	2.739 V	-2.747 V
Channel 1 (Z) - 20 Hz	21.537 V	-21.250 V	10.810 V	-10.644 V	5.405 V	-5.323 V	2.684 V	-2.652 V
Channel 1 (Z) - 40 Hz	21.488 V	-21.177 V	10.744 V	-10.570 V	5.377 V	-5.286 V	2.686 V	-2.648 V
Channel 1 (Z) - 100 Hz	21.486 V	-21.170 V	10.749 V	-10.589 V	5.375 V	-5.296 V	2.684 V	-2.644 V
Channel 2 (N) - 20 Hz	21.529 V	-21.243 V	10.805 V	-10.640 V	5.403 V	-5.321 V	2.686 V	-2.654 V
Channel 2 (N) - 40 Hz	21.478 V	-21.170 V	10.738 V	-10.566 V	5.375 V	-5.284 V	2.688 V	-2.651 V
Channel 2 (N) - 100 Hz	21.476 V	-21.164 V	10.743 V	-10.585 V	5.372 V	-5.294 V	2.687 V	-2.647 V
Channel 3 (E) - 20 Hz	21.529 V	-21.241 V	10.804 V	-10.638 V	5.403 V	-5.321 V	2.685 V	-2.652 V
Channel 3 (E) - 40 Hz	21.477 V	-21.168 V	10.736 V	-10.564 V	5.375 V	-5.284 V	2.687 V	-2.649 V
Channel 3 (E) - 100 Hz	21.475 V	-21.161 V	10.742 V	-10.584 V	5.373 V	-5.294 V	2.685 V	-2.645 V
Channel 4 (X/C) - 20 Hz	21.520 V	-21.236 V	10.801 V	-10.637 V	5.402 V	-5.321 V	2.686 V	-2.654 V
Channel 4 (X/C) - 40 Hz	21.465 V	-21.139 V	10.733 V	-10.564 V	5.374 V	-5.284 V	2.688 V	-2.651 V
Channel 4 (X/C) - 100 Hz	21.464 V	-21.156 V	10.739 V	-10.583 V	5.371 V	-5.294 V	2.686 V	-2.647 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.

3.7 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.

3.7.1 Measurand

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

3.7.2 Configuration

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

Figure 24 Input Shorted Offset Configuration Diagram

Figure 25 Input Shorted Offset Configuration Picture

Table 23 Input Shorted Offset Testbed Equipment

	Impedance
Resistor	50 (25x2) ohm

Each of the 4 recording Z, N, E, and X/C channels on the digitizers was configured with a different gain level of 1x, 2x, 4x, and 8x, respectively. This was done so that each of the gain levels could be evaluated simultaneously in the time allotted for the testing. A minimum of 12 hours of data is recorded.

3.7.3 Analysis

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

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

The mean value, in volts, is evaluated:

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

3.7.4 Result

The figures below show the waveform time series for the recording made on the digitizer channel under test. The window regions bounded by the red lines indicate the segments of data used for analysis. 10 hours of data was selected for use in analyzing the offset, chosen after the DC level of the voltage has stabilized.

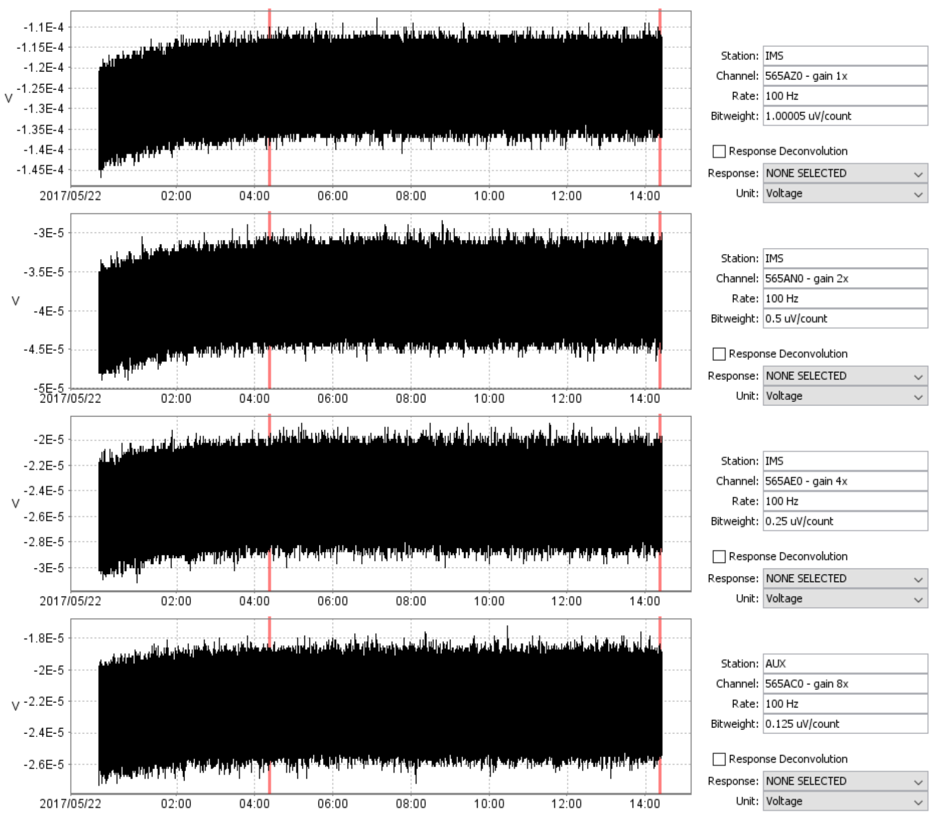

Figure 26 Input Shorted Offset Time Series: DAS-40565A

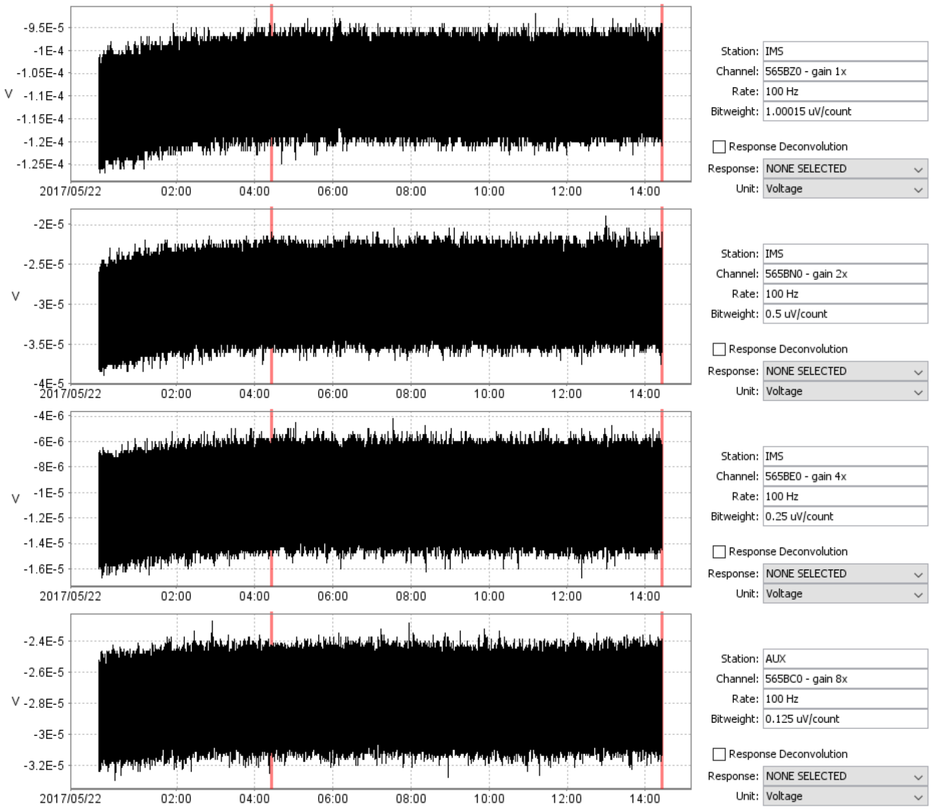

Figure 27 Input Shorted Offset Time Series: DAS-40565B

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

Table 24 Input Shorted Offset

	Offset (volts)	Offset (counts)
DAS-40565A - Z (gain 1x)	-124.53 uV	-125
DAS-40565A - N (gain 2x)	-37.70 uV	-75
DAS-40565A - E (gain 4x)	-24.35 uV	-97
DAS-40565A - X/C (gain 8x)	-22.22 uV	-178
DAS-40565B - Z (gain 1x)	-108.03 uV	-108
DAS-40565B - N (gain 2x)	-28.81 uV	-58
DAS-40565B - E (gain 4x)	-10.28 uV	-41
DAS-40565B - X/C (gain 8x)	-27.79 uV	-222

There does not appear to be any relationship between the channel offset and gain level.

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 passband.

3.8.2 Configuration

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

Figure 28 Self Noise Configuration Diagram

Figure 29 Self Noise Configuration Picture

Table 25 Self Noise Testbed Equipment

	Impedance
Resistor	50 (25x2) ohm

Each of the 4 recording Z, N, E, and X/C channels on the digitizers was configured with a different gain level of 1x, 2x, 4x, and 8x, respectively. This was done so that each of the gain levels could be evaluated simultaneously in the time allotted for the testing. A minimum of 12 hours of data is recorded.

3.8.3 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 (Merchant, 2011) from the time series using a Hann window of length 4k, 8k, and 16k for the 20 Hz, 40 Hz, and 100 Hz sample rates, respectively. 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):

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

The noise level PSD in V^2/Hz are compared to the theoretical levels of quantization noise in an ideal analog to digital converter in order to determine the number of effective noise free bits:

$$Spectral\ Noise = \left(\frac{\left(2 * V_{FS}/2^B\right)^2}{12 * F_s/2}\right)$$

Where:

$Spectral\ Noise$	= Units of V^2/Hz
V_{FS}	= Digitizer peak full scale in Volts
B	= Number of ideal bits of resolution
F_s	= Sampling frequency in Hertz

In addition, the total RMS noise is calculated over an application pass-band:

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

where $f[n]$ and $f[m]$ are the passband limits, T_s is the sampling period in seconds, and L is window length.

3.8.4 Result

The figures below show a representative waveform time series from DAS-40565A at a gain of 1x for sample rates of 100 Hz, 40 Hz, and 20 Hz. The waveforms from other gains settings and DAS-40565B are very similar in appearance. The window regions bounded by the red lines indicate the segment of data used for analysis. 10 hours of data was selected for use in analyzing the self-noise, chosen after the DC level of the voltage has stabilized.

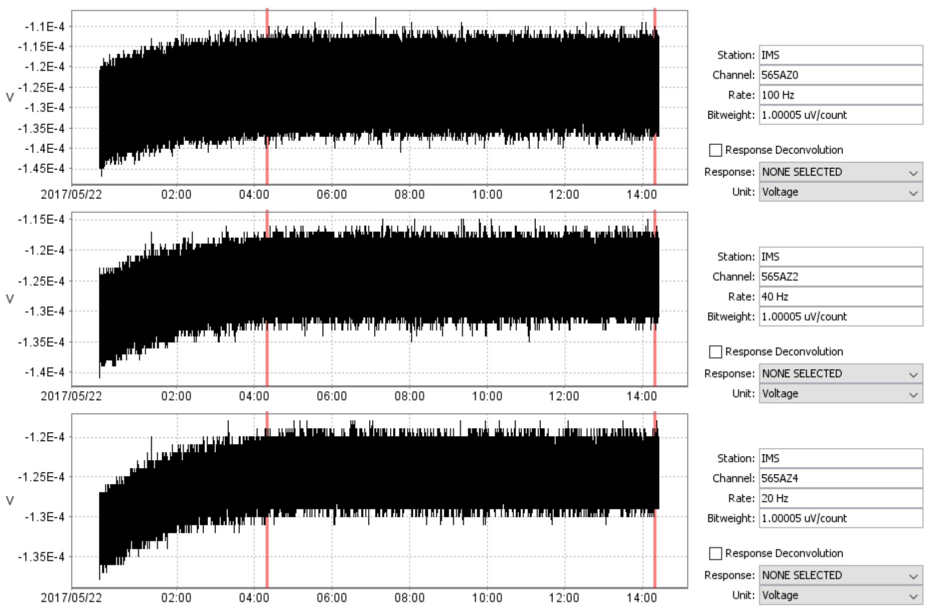

Figure 30 Self Noise Time Series: DAS-40565A, Channel Z (1x gain)

The Affinity digitizers recorded data on all four channels simultaneously at sample rates of 100 Hz, 40 Hz, and 20 Hz. A comparison of the power spectral density levels at each of the selected sample rates for DAS-40565A channel Z at a gain of 1x is shown below:

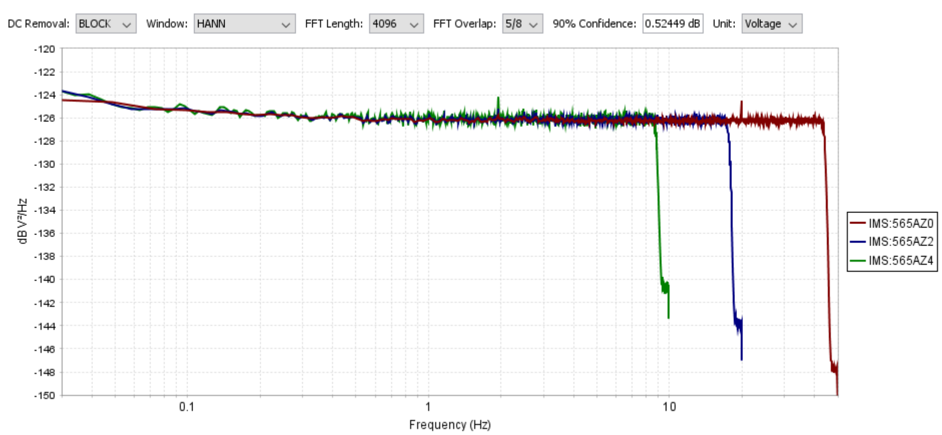

Figure 31 Self Noise Power Spectra: DAS-40565A, Channel Z (1x gain)

The observed PSD levels are unchanged between the different sample rates that were recorded. This was verified for all the channels and gain levels that were tested. The figures below show the PSD plots for each of the digitizer gain levels and sample rates, along with the reference lines representing the expected levels of quantitation noise for an ideal analog to digital conversion with peak full scales of 20 V, 10 V, 5 V, and 2.5 V at gains of 1x, 2x, 4x, and 8x, respectively.

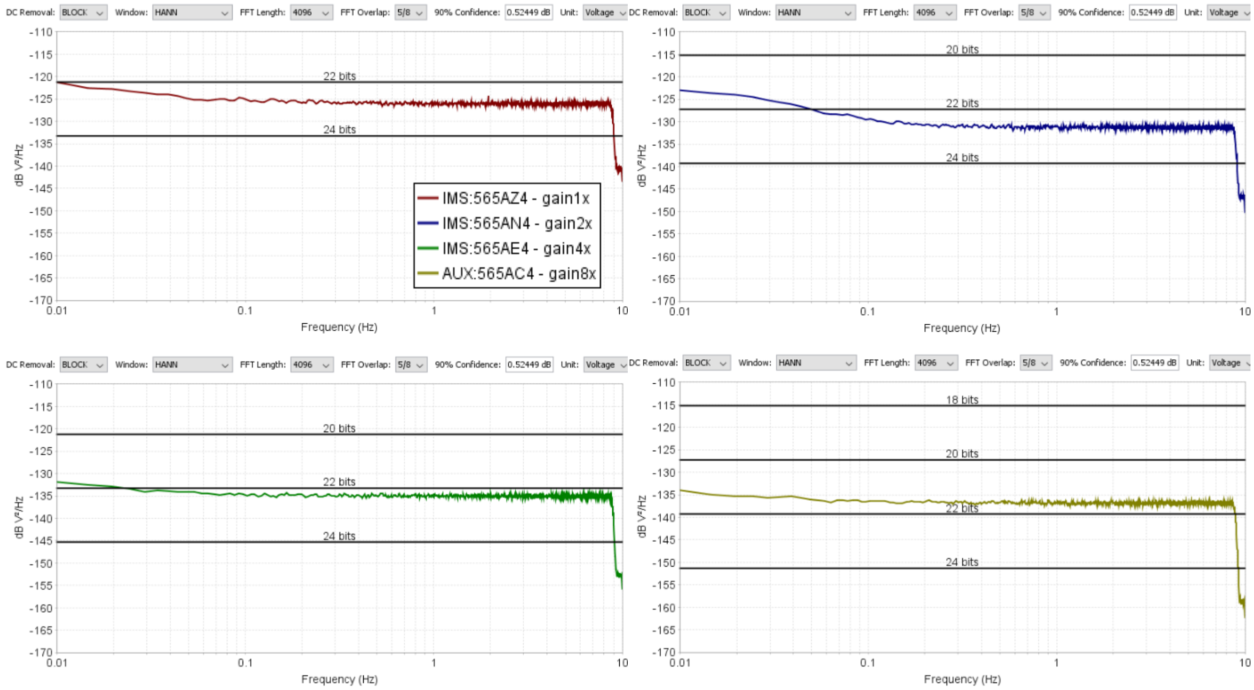

Figure 32 Self Noise gain 20 Hz Power Spectra: DAS-40565A

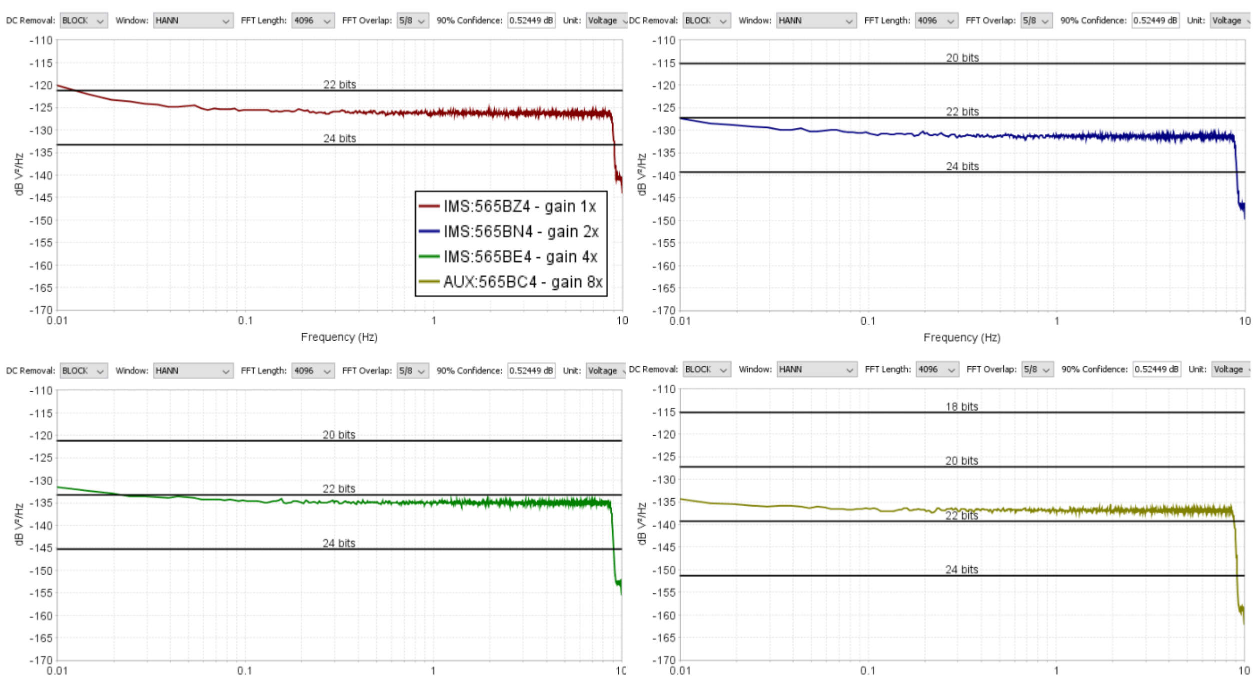

Figure 33 Self Noise gain 20 Hz Power Spectra: DAS-40565B

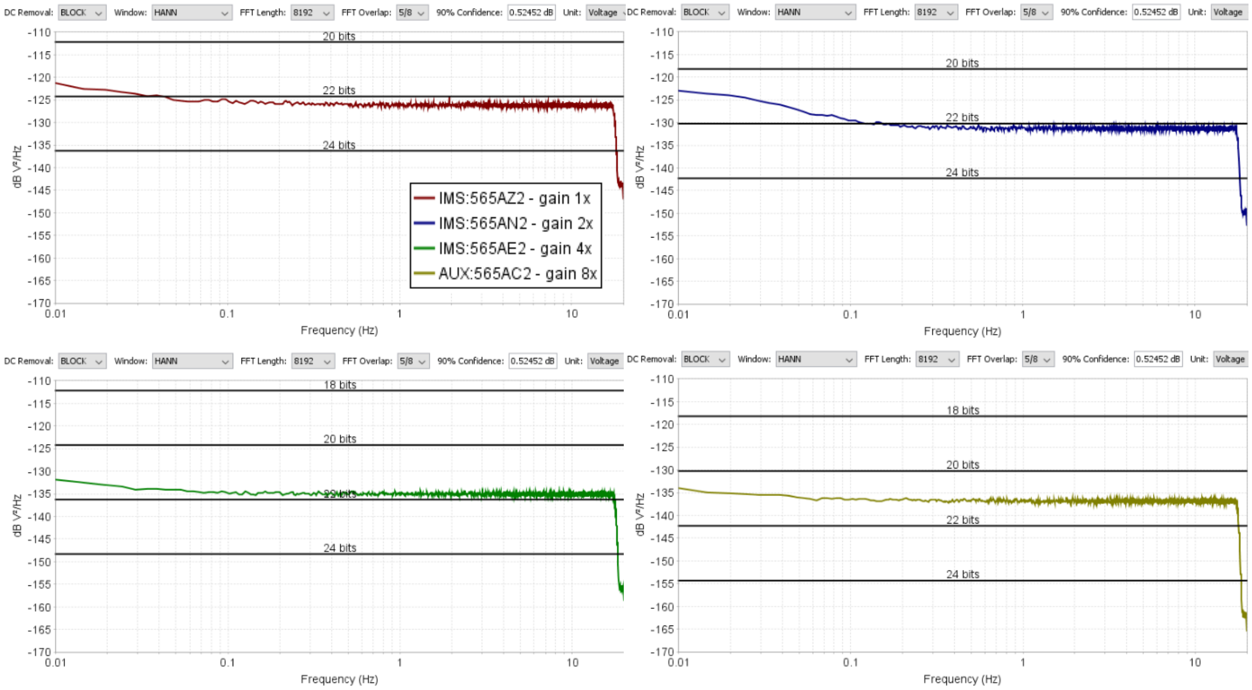

Figure 34 Self Noise gain 40 Hz Power Spectra: DAS-40565A

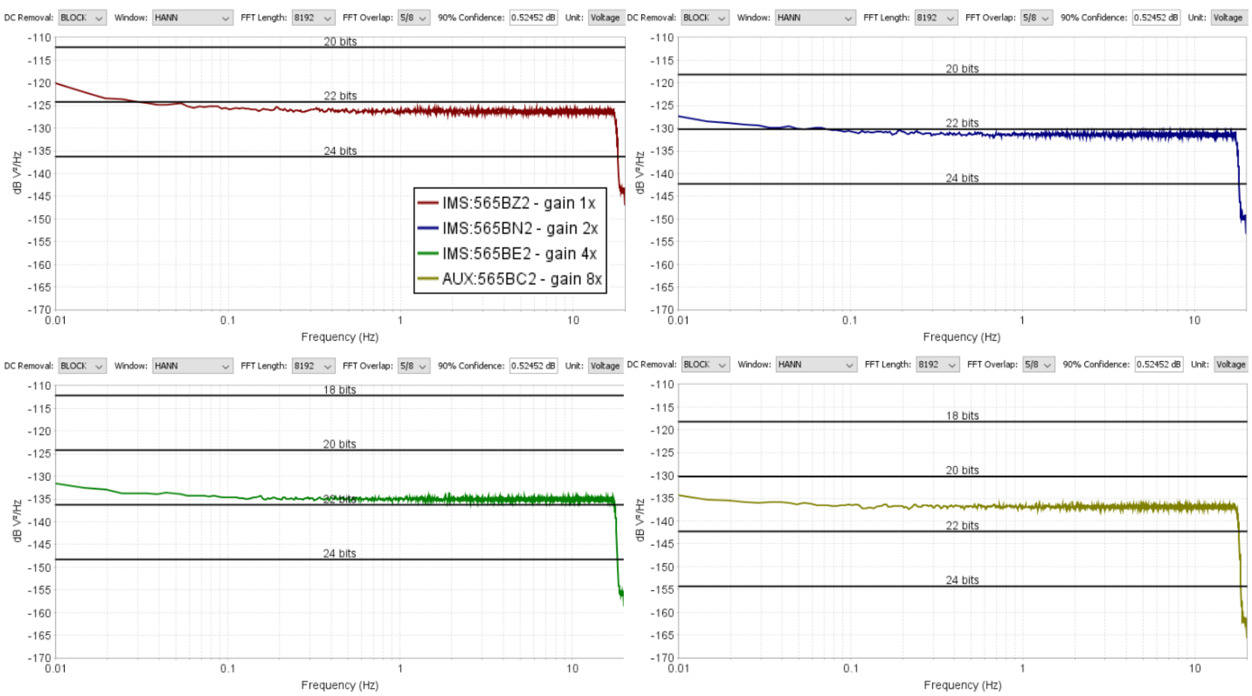

Figure 35 Self Noise gain 40 Hz Power Spectra: DAS-40565B

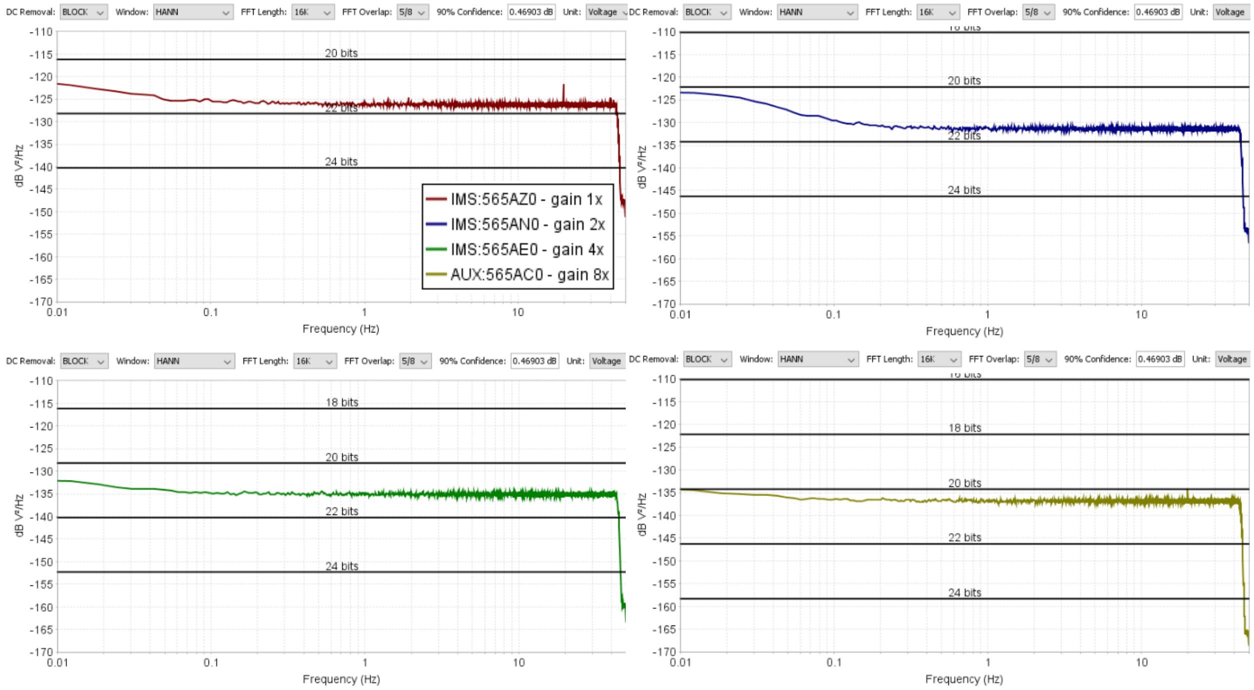

Figure 36 Self Noise gain 100 Hz Power Spectra: DAS-40565A

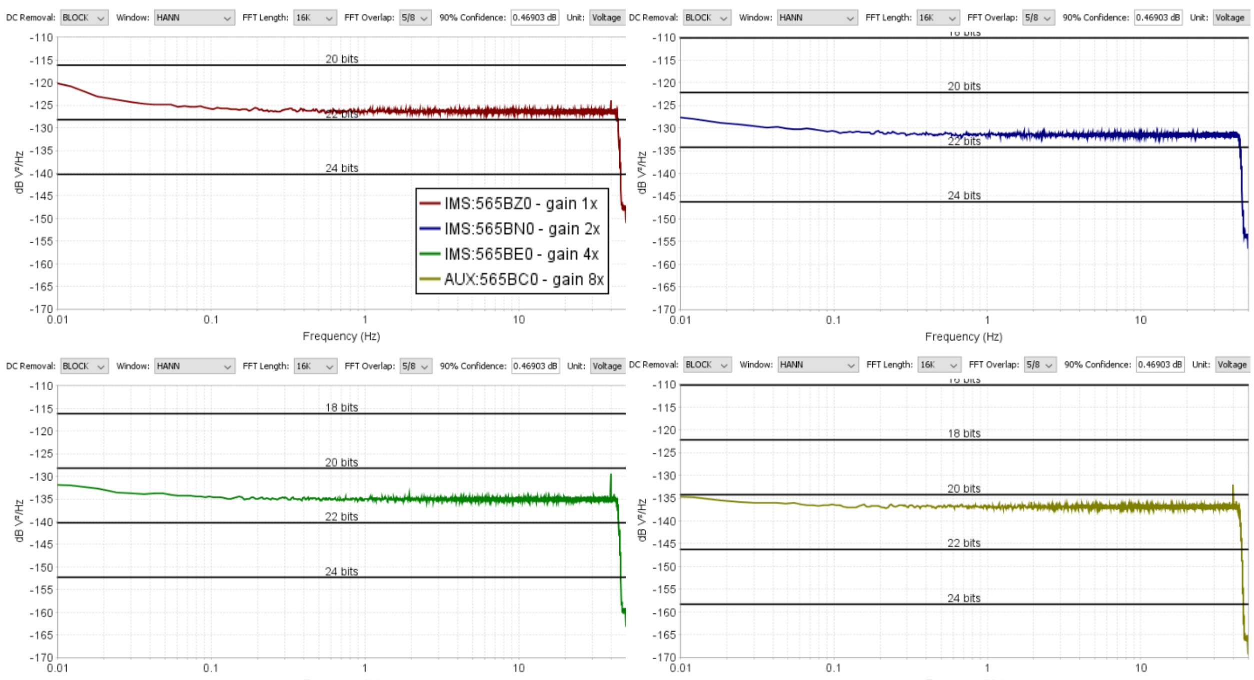

Figure 37 Self Noise gain 100 Hz Power Spectra: DAS-40565B

Comparing the noise PSD levels in Figure 32 through Figure 37 at 0.1 Hz and above to the idealized analog to digital quantization lines, the Affinity digitizers were observed to have effective noise free bits as shown in the table below:

Table 26 Noise Free Bits

	DAS-40565A			DAS-40565B		
	20 Hz Sample Rate	40 Hz Sample Rate	100 Hz Sample Rate	20 Hz Sample Rate	40 Hz Sample Rate	100 Hz Sample Rate
Gain 1x	22.8 bits	22.3 bits	21.6 bits	22.8 bits	22.4 bits	21.7 bits
Gain 2x	22.6 bits	22.1 bits	21.5 bits	22.6 bits	22.2 bits	21.5 bits
Gain 4x	22.3 bits	21.8 bits	21.1 bits	22.3 bits	21.8 bits	21.1 bits
Gain 8x	21.6 bits	21.1 bits	20.5 bits	21.6 bits	21.1 bits	20.5 bits

The number of effective bits varies with both gain and sample rate, as expected, with values ranging from 20.5 to 22.8 bits.

The 100 Hz Self Noise power spectra are shown below in the combined plots to better compare the relative noise levels at each gain setting.

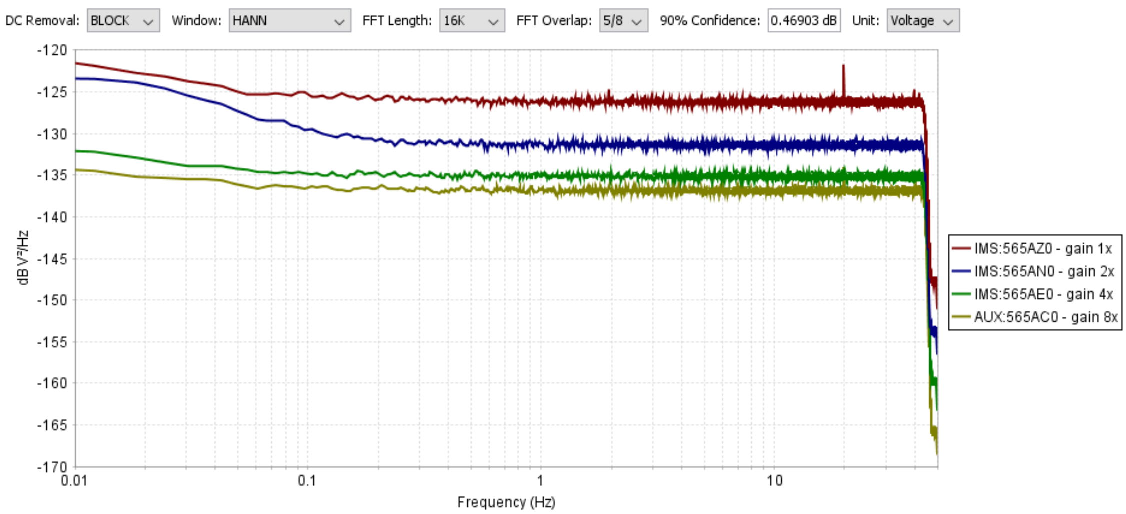

Figure 38 Self Noise 100 Hz Power Spectra: DAS-40565A

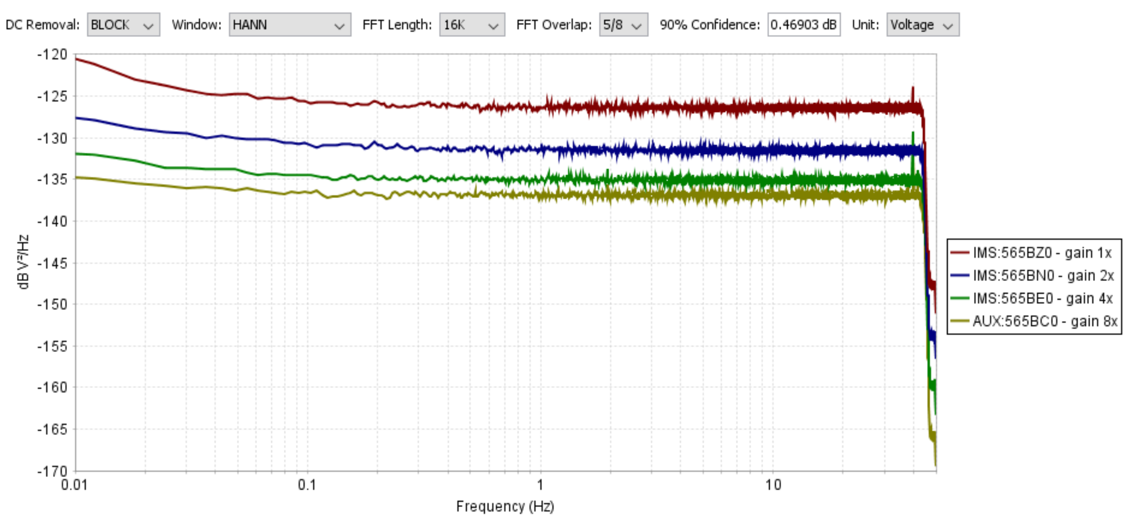

Figure 39 Self Noise 100 Hz Power Spectra: DAS-40565B

Both digitizers performed very similarly, with the exception of DAS-40565A at a gain of 2x exhibiting elevated noise below 0.1 Hz. Also, as expected, there are diminishing returns to increasing the digitizer gain, especially at gains of 4x and 8x.

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

Table 27 Self Noise RMS: DAS-40565A

Frequency Passband	Z - gain 1x		N - gain 2x		E - gain 4x		X/C - gain 8x	
	Volts	Counts	Volts	Counts	Volts	Counts	Volts	Counts
0 Hz - 10 Hz (20 sps)	1.484 uV rms	1.484 cnt rms	0.825 uV rms	1.649 cnt rms	0.527 uV rms	2.108 cnt rms	0.429 uV rms	3.431 cnt rms
0 Hz - 20 Hz (40 sps)	2.069 uV rms	2.069 cnt rms	1.206 uV rms	2.294 cnt rms	0.779 uV rms	2.958 cnt rms	0.638 uV rms	4.832 cnt rms
0 Hz - 50 Hz (100 sps)	3.247 uV rms	3.247 cnt rms	1.795 uV rms	3.590 cnt rms	1.163 uV rms	4.652 cnt rms	0.953 uV rms	7.621 cnt rms
20 mHz - 1 Hz	0.500 uV rms	0.500 cnt rms	0.289 uV rms	0.577 cnt rms	0.176 uV rms	0.704 cnt rms	0.144 uV rms	1.152 cnt rms
20 mHz - 4 Hz	0.982 uV rms	0.982 cnt rms	0.548 uV rms	1.096 cnt rms	0.350 uV rms	1.399 cnt rms	0.286 uV rms	2.288 cnt rms
20 mHz - 16 Hz	1.944 uV rms	1.944 cnt rms	1.076 uV rms	2.153 cnt rms	0.697 uV rms	2.788 cnt rms	0.570 uV rms	4.564 cnt rms
0.5 Hz - 16 Hz	1.911 uV rms	1.911 cnt rms	1.055 uV rms	2.109 cnt rms	0.686 uV rms	2.743 cnt rms	0.561 uV rms	4.491 cnt rms

Table 28 Self Noise RMS: DAS-40565B

Frequency Passband	Z - gain 1x		N - gain 2x		E - gain 4x		X/C - gain 8x	
	Volts	Counts	Volts	Counts	Volts	Counts	Volts	Counts
0 Hz - 10 Hz (20 sps)	1.462 uV rms	1.462 cnt rms	0.806 uV rms	1.612 cnt rms	0.529 uV rms	2.117 cnt rms	0.426 uV rms	3.404 cnt rms
0 Hz - 20 Hz (40 sps)	2.032 uV rms	2.032 cnt rms	1.125 uV rms	2.251 cnt rms	0.743 uV rms	2.971 cnt rms	0.600 uV rms	4.802 cnt rms
0 Hz - 50 Hz (100 sps)	3.178 uV rms	3.178 cnt rms	1.765 uV rms	3.530 cnt rms	1.169 uV rms	4.675 cnt rms	0.948 uV rms	7.583 cnt rms
20 mHz - 1 Hz	0.487 uV rms	0.487 cnt rms	0.270 uV rms	0.540 cnt rms	0.177 uV rms	0.707 cnt rms	0.143 uV rms	1.142 cnt rms
20 mHz - 4 Hz	0.960 uV rms	0.960 cnt rms	0.532 uV rms	1.064 cnt rms	0.352 uV rms	1.407 cnt rms	0.284 uV rms	2.272 cnt rms
20 mHz - 16 Hz	1.903 uV rms	1.903 cnt rms	1.058 uV rms	2.115 cnt rms	0.700 uV rms	2.800 cnt rms	0.567 uV rms	4.534 cnt rms
0.5 Hz - 16 Hz	1.871 uV rms	1.871 cnt rms	1.040 uV rms	2.080 cnt rms	0.689 uV rms	2.755 cnt rms	0.558 uV rms	4.462 cnt rms

The first three rows of values in the tables above contain the total RMS noise in the recording channel for each of the 20, 40, and 100 Hz sample rates. The remaining rows contain noise values for common IMS frequency passbands.

Comparing the total RMS noise across the various frequency passbands, the two digitizers are very similar in their performance. As expected, the total noise increases with larger frequency passbands. Increasing the gain level at 4x and 8x results in higher total self-noise measured in counts again confirming that there are diminishing returns to these increased gain levels.

Digitizer self-noise values are reported in the table below 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 +/- 0.47 dB based upon the number of time-windows and the resulting spectral averaging that was performed when computing the power spectral densities.

Table 29 Self-Noise PSD

	DAS-40565A				DAS-40565B			
Frequency (Hz)	Z (gain 1x)	N (gain 2x)	E (gain 4x)	X/C (gain 8x)	Z (gain 1x)	N (gain 2x)	E (gain 4x)	X/C (gain 8x)
0.0100	-121.27	-122.96	-131.85	-134.09	-120.12	-127.49	-131.63	-134.10
0.0125	-122.46	-123.74	-132.78	-134.76	-121.53	-128.21	-132.40	-135.24
0.0160	-122.95	-123.88	-132.49	-135.30	-122.62	-128.83	-132.70	-135.61
0.0200	-123.19	-124.36	-133.12	-135.33	-123.82	-129.19	-133.14	-135.41
0.0250	-123.32	-124.64	-133.51	-135.33	-123.61	-129.37	-133.88	-135.93
0.0315	-124.00	-125.62	-134.18	-135.68	-124.37	-129.44	-133.55	-136.13
0.0400	-124.05	-126.16	-133.94	-135.60	-124.91	-130.12	-134.06	-135.95
0.0500	-125.09	-127.25	-134.15	-136.16	-124.96	-130.19	-133.83	-136.58
0.0630	-125.58	-128.49	-134.60	-136.83	-125.47	-130.33	-134.50	-136.45
0.0800	-125.25	-128.64	-134.80	-136.32	-125.35	-130.55	-134.53	-136.79
0.1000	-125.46	-129.59	-134.78	-136.55	-125.85	-130.94	-134.59	-136.64
0.1250	-125.89	-130.34	-134.88	-136.50	-125.85	-130.99	-135.04	-137.23
0.1600	-125.75	-130.43	-134.74	-136.72	-126.10	-130.92	-134.83	-136.89
0.2000	-125.94	-130.82	-134.79	-136.63	-125.81	-130.77	-135.06	-136.82
0.2500	-125.96	-131.06	-135.22	-136.77	-126.34	-131.23	-135.03	-136.73
0.3150	-126.03	-130.96	-135.15	-136.67	-125.97	-131.37	-135.03	-136.70
0.4000	-126.10	-131.14	-135.25	-136.90	-126.23	-131.53	-134.99	-136.78
0.5000	-125.96	-131.38	-134.98	-136.84	-126.29	-131.51	-134.99	-136.83
0.6300	-126.24	-131.46	-135.08	-136.93	-126.42	-131.69	-135.04	-136.86
0.8000	-126.13	-131.46	-135.03	-136.86	-126.42	-131.50	-135.10	-136.89
1.0000	-126.20	-131.39	-135.06	-136.95	-126.55	-131.49	-135.21	-136.98
1.2500	-126.27	-131.32	-135.09	-137.06	-126.37	-131.44	-135.02	-136.97
1.6000	-126.27	-131.41	-135.16	-136.88	-126.40	-131.50	-135.14	-136.99
2.0000	-126.25	-131.43	-135.18	-136.90	-126.45	-131.53	-135.16	-136.99
2.5000	-126.19	-131.41	-135.14	-136.93	-126.52	-131.56	-135.17	-136.95
3.1500	-126.22	-131.42	-135.20	-136.93	-126.45	-131.57	-135.07	-136.98
4.0000	-126.31	-131.45	-135.18	-136.91	-126.37	-131.58	-135.16	-136.94
5.0000	-126.29	-131.44	-135.21	-136.94	-126.48	-131.58	-135.15	-136.97
6.3000	-126.31	-131.42	-135.18	-136.95	-126.51	-131.64	-135.18	-136.97
8.0000	-126.30	-131.44	-135.18	-136.94	-126.44	-131.57	-135.18	-137.03
10.0000	-126.27	-131.44	-135.24	-136.93	-126.46	-131.59	-135.18	-136.99
12.5000	-126.30	-131.48	-135.20	-136.95	-126.51	-131.61	-135.15	-136.97
16.0000	-126.27	-131.44	-135.19	-136.93	-126.48	-131.59	-135.14	-136.97
20.0000	-126.31	-131.46	-135.20	-136.93	-126.50	-131.59	-135.17	-136.95
25.0000	-126.32	-131.45	-135.22	-136.95	-126.49	-131.58	-135.17	-136.96
31.5000	-126.30	-131.47	-135.23	-136.93	-126.47	-131.59	-135.20	-136.98
40.0000	-126.30	-131.46	-135.23	-136.93	-126.47	-131.59	-135.16	-136.97

3.9 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.

3.9.1 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).

3.9.2 Configuration

There is no test configuration for the dynamic range test.

3.9.3 Analysis

The dynamic range over a given passband 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 to convert them to full scale peak values. The passband over which the noise is integrated should be selected to be consistent with the application passband and the sampling rate that is being used.

3.9.4 Result

The following tables contain the dynamic ranges that were measured at the various frequency passbands and gain levels.

Table 30 Dynamic Range: DAS-40565A

	Z - gain 1x (20 Vp)	N - gain 2x (10 Vp)	E - gain 4x (5 Vp)	X/C - gain 8x (2.5 Vp)
0 Hz - 10 Hz (20 sps)	139.58 dB	138.66 dB	136.53 dB	132.31 dB
0 Hz - 20 Hz (40 sps)	136.69 dB	135.80 dB	133.59 dB	129.33 dB
0 Hz - 50 Hz (100 sps)	132.78 dB	131.91 dB	129.66 dB	125.37 dB
20 mHz - 1 Hz	149.03 dB	147.78 dB	146.06 dB	141.78 dB
20 mHz - 4 Hz	143.17 dB	142.22 dB	140.09 dB	135.82 dB
20 mHz - 16 Hz	137.24 dB	136.35 dB	134.11 dB	129.82 dB
0.5 Hz - 16 Hz	137.39 dB	136.53 dB	134.24 dB	129.96 dB

Table 31 Dynamic Range: DAS-40565B

	Z - gain 1x (20 Vp)	N - gain 2x (10 Vp)	E - gain 4x (5 Vp)	X/C - gain 8x (2.5 Vp)
0 Hz - 10 Hz (20 sps)	139.71 dB	138.86 dB	136.49 dB	132.37 dB
0 Hz - 20 Hz (40 sps)	136.85 dB	135.96 dB	133.55 dB	129.38 dB
0 Hz - 50 Hz (100 sps)	132.97 dB	132.06 dB	129.61 dB	125.41 dB
20 mHz - 1 Hz	149.26 dB	148.36 dB	146.02 dB	141.86 dB
20 mHz - 4 Hz	143.36 dB	142.47 dB	140.05 dB	135.88 dB
20 mHz - 16 Hz	137.42 dB	136.50 dB	134.07 dB	129.88 dB
0.5 Hz - 16 Hz	137.57 dB	136.65 dB	134.21 dB	130.02 dB

The first three rows of values in the tables above contain the dynamic ranges of the recording channel for each of the 20, 40, and 100 Hz sample rates. The remaining rows contain dynamic ranges for common IMS frequency passbands.

The Affinity digitizer channels were observed to have dynamic ranges between 133 - 149 dB at a gain of 1x, 132 – 148 dB at a gain of 2x, 130 – 146 dB at a gain of 4x, and 125 – 142 dB at a gain of 8x. There was an approximate 1 dB reduction in dynamic range when switching gains between 1x and 2x, a 2 dB reduction from 2x to 4x, and a 4 dB reduction from 4x to 8x. These values are consistent with the observed self-noise levels at each gain and the associated passbands

3.10 System Noise

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

3.10.1 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 $(Pa)^2$/Hz versus frequency.

3.10.2 Configuration

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.

3.10.3 Result

The PSD of the system noise is shown in the plots below. Only the noise data from DAS-40565B is shown, as the two digitizers self-noise performance were highly similar. Where available, reference sensor and background noise models are provided for comparison.

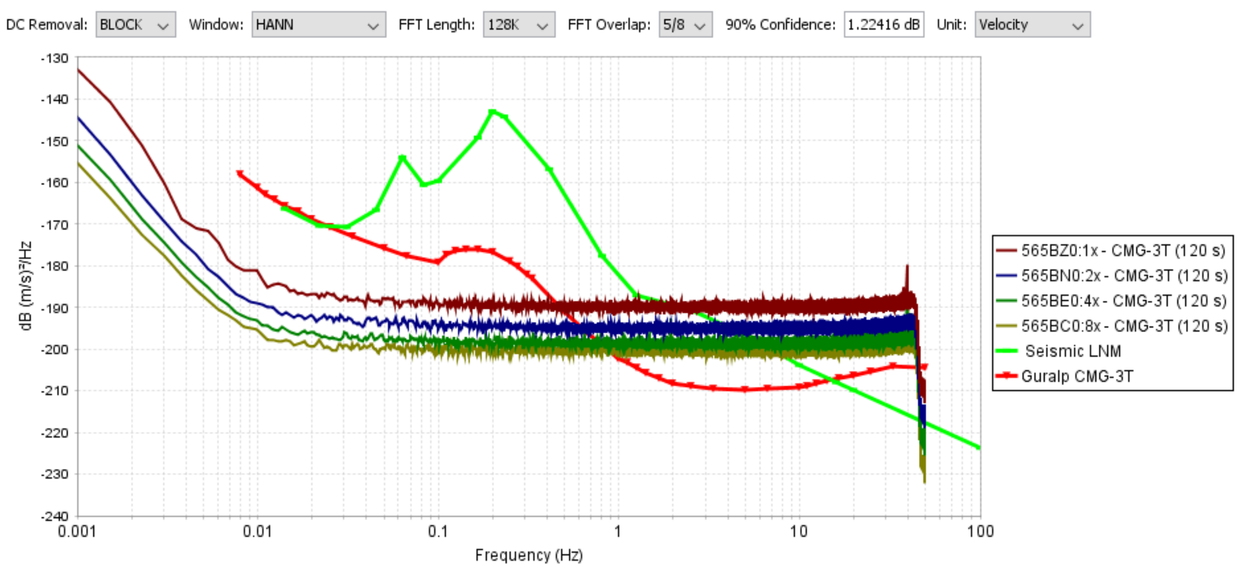

Figure 40 Seismic System Noise for Guralp CMG-3T (1500 V/(m/s) and 120 sec corner) at gains of 1, 2, 4, and 8

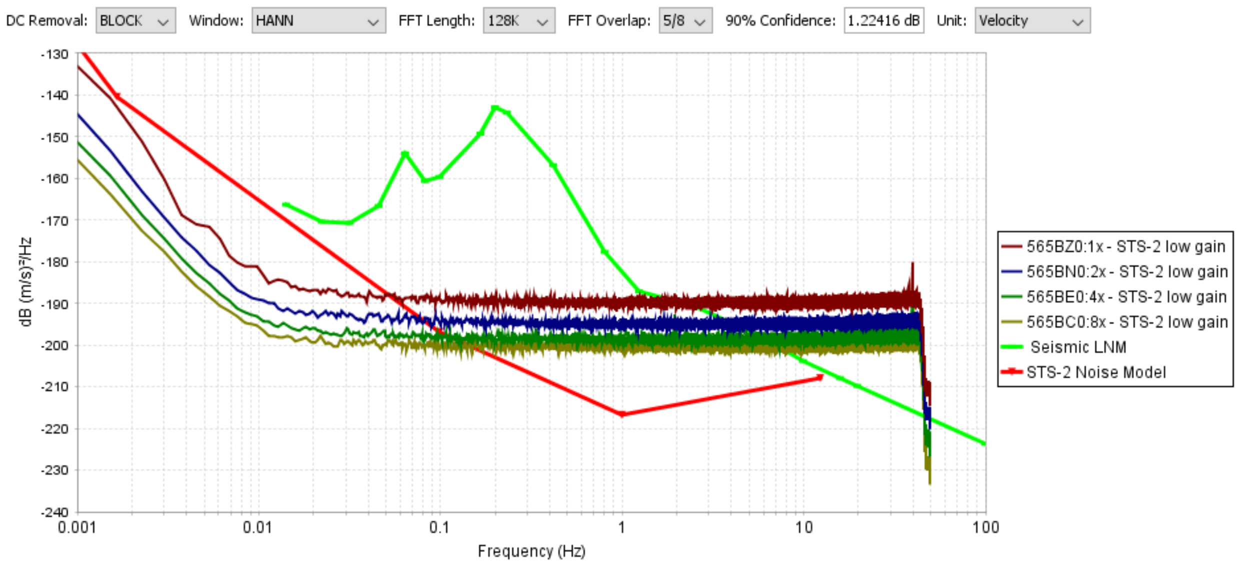

Figure 41 Seismic System Noise for STS-2 low gain at gains of 1, 2, 4, and 8

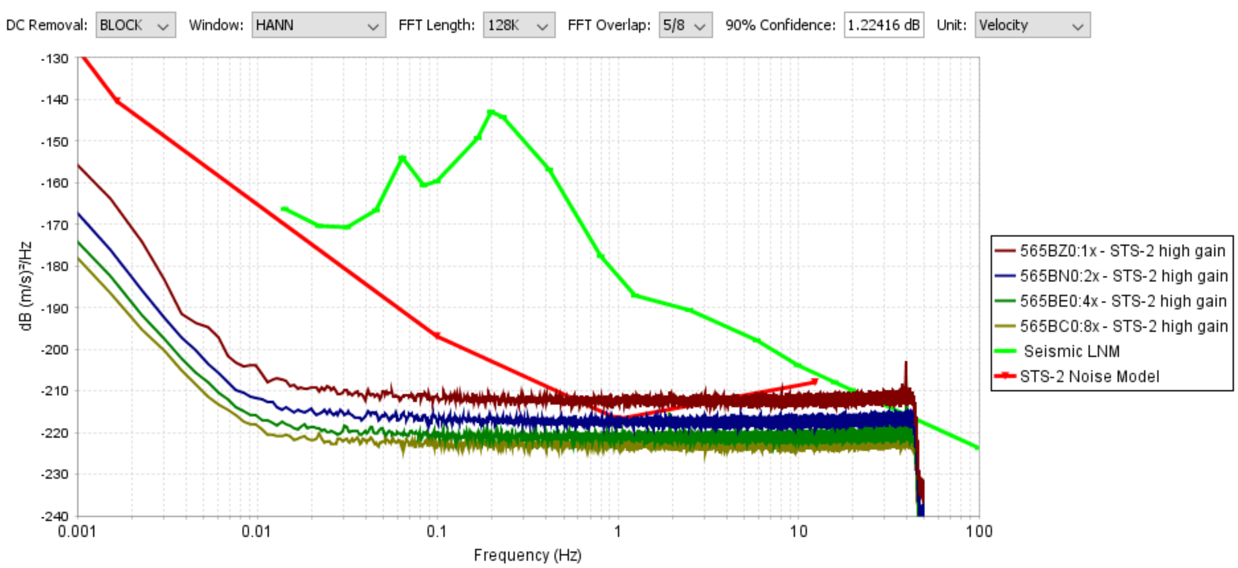

Figure 42 Seismic System Noise for STS-2 high gain at gains of 1, 2, 4, and 8

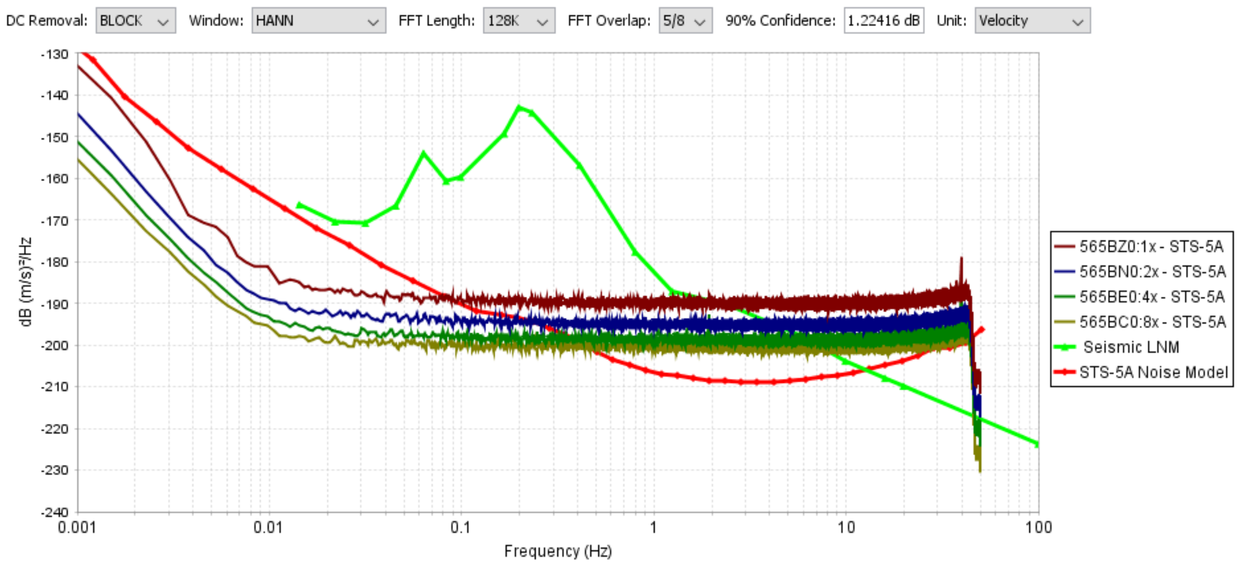

Figure 43 Seismic System Noise for Kinematrics STS-5A at gains of 1, 2, 4, and 8

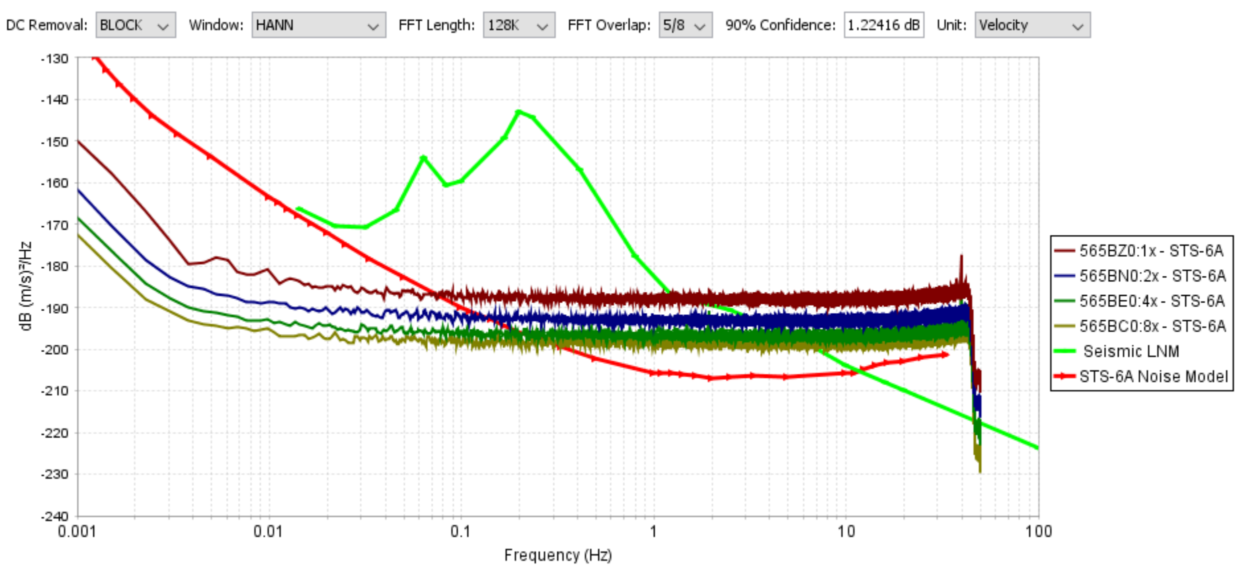

Figure 44 Seismic System Noise for Kinematrics STS-6A at gains of 1, 2, 4, and 8

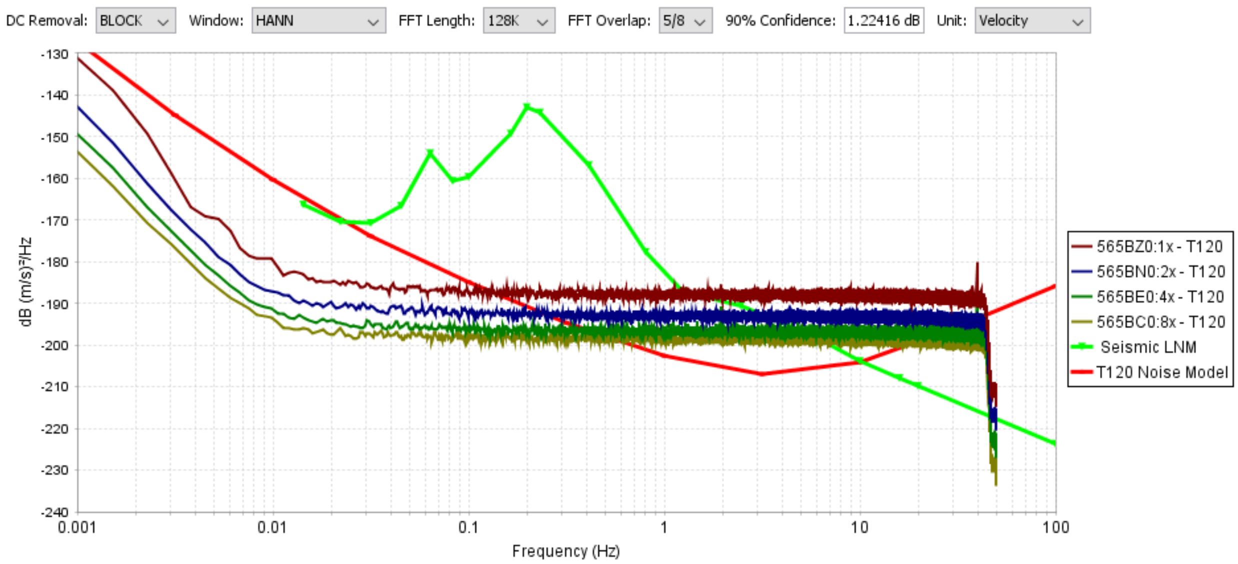

Figure 45 Seismic System Noise for Trillium 120 at gains of 1, 2, 4, and 8

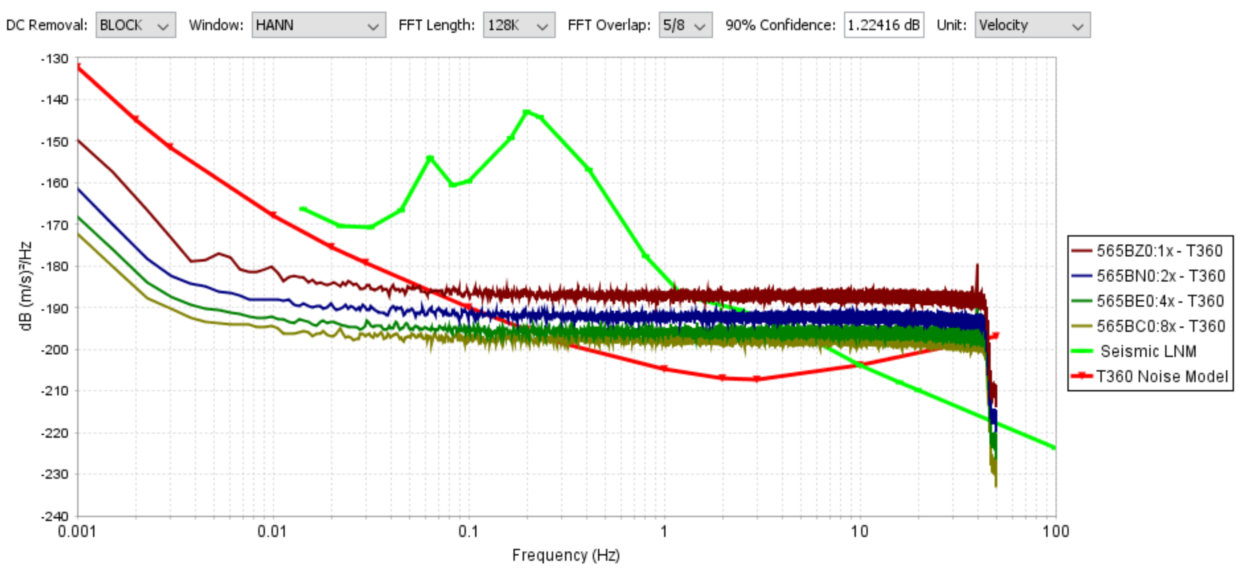

Figure 46 Seismic System Noise for Trillium 360 at gains of 1, 2, 4, and 8

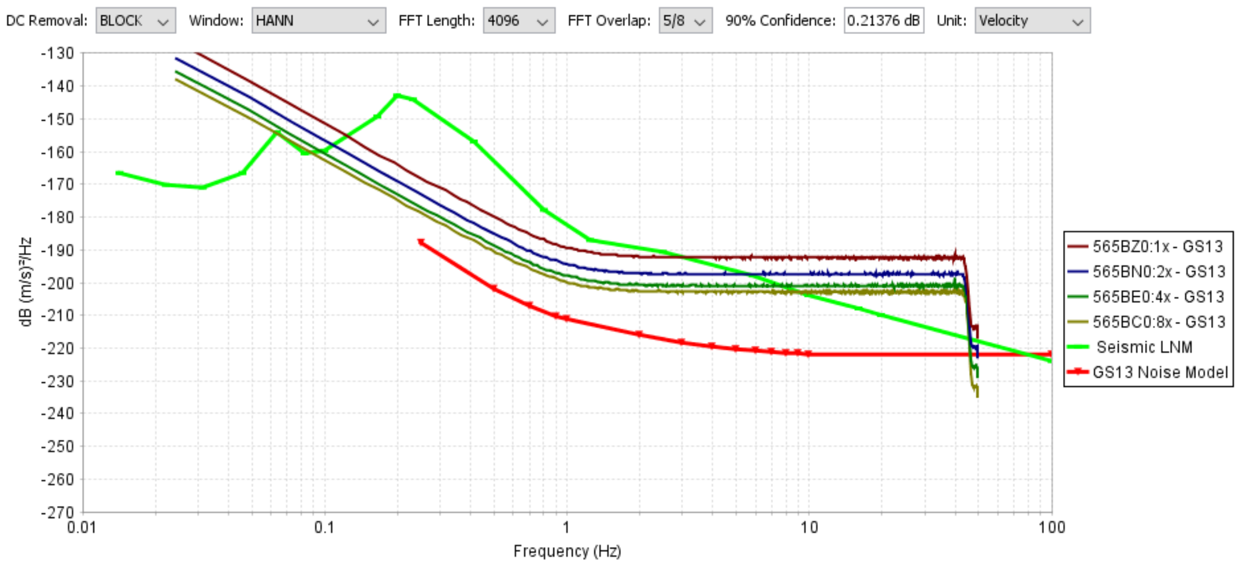

Figure 47 Seismic System Noise for Geotech GS13 at gains of 1, 2, 4, and 8

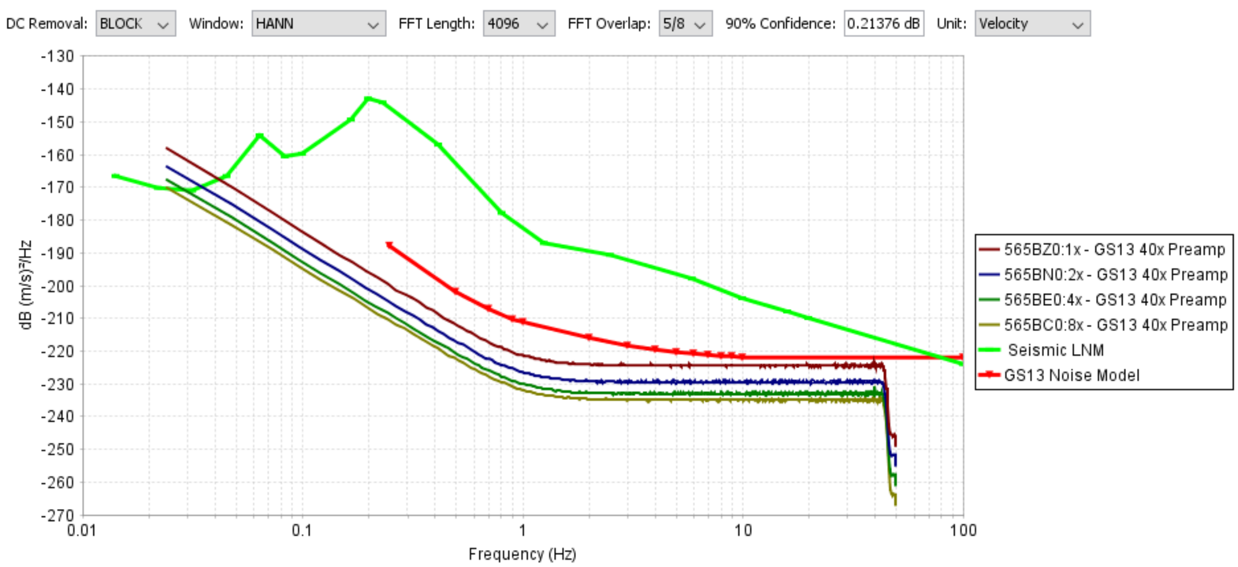

Figure 48 Seismic System Noise for Geotech GS13 and 40x Preamp at gains of 1, 2, 4, and 8

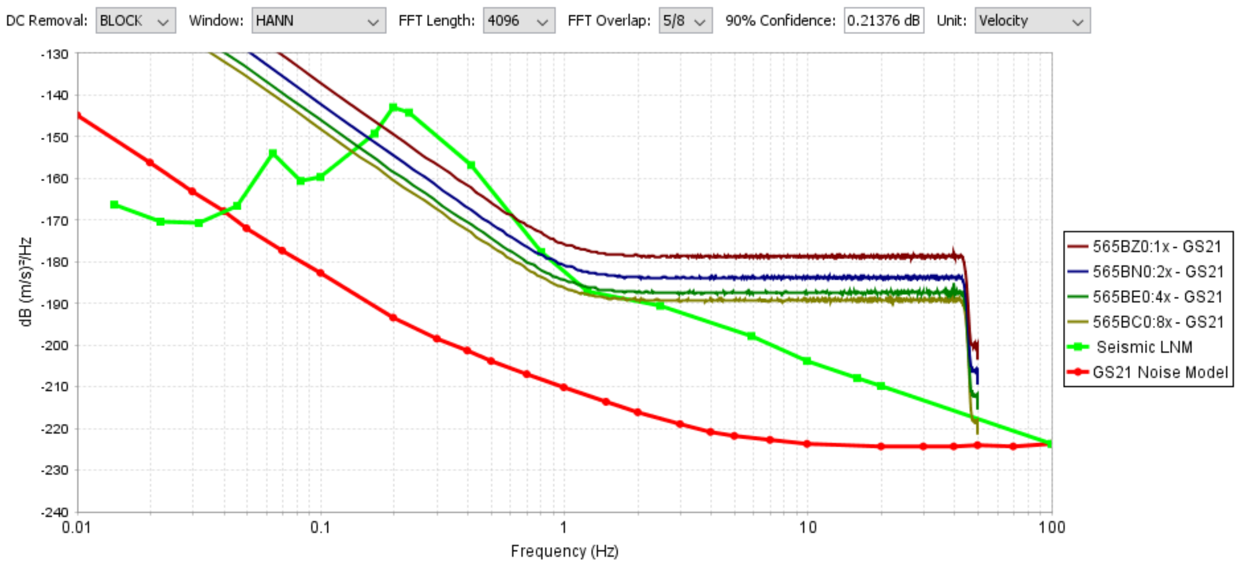

Figure 49 Seismic System Noise for Geotech GS21 at gains of 1, 2, 4, and 8

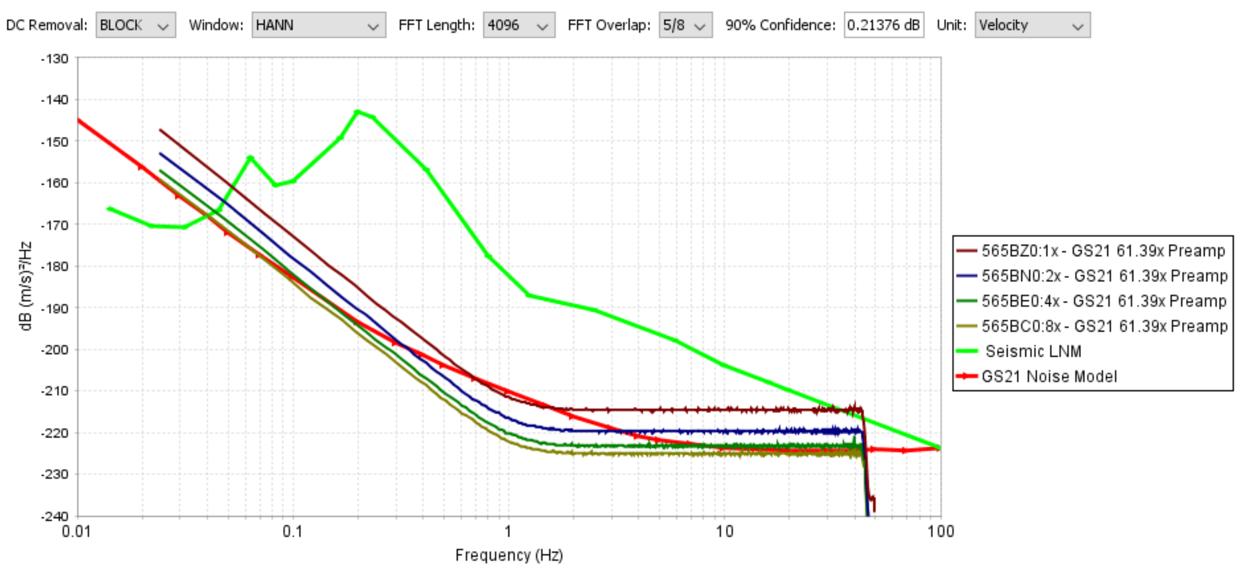

Figure 50 Seismic System Noise for Geotech GS21 and 61.39x Preamp at gains of 1, 2, 4, and 8

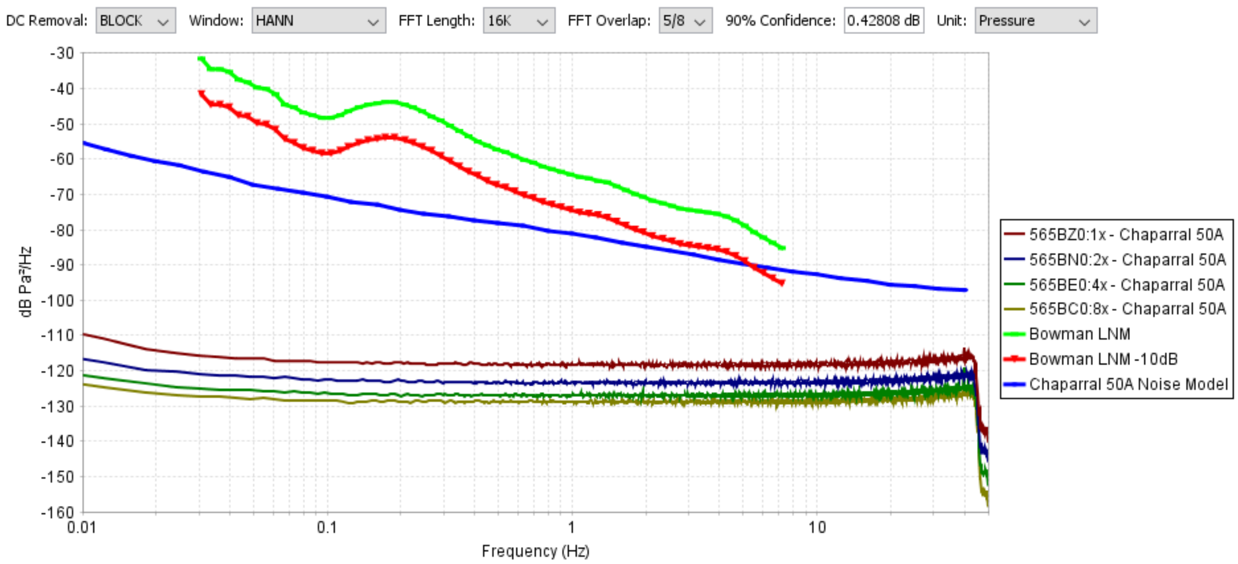

Figure 51 Infrasound System Noise for Chaparral 50A at gains of 1, 2, 4, and 8

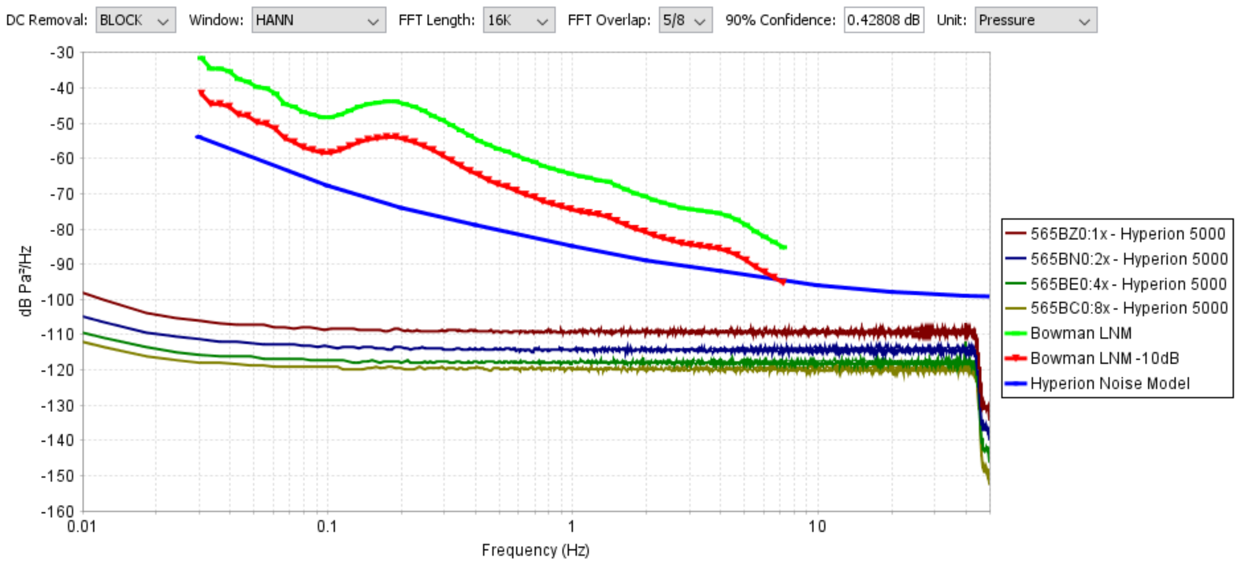

Figure 52 Infrasound System Noise for Hyperion 5000 at gains of 1, 2, 4, and 8

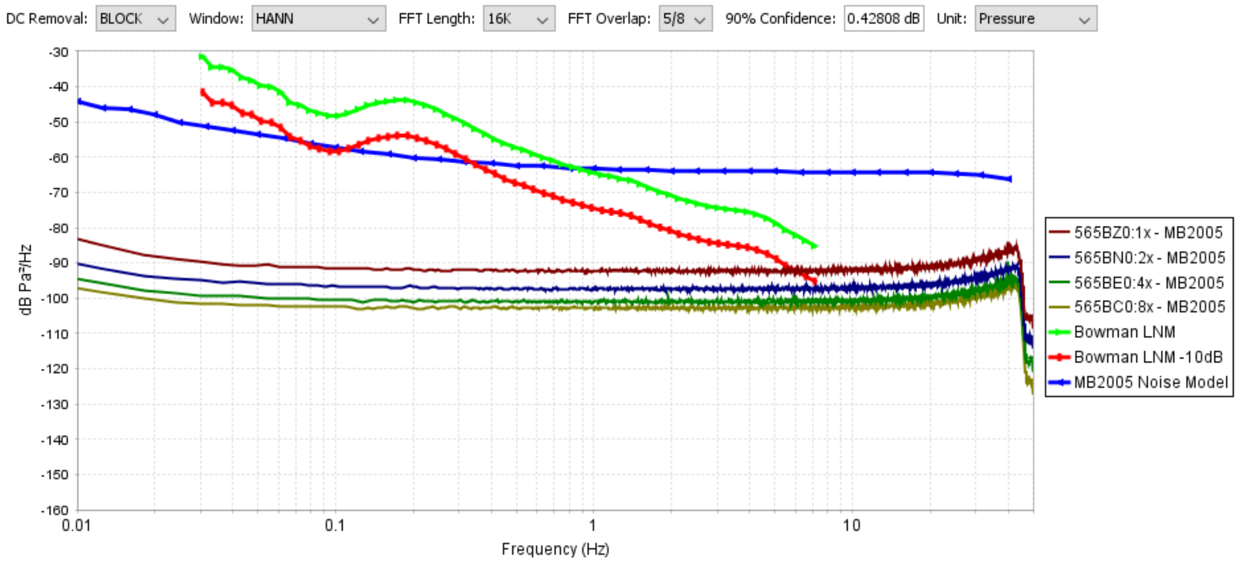

Figure 53 Infrasound System Noise for MB2005 at gains of 1, 2, 4, and 8

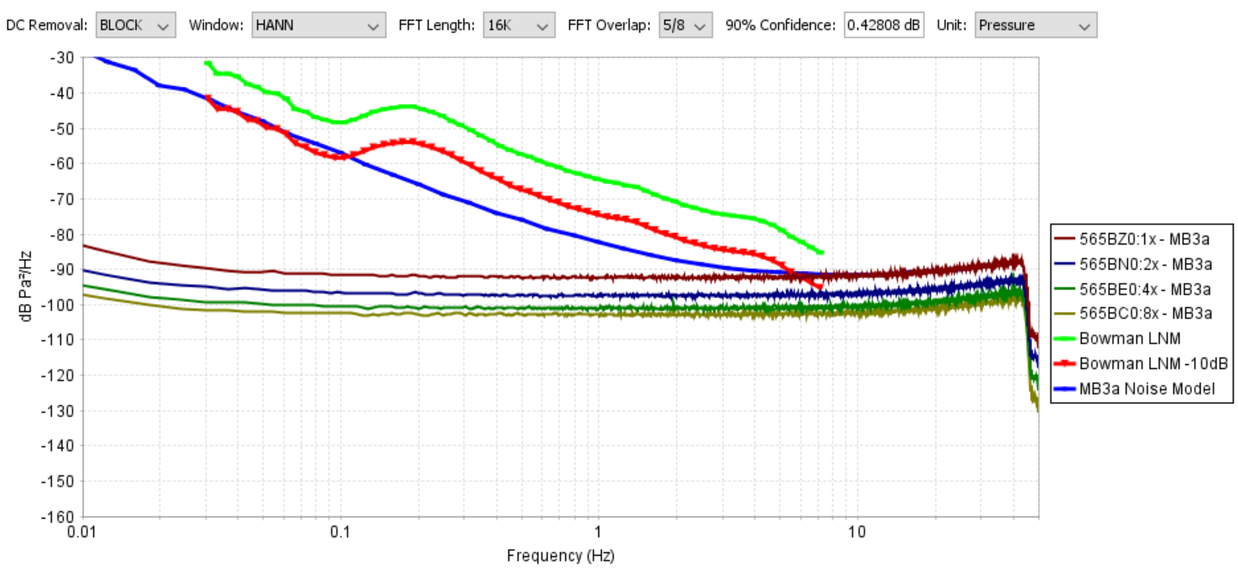

Figure 54 Infrasound System Noise for MB3a at gains of 1, 2, 4, and 8

3.11 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.

3.11.1 Measurand

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

3.11.2 Configuration

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

Figure 55 Temperature Self Noise Configuration Diagram

Figure 56 Temperature Self Noise Configuration Picture

Table 32 Self Noise Testbed Equipment

	Manufacturer / Model	Serial Number
50 (25x2) ohm Resistor	N/A	N/A
Temperature Chamber	ESPEC EPL-2H	ESPEC EPL-2H

The temperature chamber was programmed to cycle the Affinity digitizer for 10 hours at -10 C and 10 hours at +40 C before returning to +20 C during an overnight period.

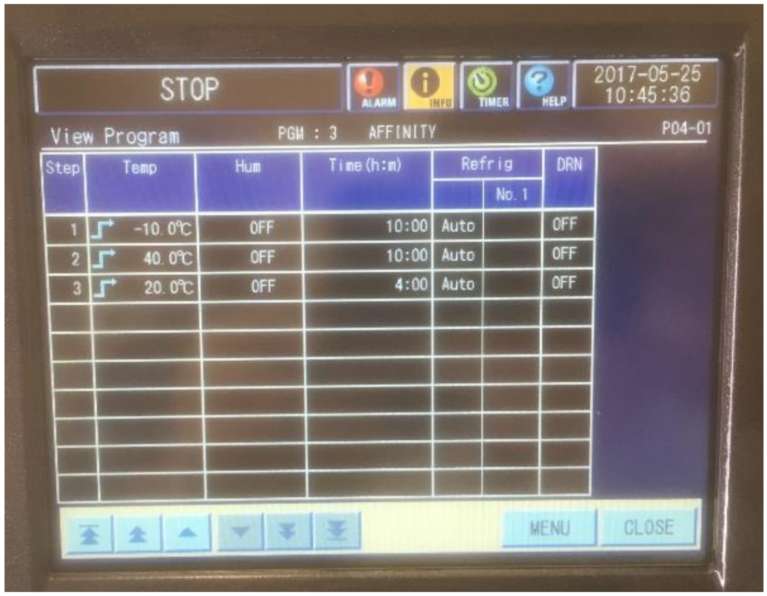

Figure 57 Temperature Chamber Program

3.11.3 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 (Merchant, 2011) from the time series using a 16k-sample Hann window for the 100 Hz sample rate data. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation passband 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.

3.11.4 Result

The time series plot from DAS-40565B is shown below. Only the data from 100 Hz is shown as the other sample rates are otherwise identical.

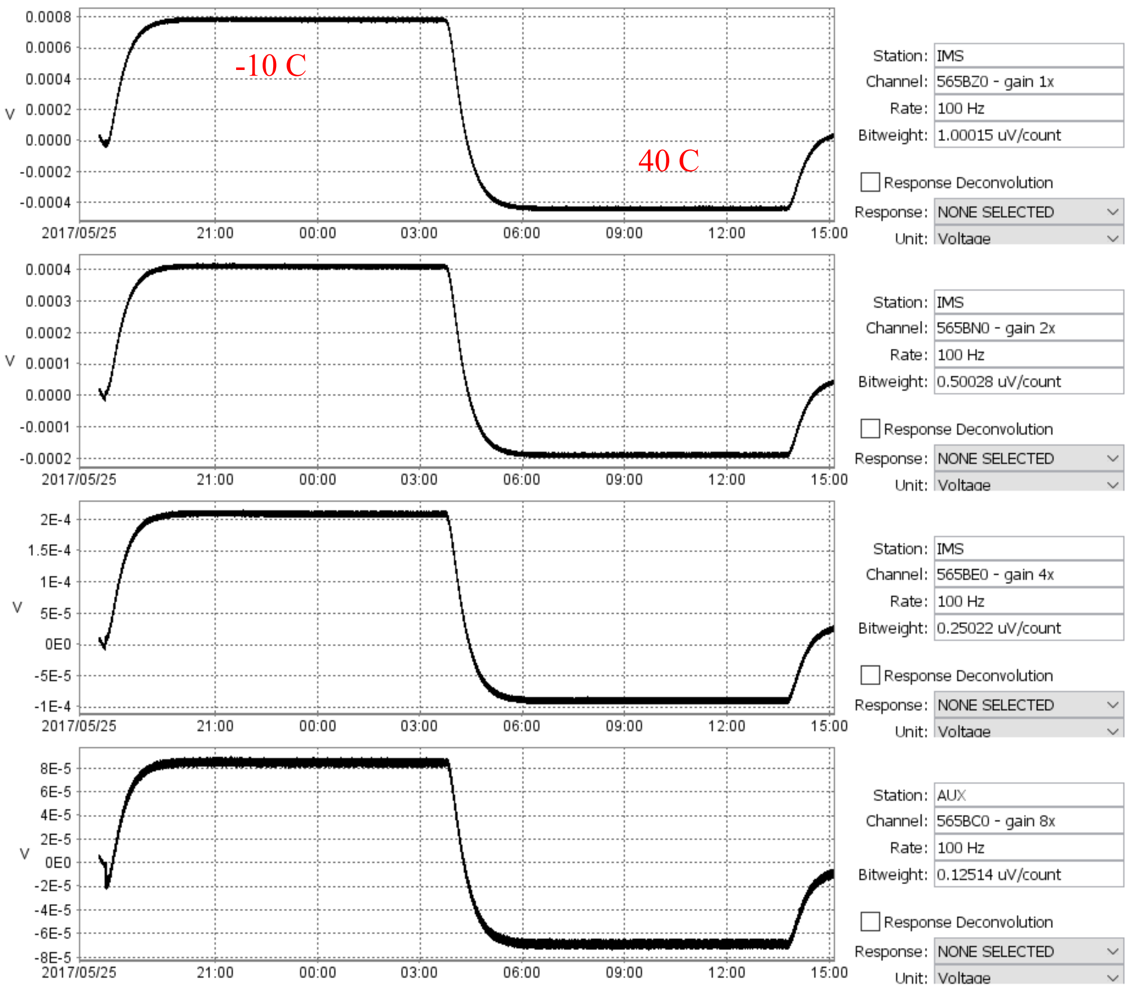

Figure 58 Temperature Self Noise Time Series, DAS-40565B

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

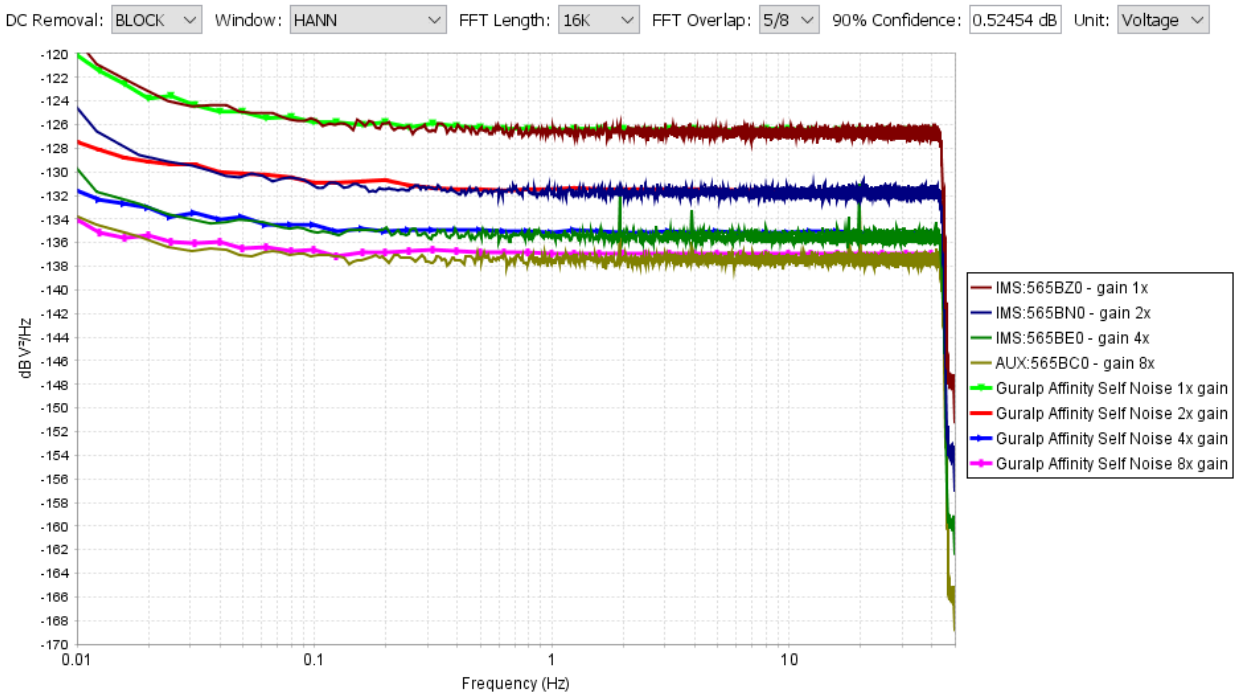

Figure 59 Temperature Self Noise Power Spectra, DAS-40565B, -10 C

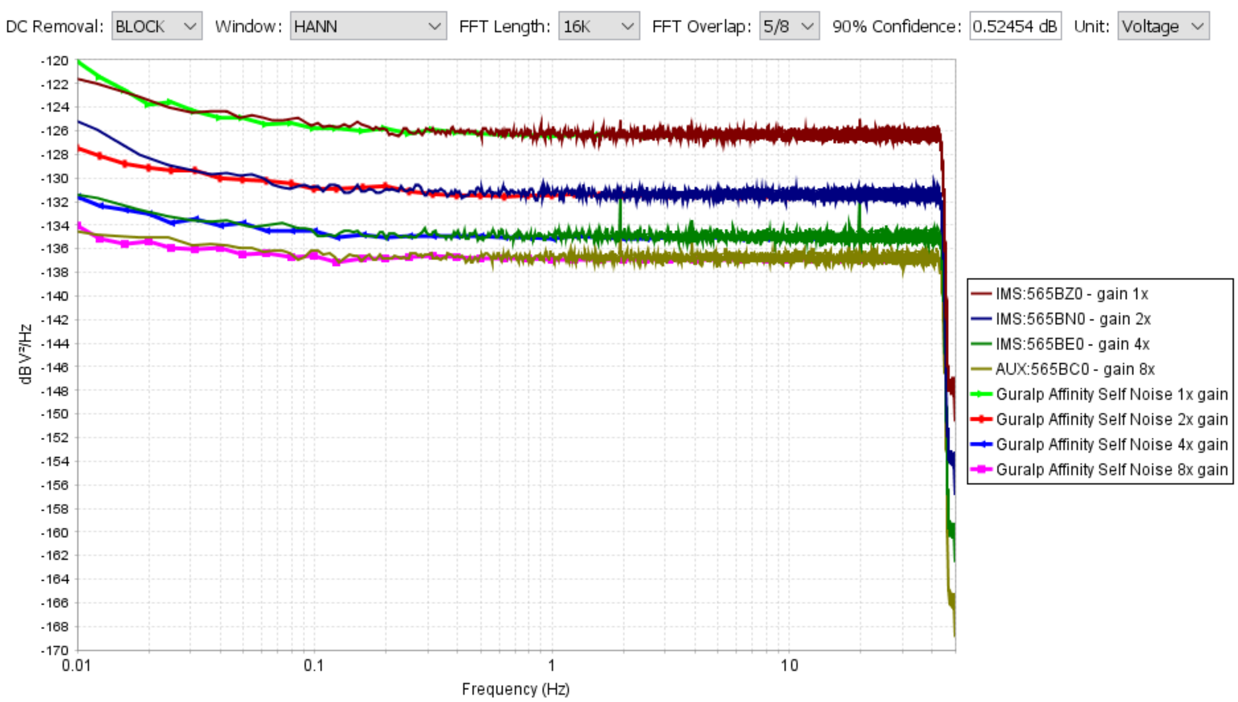

Figure 60 Temperature Self Noise Power Spectra, DAS-40565B, +40 C

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 change in the DC offset related to temperature.

Table 33 Temperature Self Noise DC Offset

Temperature	Z - gain 1x	N - gain 2x	E - gain 4x	X/C - gain 8x
-10 C	0.78 mV	0.41 mV	0.21 mV	0.085 mV
+40C	-0.44 mV	-0.19 mV	-0.09 mV	-0.069 mV
+20 C	-0.055 mV	-0.055 mV	0.03 mV	-0.006 mV

The DC offset of the Affinity digitizer channels were observed to shift as shown in the table above.

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 amplitude and 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.

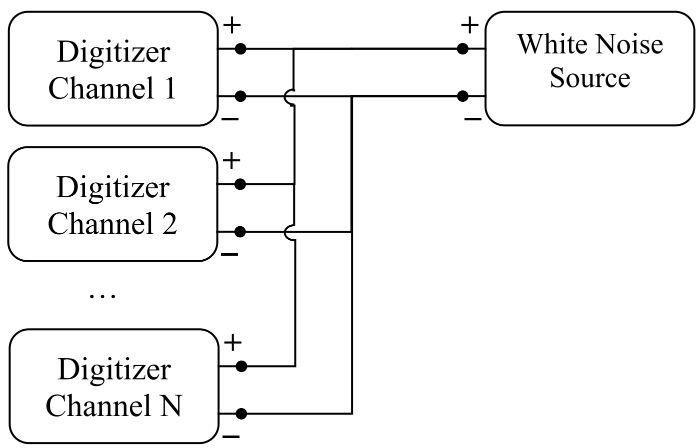

Figure 61 Response Verification Configuration Diagram

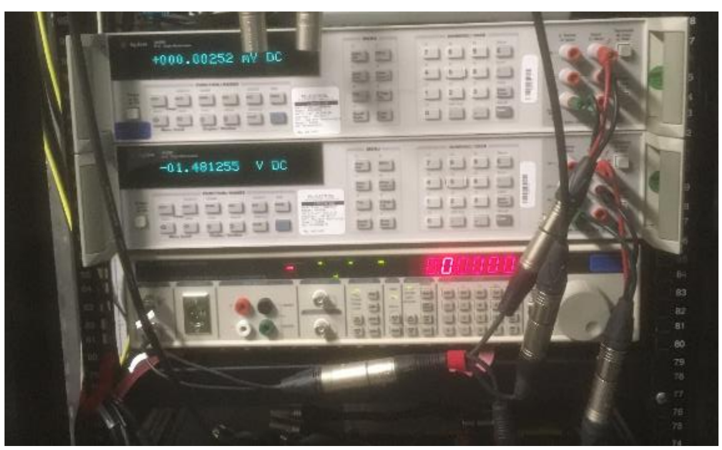

Figure 62 Response Verification Configuration Picture

Table 34 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 bit-weight, 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 the evaluated sample rates and gain configurations. In all cases, the coherence was identically 1.0 across the entire passband. Data was collected simultaneously at sample rates of 20 Hz, 40 Hz, and 100 Hz. The results were identical at the various sample rates, therefore only the 100 Hz data is shown below. The power spectra, coherence, relative amplitude, and relative phase are shown in the plots below.

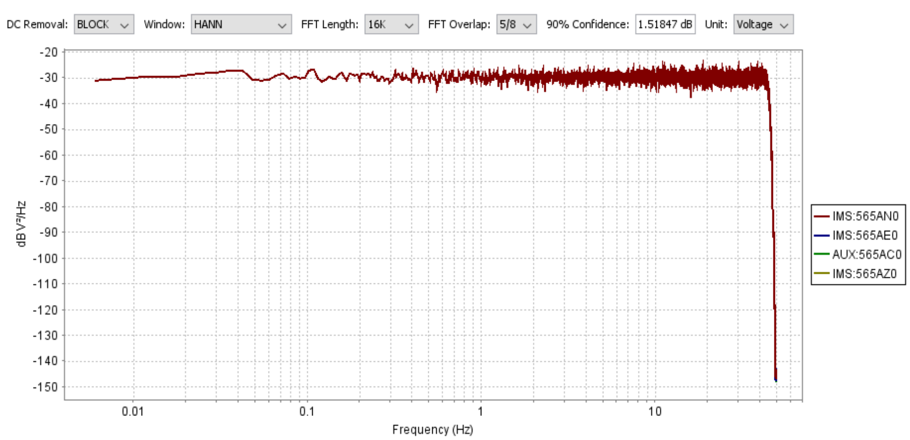

Figure 63 White Noise Power Spectra

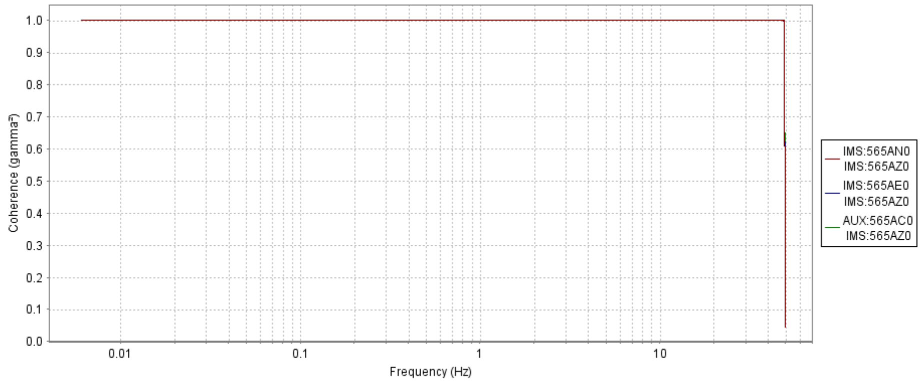

Figure 64 White Noise Coherence

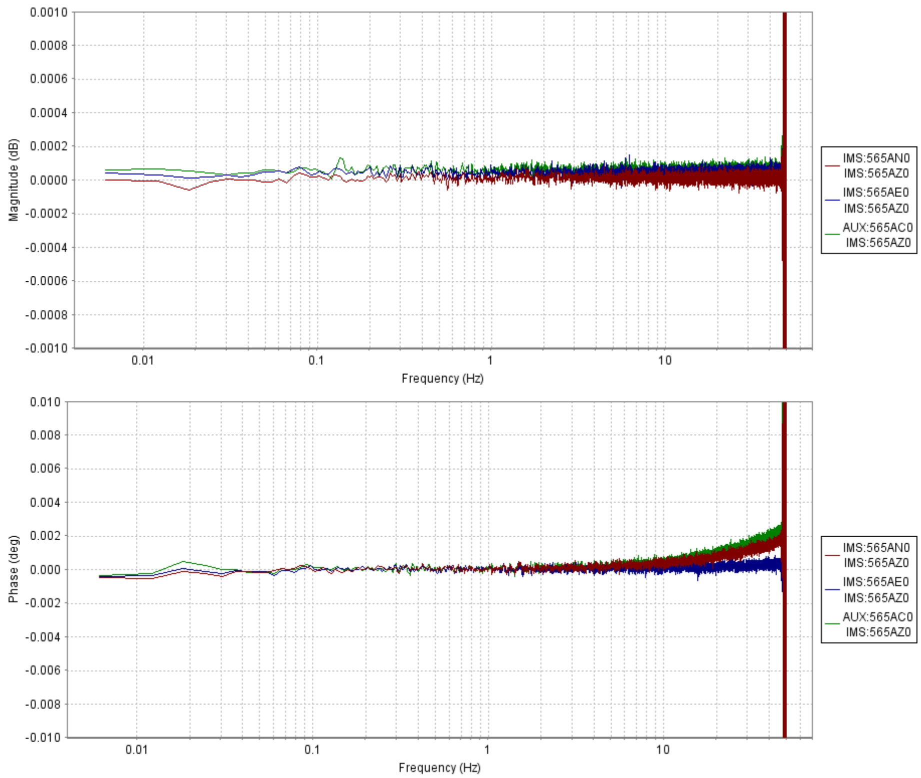

Figure 65 Relative Amplitude and Phase 100 Hz, Gain 1: DAS-40565A

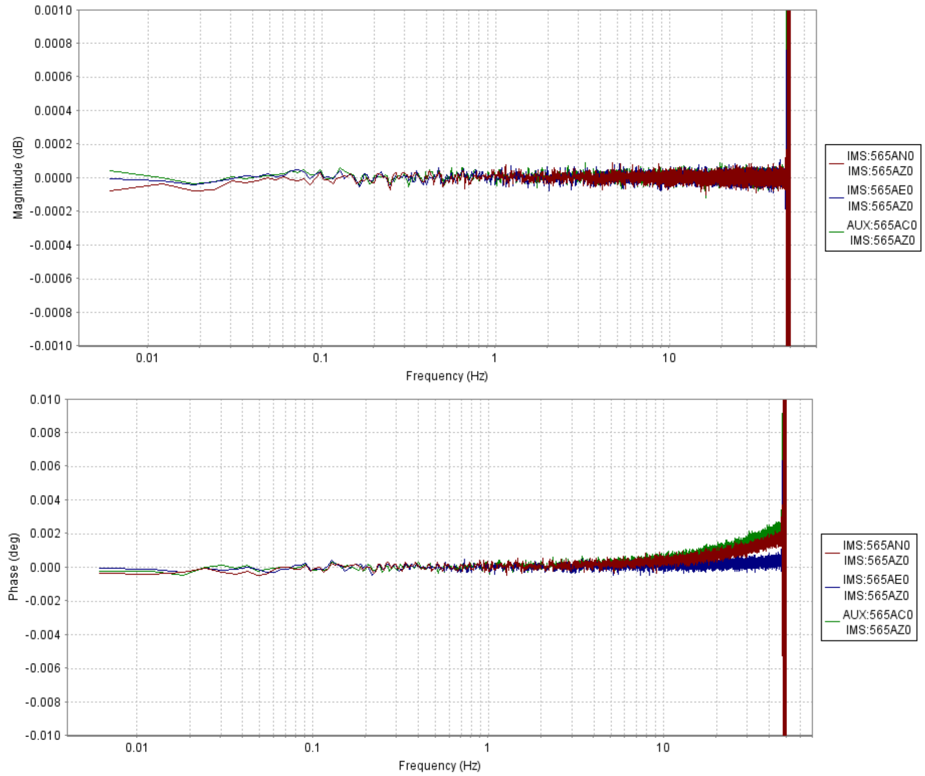

Figure 66 Relative Amplitude and Phase 100 Hz, Gain 2: DAS-40565A

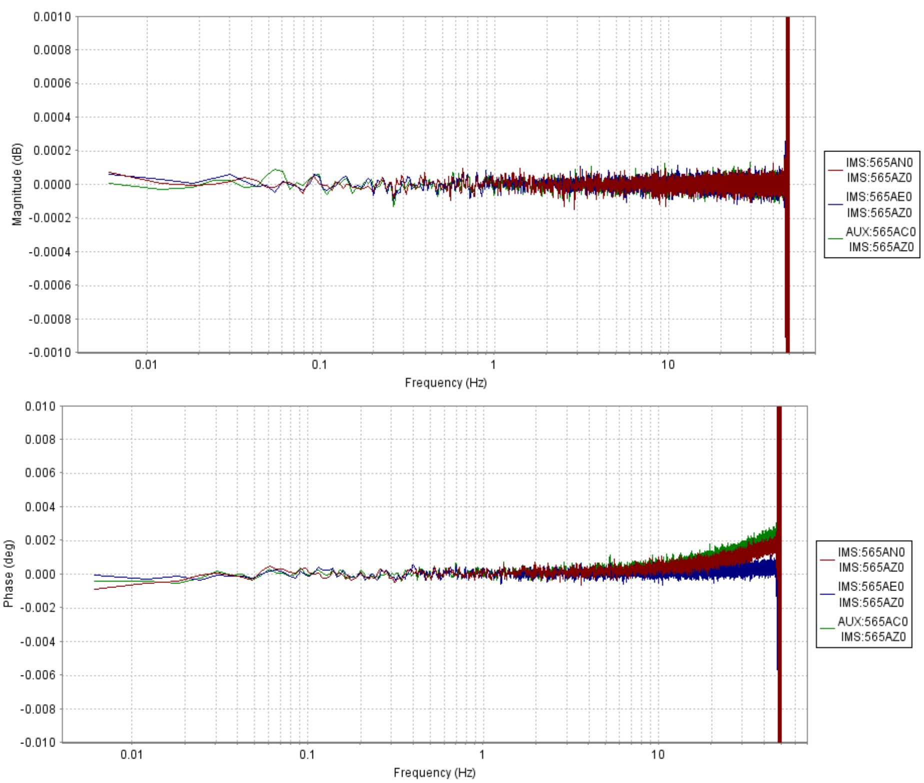

Figure 67 Relative Amplitude and Phase 100 Hz, Gain 4: DAS-40565A

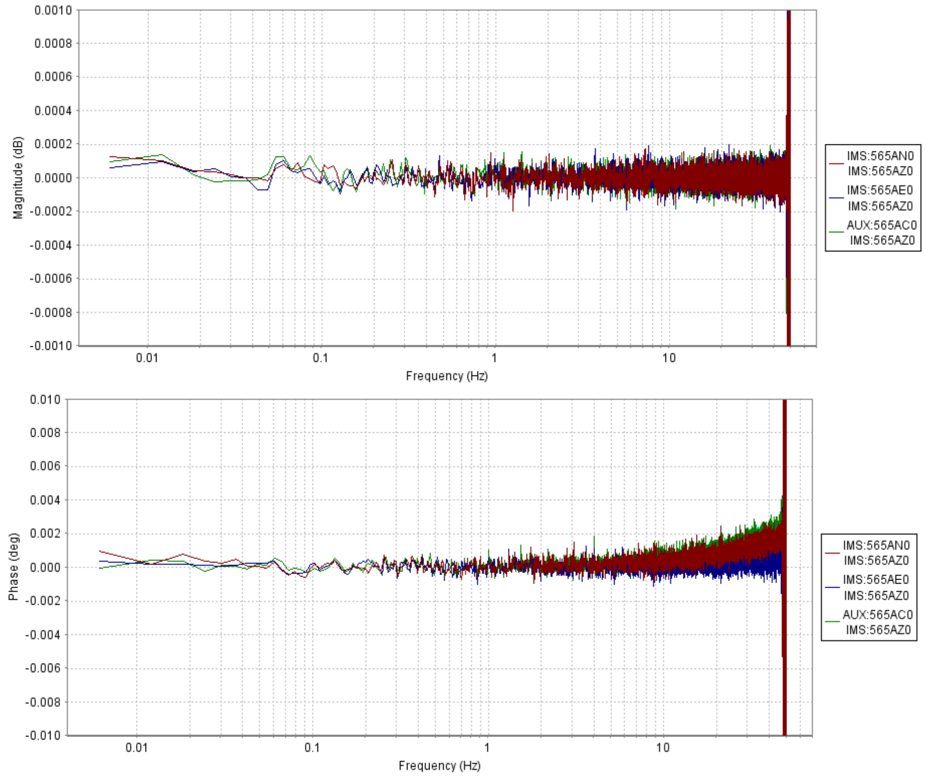

Figure 68 Relative Amplitude and Phase 100 Hz, Gain 8: DAS-40565A

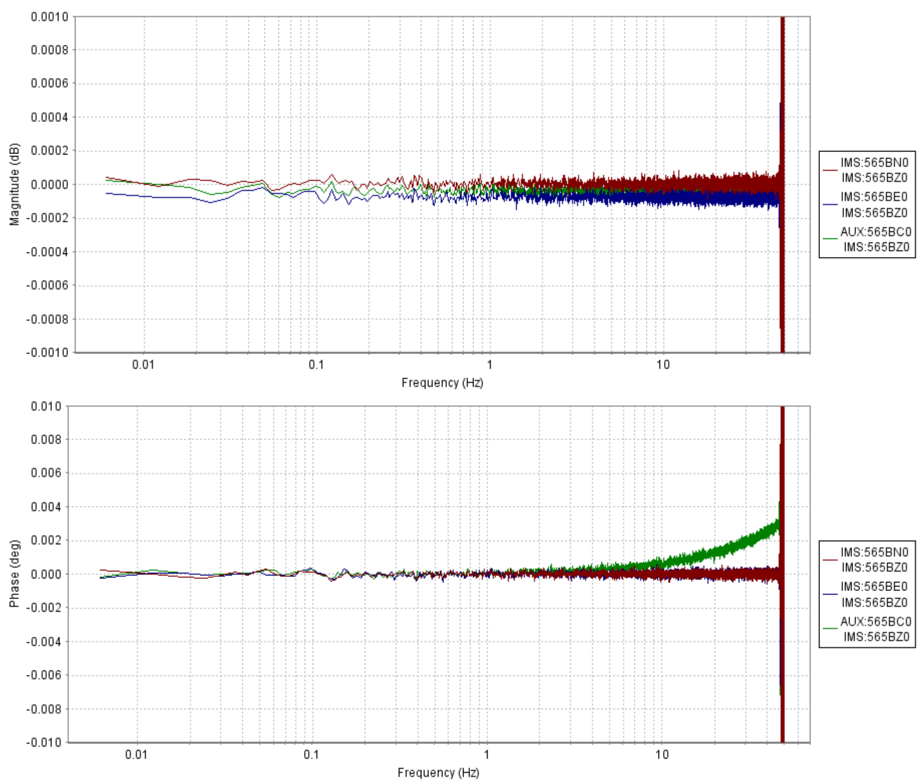

Figure 69 Relative Amplitude and Phase 100 Hz, Gain 1: DAS-40565B

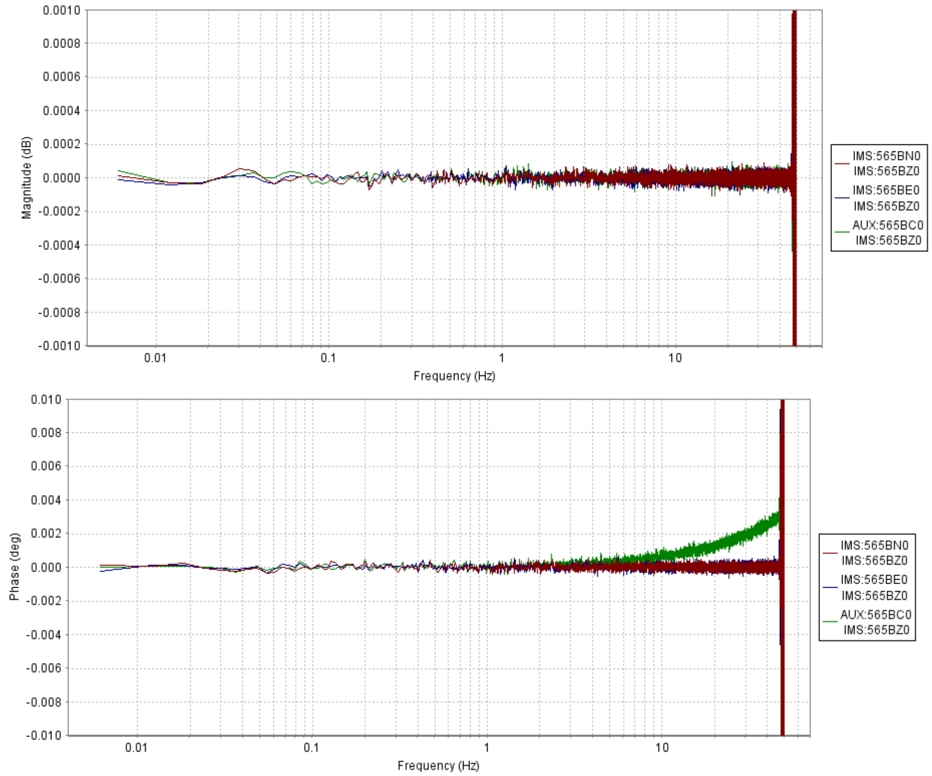

Figure 70 Relative Amplitude and Phase 100 Hz, Gain 2: DAS-40565B

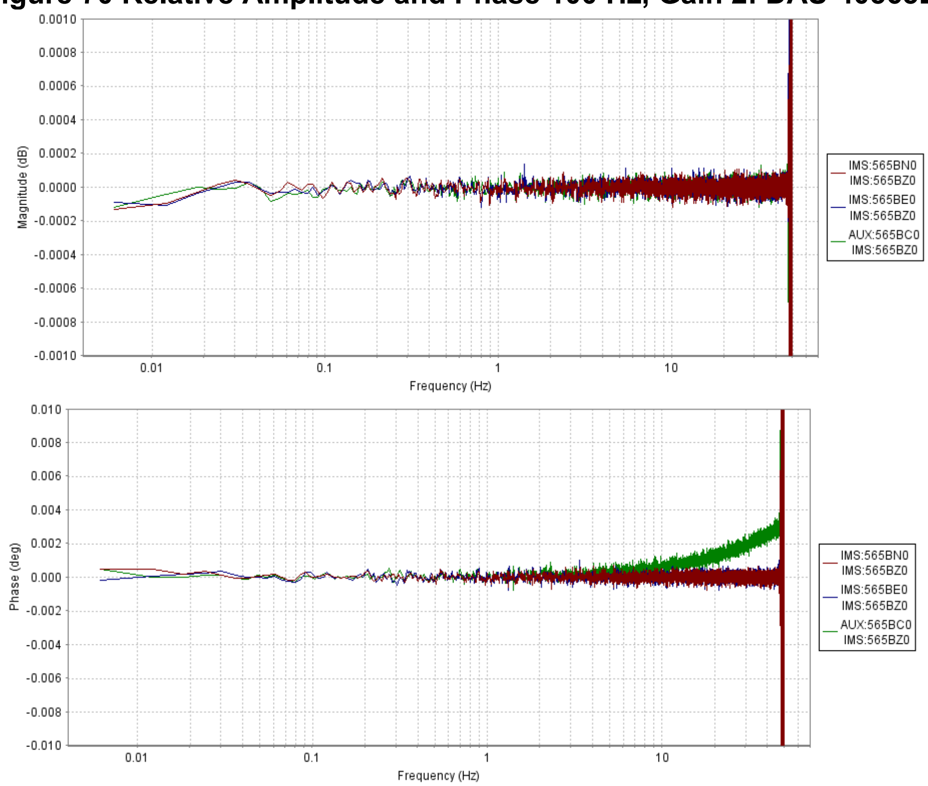

Figure 71 Relative Amplitude and Phase 100 Hz, Gain 4: DAS-40565B

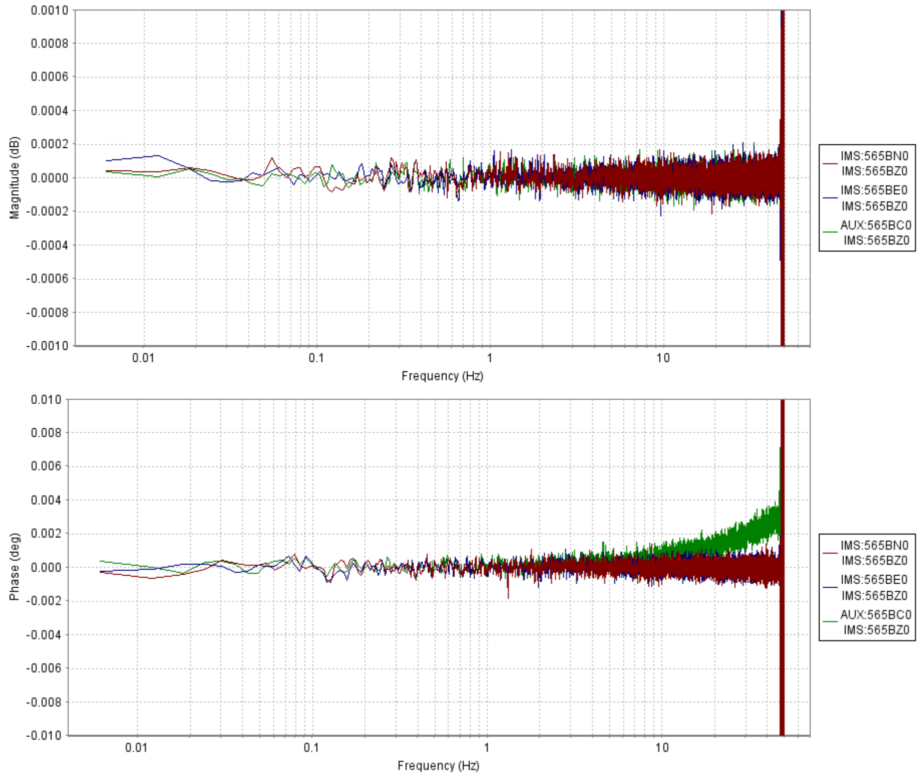

Figure 72 Relative Amplitude and Phase 100 Hz, Gain 8: DAS-40565B

In all cases, the relative amplitudes were effectively zero across the passband. This indicates that there were no differences in response between the digitizer channels and confirms that the bit-weights that were applied from the AC Accuracy test are valid. 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.

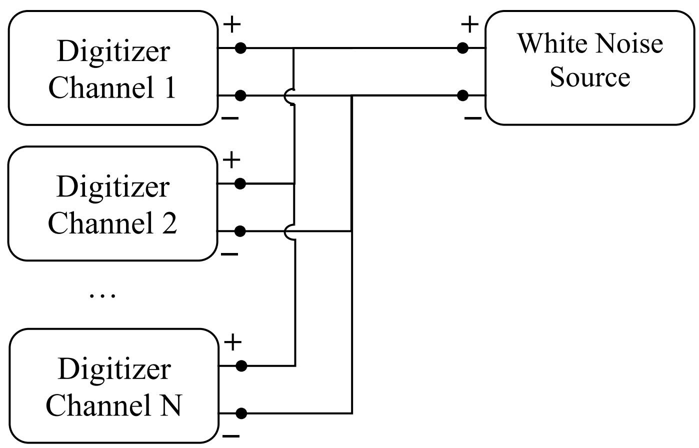

Figure 73 Relative Transfer Function Configuration Diagram

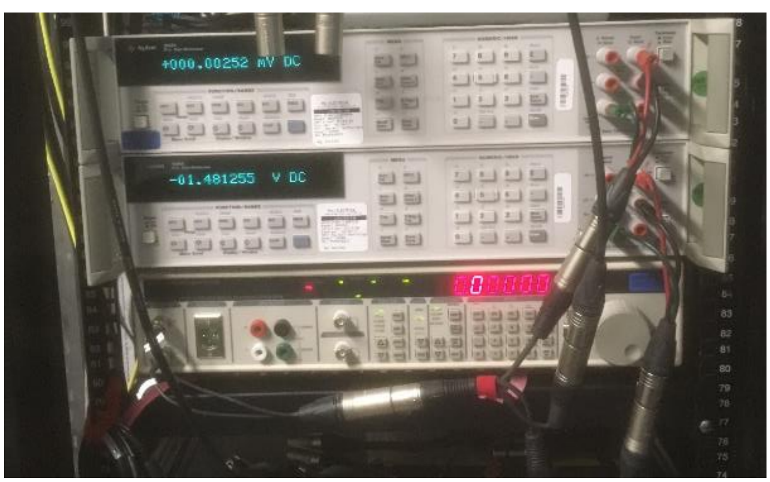

Figure 74 Relative Transfer Function Configuration Picture

Table 35 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 bit-weight, 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 (Merchant, 2011) from the power spectral density:

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

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 in the figures below for both digitizers at a gain of 1x and a sample rate of 100 Hz. The phase delay plots for other gains and sample rates are not shown as they are nearly identical. To the extent that delay is a constant time offset, the phase delay is observed to be linear with respect to frequency.

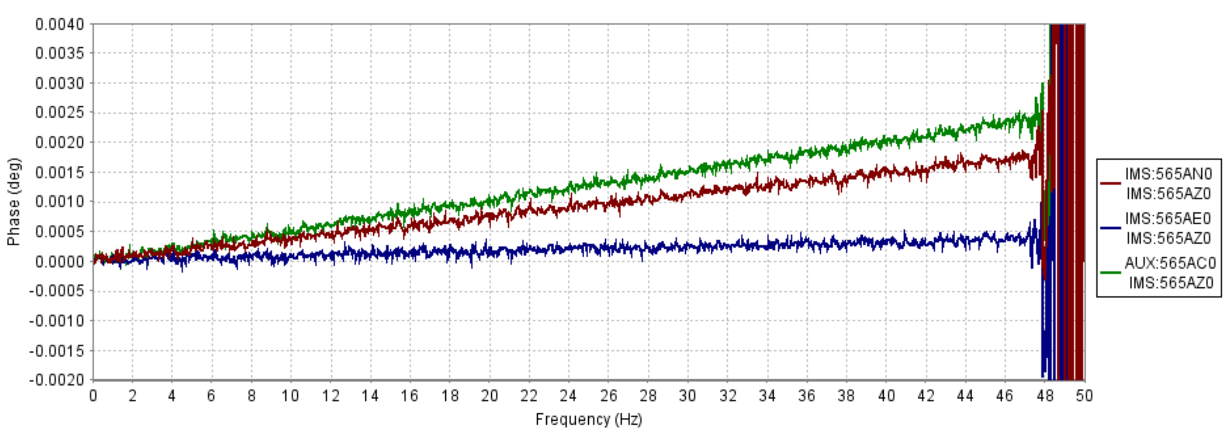

Figure 75 Relative Transfer Function DAS-40565A, Gain 1

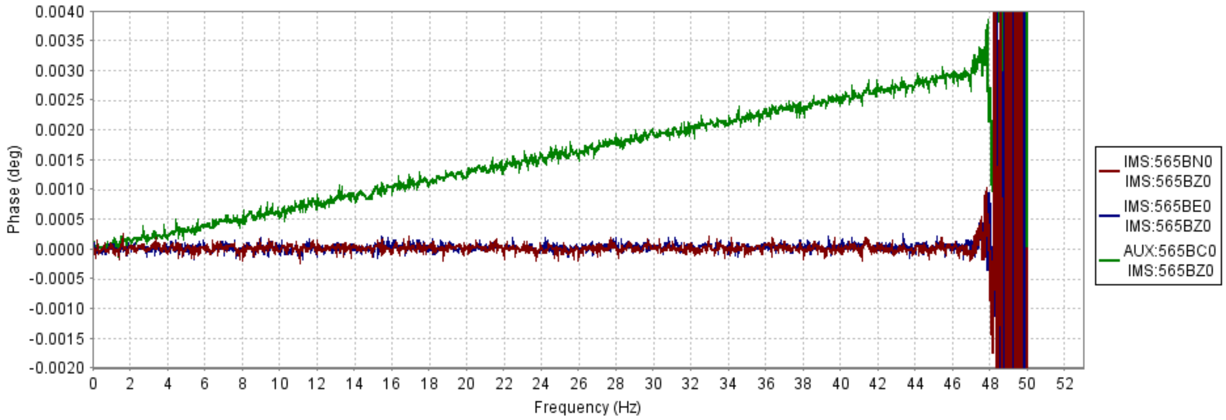

Figure 76 Relative Transfer Function DAS-40565B, Gain 1

All of the phase delays are indeed linear with respect to frequency. The constant channel-to-channel timing skew, relative to channel 1 (Z), corresponding to these phase delays is shown in the tables below.

Table 36 Relative Transfer Function Timing Skew relative to Channel 1 (Z): DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z)	N/A	N/A	N/A	N/A
Channel 2 (N)	0.1027 us	0.1023 us	0.1042 us	0.1106 us
Channel 3 (E)	0.0209 us	0.0205 us	0.0217 us	0.0240 us
Channel 4 (X/C)	0.1382 us	0.1378 us	0.1376 us	0.1393 us

Table 37 Relative Transfer Function Timing Skew relative to Channel 1 (Z): DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z)	N/A	N/A	N/A	N/A
Channel 2 (N)	-0.0009 us	-0.0006 us	-0.0017 us	-0.0059 us
Channel 3 (3)	0.0003 us	0.0006 us	-0.0003 us	-0.0029 us
Channel 4 (X/C)	0.1734 us	0.1745 us	0.1771 us	0.1757 us

All of the Affinity digitizer channels were observed to have a timing skew that was within less than 0.18 microsecond of one another. Also, the relative timing skew between channels was not affected by the gain level.

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 passband in Hertz.

3.14.2 Configuration

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

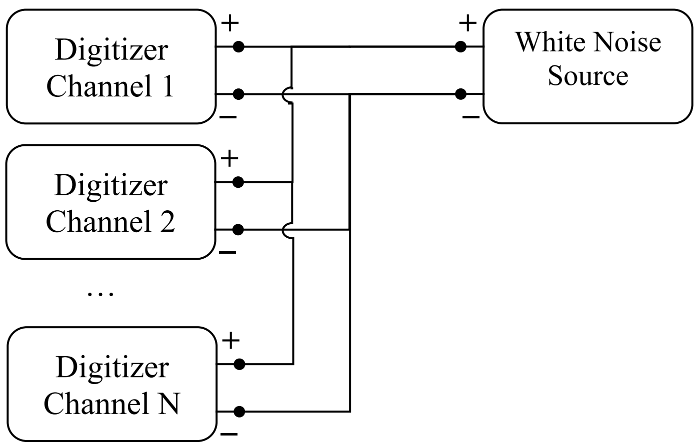

Figure 77 Analog Bandwidth Configuration Diagram

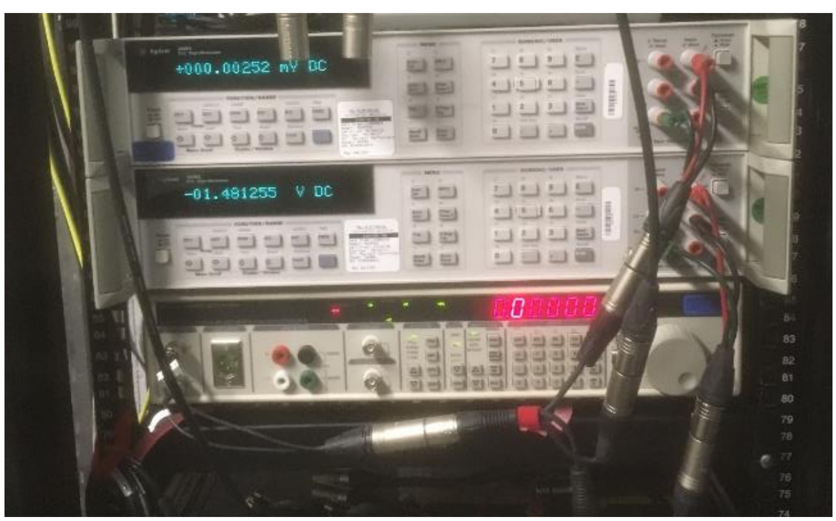

Figure 78 Analog Bandwidth Configuration Picture

Table 38 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:

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

The PSD is computed (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 digitizer channels are shown in the plots below.

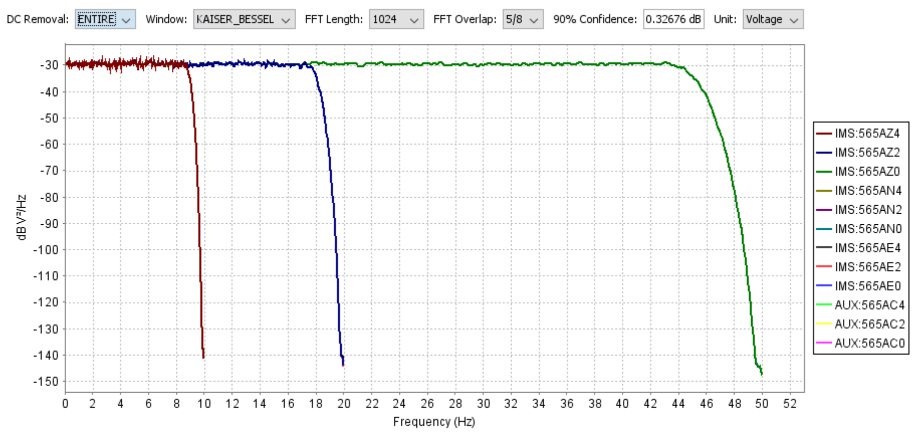

Figure 79 Analog Bandwidth Gain 1: DAS-40565A

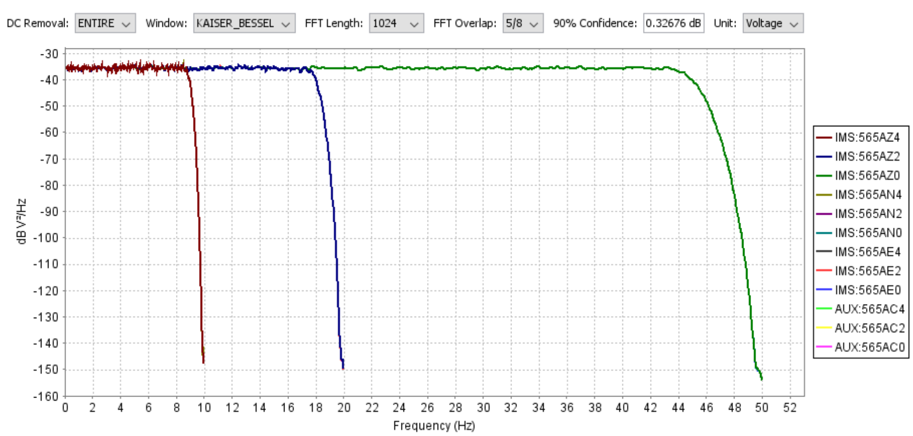

Figure 80 Analog Bandwidth Gain 2: DAS-40565A

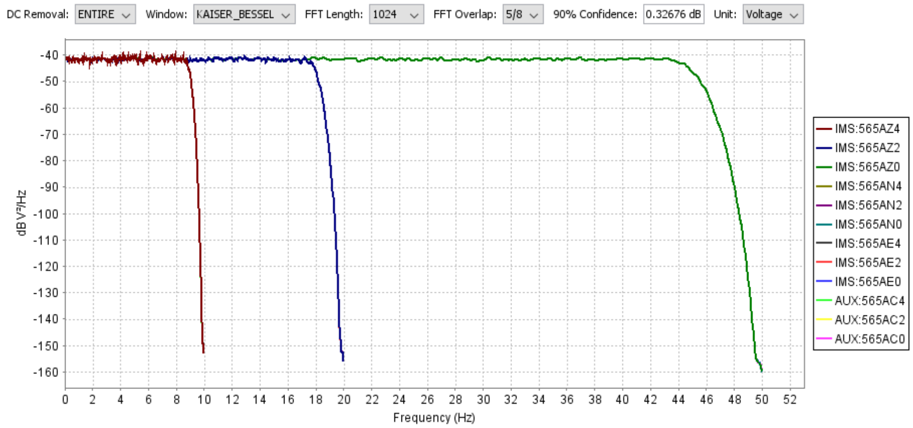

Figure 81 Analog Bandwidth Gain 4: DAS-40565A

Figure 82 Analog Bandwidth Gain 8: DAS-40565A

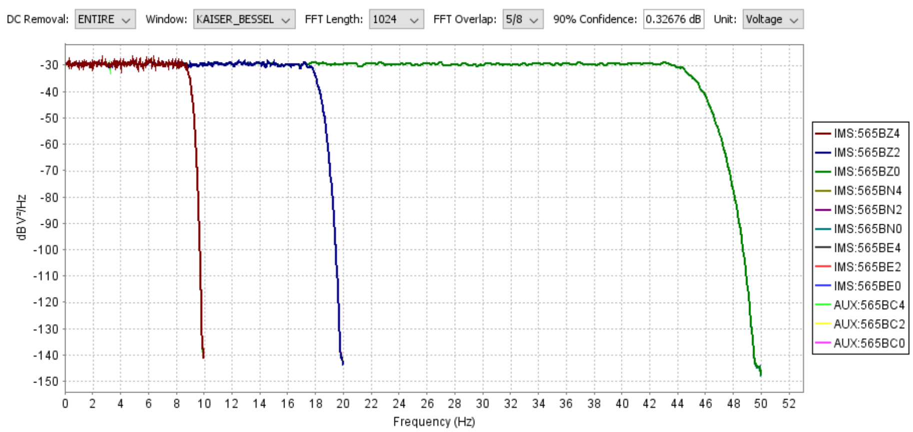

Figure 83 Analog Bandwidth Gain 1: DAS-40565B

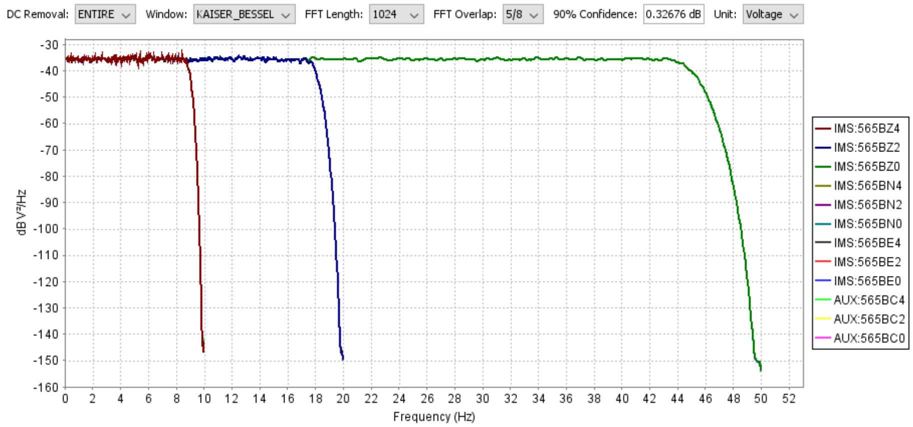

Figure 84 Analog Bandwidth Gain 2: DAS-40565B

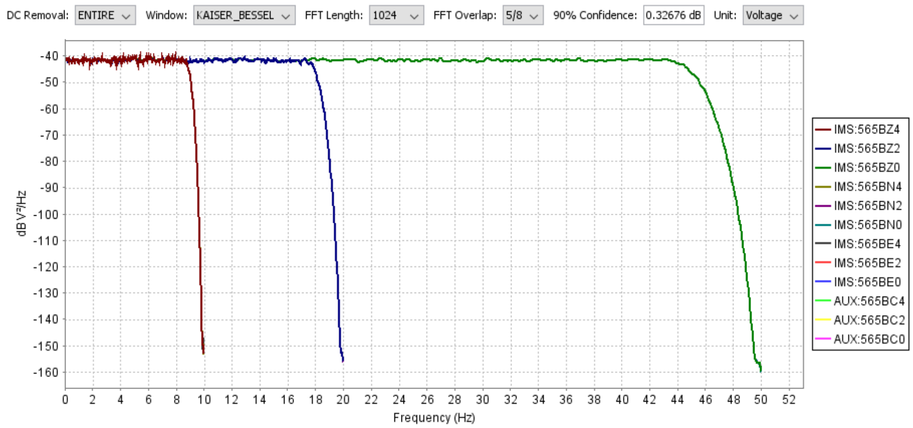

Figure 85 Analog Bandwidth Gain 4: DAS-40565B

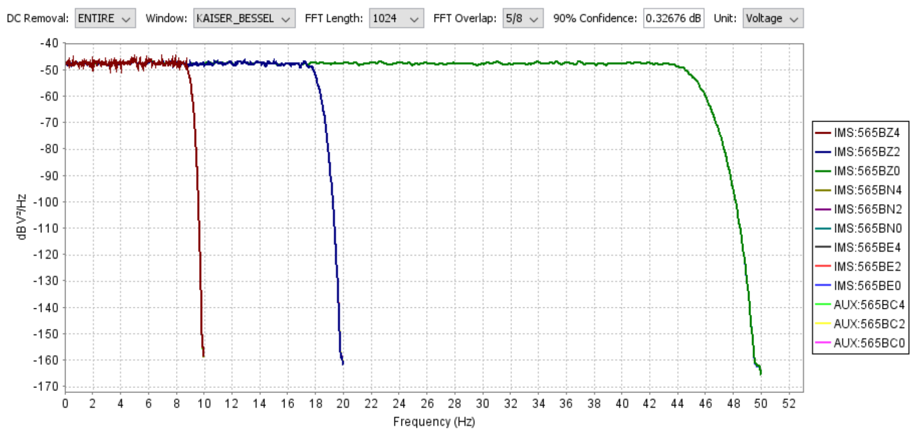

Figure 86 Analog Bandwidth Gain 8: DAS-40565B

Table 39 Analog Bandwidth: DAS-40565A

		Gain 1x		Gain 2x		Gain 4x		Gain 8x	
Channel	Sample Rate	3 dB Frequency	% of Nyquist	3 dB Frequency	% of Nyquist	3 dB Frequency	% of Nyquist	3 dB Frequency	% of Nyquist
Z	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%
N	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%
E	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%
C/X	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%

Table 40 Analog Bandwidth: DAS-40565B

		Gain 1x		Gain 2x		Gain 4x		Gain 8x	
Channel	Sample Rate	3 dB Frequency	% of Nyquist	3 dB Frequency	% of Nyquist	3 dB Frequency	% of Nyquist	3 dB Frequency	% of Nyquist
Z	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%
N	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%
E	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%
C/X	20 Hz	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%	8.848 Hz	88.48%
	40 Hz	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%	17.930 Hz	89.65%
	100 Hz	44.727 Hz	89.45%	44.727 Hz	89.45%	44.727 Hz	89.45%	44.824 Hz	89.65%

All of the channels were observed to have similar high frequency passband limits for a common sample rate and gain setting. The passband limits were consistently 88.48%, 89.65%, and 89.45% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, and 100 Hz. There was no significant different in passband across the gain levels or between the two Affinity digitizers.

3.15 Incoherent Noise

The Incoherent Noise test measures the amount of noise present on a digitizer while collecting waveform data from input channels that are recording a common broad-band signal.

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.

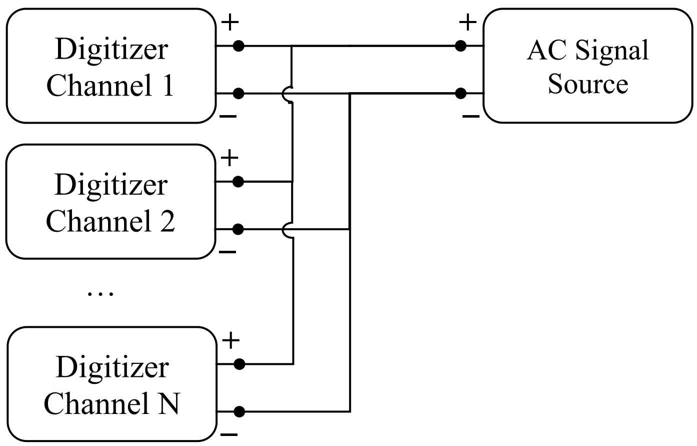

Figure 87 Incoherent Noise Configuration Diagram

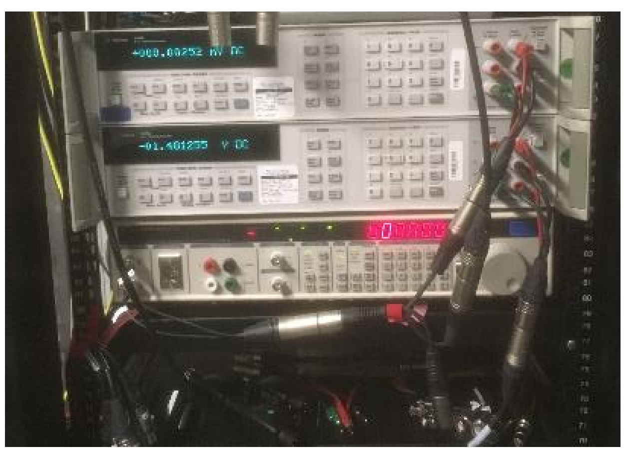

Figure 88 Incoherent Noise Configuration Picture

Table 41 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 digitizer is shown in the plot below.

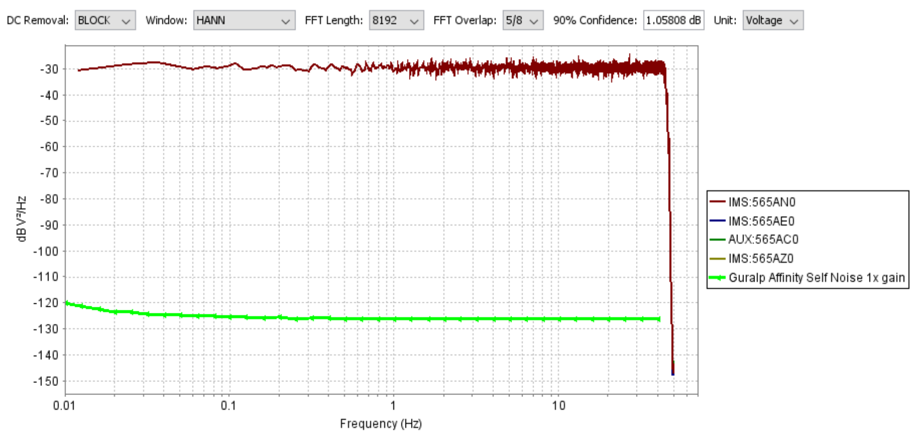

Figure 89 Incoherent Noise Raw Power Spectra, 100 Hz.

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

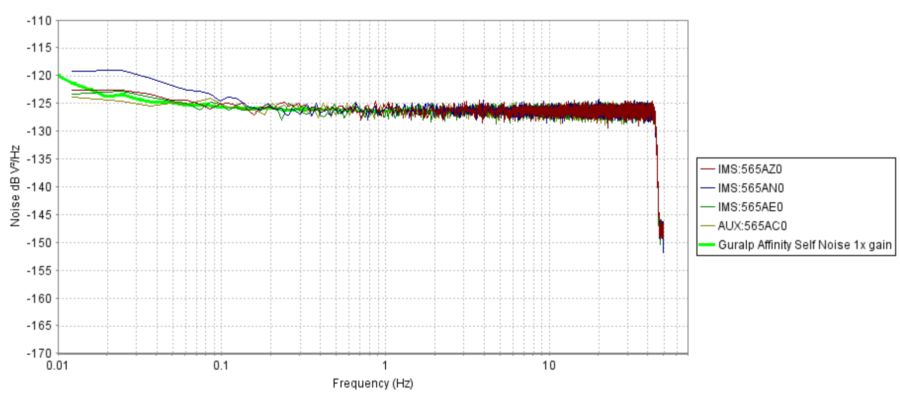

Figure 90 Incoherent Noise, Gain 1: DAS-40565A

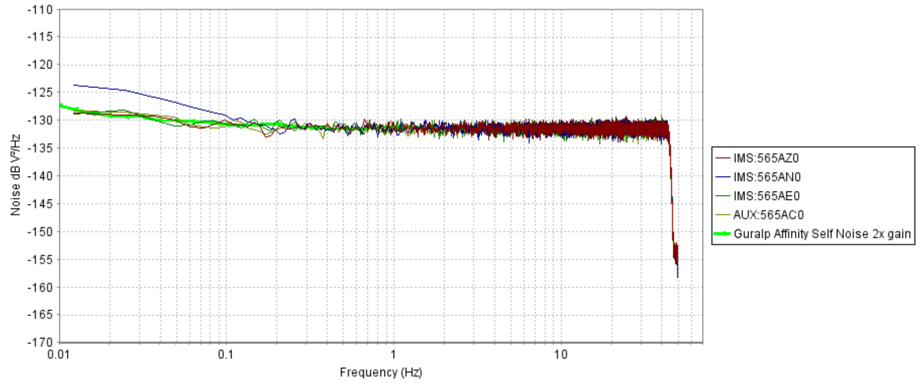

Figure 91 Incoherent Noise, Gain 2: DAS-40565A

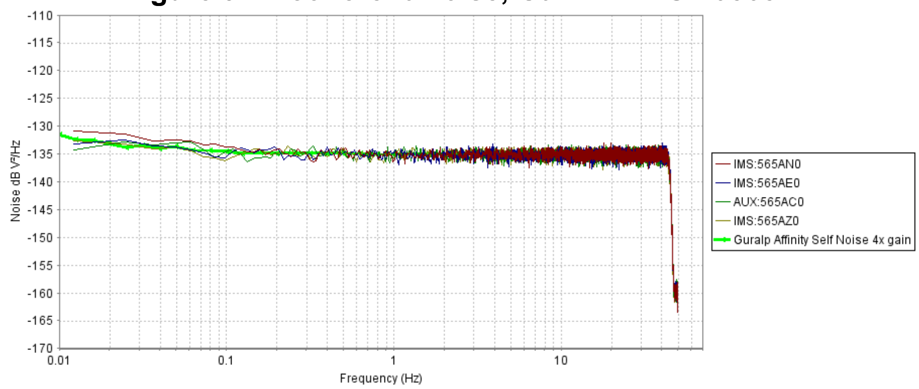

Figure 92 Incoherent Noise, Gain 4: DAS-40565A

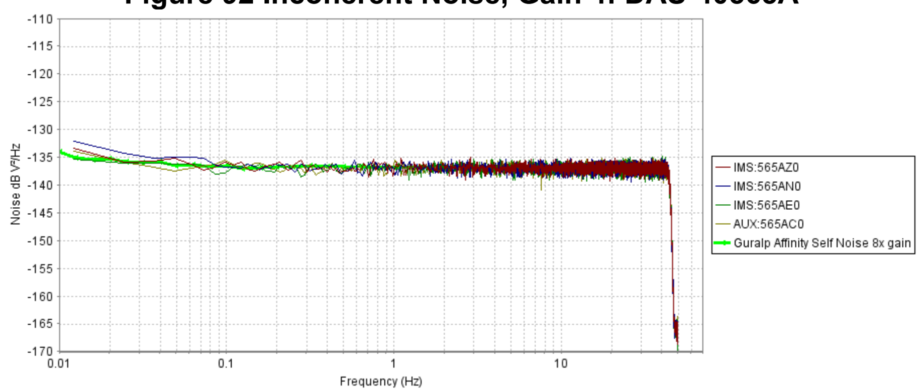

Figure 93 Incoherent Noise, Gain 8: DAS-40565A

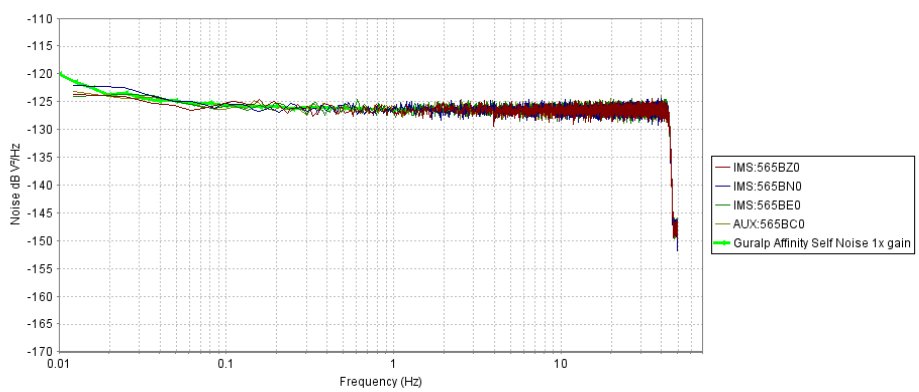

Figure 94 Incoherent Noise, Gain 1: DAS-40565B

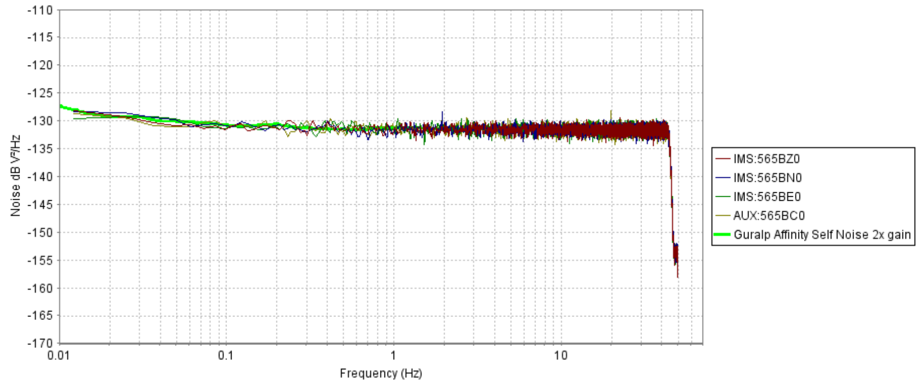

Figure 95 Incoherent Noise, Gain 2: DAS-40565B

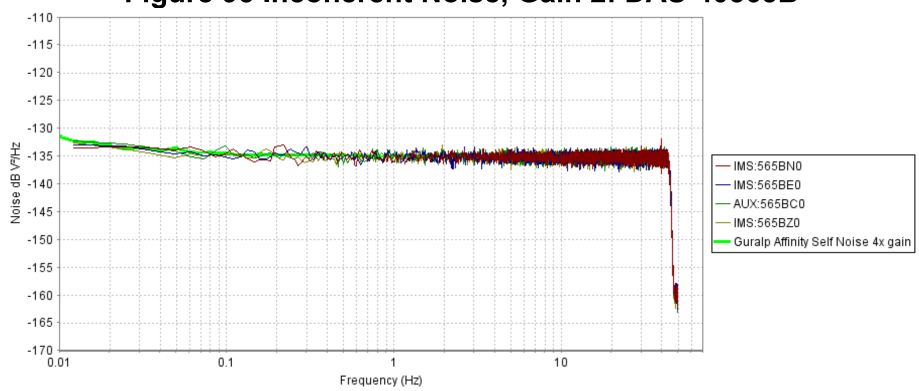

Figure 96 Incoherent Noise, Gain 4: DAS-40565B

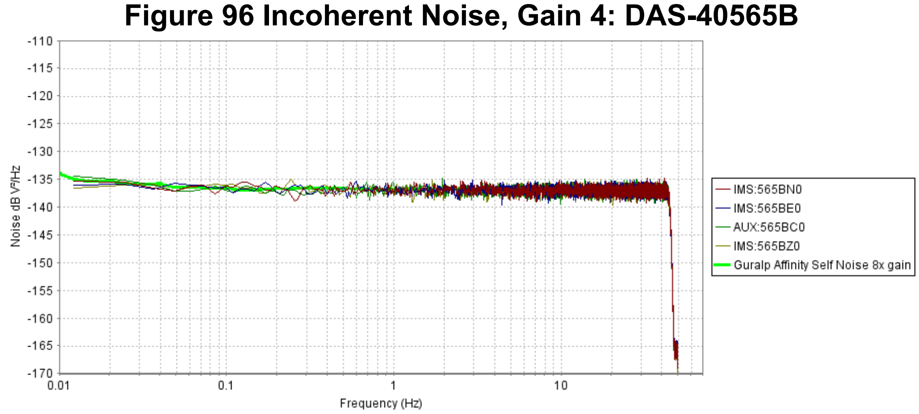

Figure 97 Incoherent Noise, Gain 8: DAS-40565B

In all cases, the incoherence noise present while the digitizer channels were being actively driven by a broadband signal matched very closely with the observed self-noise while terminated. Note, however, that the incoherent noise was very lightly elevated by 2 – 3 dB on the N channel of DAS-40565A at gains of 1x and 2x below 0.1 Hz.

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.

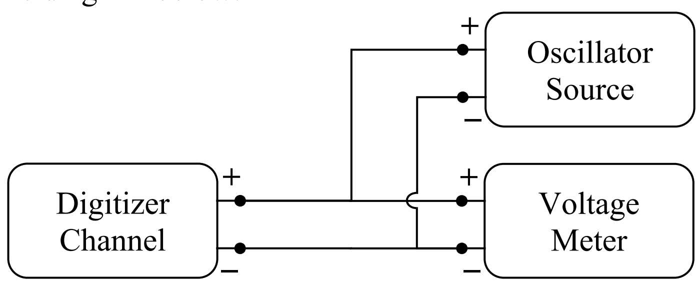

Figure 98 Total Harmonic Distortion Configuration Diagram

Table 42 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 often corrupted with noise from electronics that refresh at a 1 Hz multiple.

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 sufficiently above 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 30 minutes 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 bit-weight, 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 (Merchant, 2011) from the time series using a 2k-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.

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

Over frequencies (in Hertz):

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

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 of the 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 recorded on 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 30 minute, 1.41 Hz, 10 V peak sinusoid that was used to measure harmonic distortion.

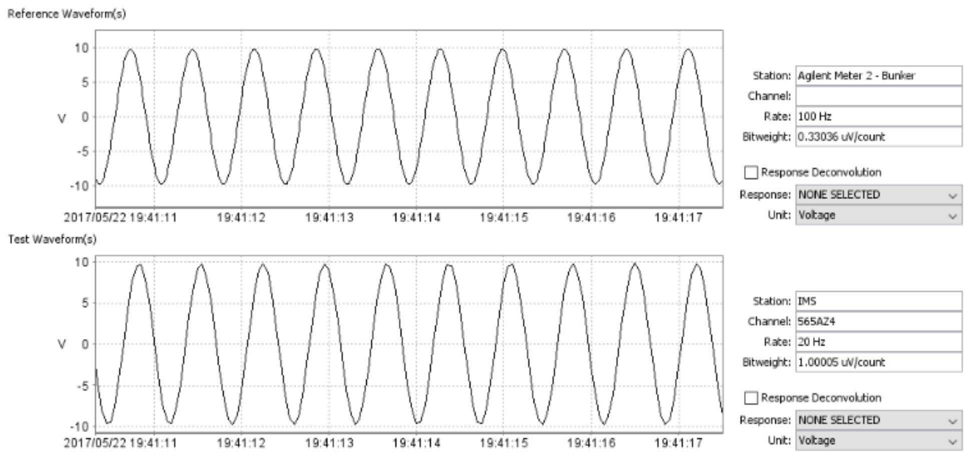

Figure 99 THD Waveform Time Series

The figure below shows a representative THD for the channels evaluated.

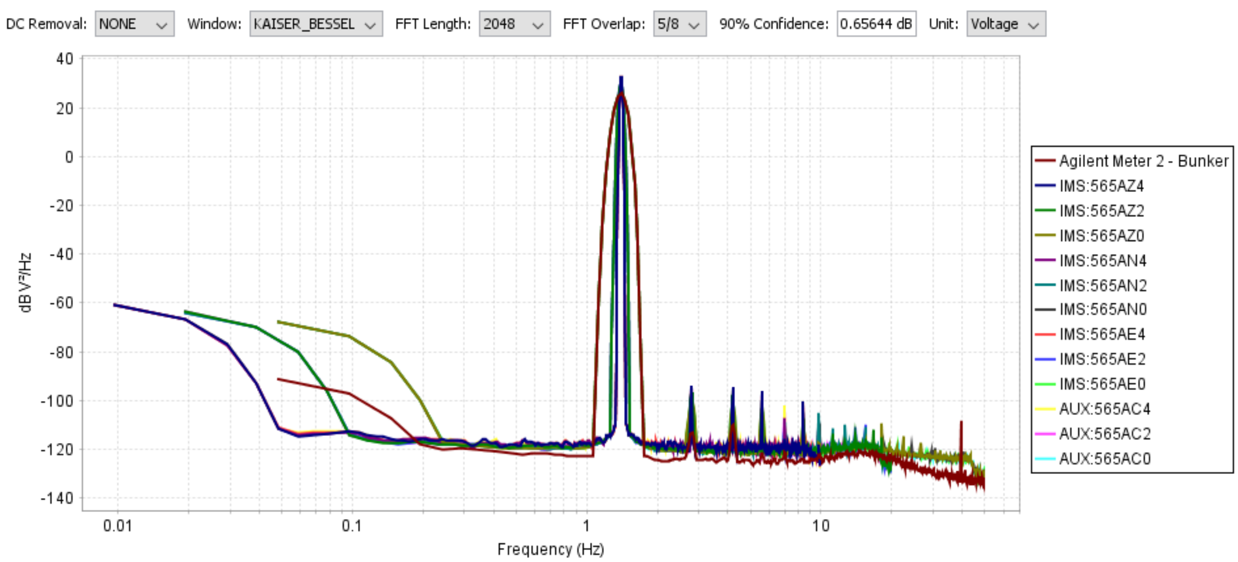

Figure 100 THD Power Spectra

The tables below contain the measured THD values for both digitizers for each of the channels, sample rates, and gain levels.

Table 43 Total Harmonic Distortion: DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Reference	-132.34 dB	-130.05 dB	-128.85 dB	-131.49 dB
Channel 1 (Z) - 20 Hz	-123.34 dB	-121.70 dB	-120.13 dB	-118.48 dB
Channel 1 (Z) - 40 Hz	-123.76 dB	-121.04 dB	-119.35 dB	-117.88 dB
Channel 1 (Z) - 100 Hz	-124.08 dB	-120.37 dB	-118.06 dB	-117.52 dB
Channel 2 (N) - 20 Hz	-123.32 dB	-125.23 dB	-123.00 dB	-121.10 dB
Channel 2 (N) - 40 Hz	-123.79 dB	-123.57 dB	-121.25 dB	-120.55 dB
Channel 2 (N) - 100 Hz	-124.16 dB	-122.53 dB	-119.45 dB	-119.76 dB
Channel 3 (E) - 20 Hz	-124.45 dB	-123.28 dB	-122.91 dB	-119.74 dB
Channel 3 (E) - 40 Hz	-124.98 dB	-122.51 dB	-121.27 dB	-119.11 dB
Channel 3 (E) - 100 Hz	-126.05 dB	-121.48 dB	-119.46 dB	-118.65 dB
Channel 4 (X/C) - 20 Hz	-121.81 dB	-123.84 dB	-124.89 dB	-120.22 dB
Channel 4 (X/C) - 40 Hz	-122.05 dB	-123.00 dB	-122.81 dB	-119.62 dB
Channel 4 (X/C) - 100 Hz	-122.33 dB	-122.07 dB	-120.68 dB	-119.16 dB

Table 44 Total Harmonic Distortion: DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Reference	-132.34 dB	-130.05 dB	-128.85 dB	-131.49 dB
Channel 1 (Z) - 20 Hz	-125.40 dB	-124.69 dB	-122.10 dB	-119.72 dB
Channel 1 (Z) - 40 Hz	-124.61 dB	-123.50 dB	-120.69 dB	-119.21 dB
Channel 1 (Z) - 100 Hz	-124.17 dB	-122.28 dB	-118.93 dB	-118.73 dB
Channel 2 (N) - 20 Hz	-123.01 dB	-122.44 dB	-120.37 dB	-122.98 dB
Channel 2 (N) - 40 Hz	-122.44 dB	-121.62 dB	-119.44 dB	-121.99 dB
Channel 2 (N) - 100 Hz	-122.13 dB	-121.00 dB	-118.68 dB	-121.15 dB
Channel 3 (E) - 20 Hz	-124.89 dB	-124.01 dB	-121.91 dB	-122.95 dB
Channel 3 (E) - 40 Hz	-124.44 dB	-123.01 dB	-120.69 dB	-122.15 dB
Channel 3 (E) - 100 Hz	-124.01 dB	-122.22 dB	-119.52 dB	-121.23 dB
Channel 4 (X/C) - 20 Hz	-123.71 dB	-122.92 dB	-122.11 dB	-126.14 dB
Channel 4 (X/C) - 40 Hz	-122.83 dB	-121.66 dB	-120.44 dB	-124.49 dB
Channel 4 (X/C) - 100 Hz	-122.21 dB	-120.56 dB	-119.00 dB	-122.69 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 digitizer.

The observed harmonic distortion ranged between -126.05 dB and -121.81 dB at a gain of 1x, -125.23 dB and -120.37 dB at a gain of 2x, -124.89 dB and -118.06 dB at a gain of 4x, and -126.14 dB and -117.52 dB at a gain of 8x.

In addition to the primary recording channels, the multiplexed channels on the auxiliary port were configured to record at 10 Hz. The THD on those channels were measured using a 5 V, 1.41 Hz sinusoid from the SRS DS360 signal generator and shown in the figure and table below:

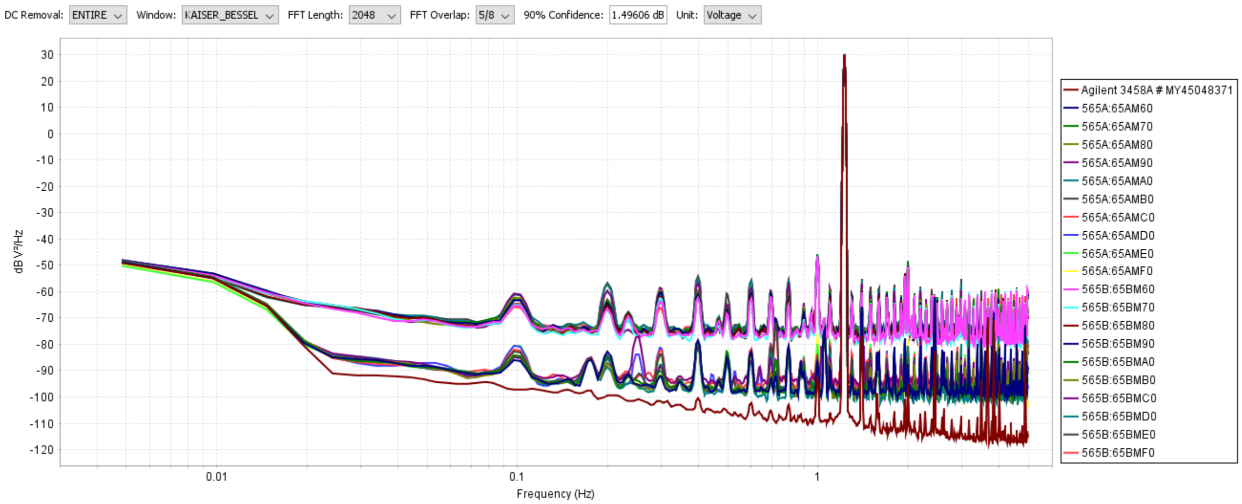

Figure 101 THD Power Spectra – Multiplexed Channels

It is observed in the power spectra above that the multiplexed channels exhibit more noise than the primary channels, likely due to the channels being single-ended referenced to ground and not differential. Any increase in signal power at harmonics of the fundamental frequency will result in increased THD levels, as shown in the table below.

Table 45 Total Harmonic Distortion: Multiplexed Channels

Channel	DAS-40565A	DAS-40565B
Reference	-98.75 dB	-98.75 dB
M60	-91.28 dB	-89.01 dB
M70	-91.25 dB	-87.49 dB
M80	-91.27 dB	-88.92 dB
M90	-91.27 dB	-88.68 dB
MA0	-91.29 dB	-90.20 dB
MB0	-91.31 dB	-88.44 dB
MC0	-91.30 dB	-88.32 dB
MD0	-91.30 dB	-88.76 dB
ME0	-91.29 dB	-88.65 dB
MF0	-91.30 dB	-86.09 dB

The measured THD values on the multiplexed channels were better than -91.25 dB on DAS-40565A and -86.09 dB on DAS-40565B. In all cases, the reference measurement of the signal generated by the low distortion oscillator of -98.75 dB exceeded the measurement made on the digitizer channel indicating that the distortion observed is due to the digitizer.

3.17 Modified Noise Power Ratio

The Modified Noise Power Ratio test measures the linearity of the digitizer channels across a range of amplitudes.

3.17.1 Measurand

The quantity being measured is the ratio between signal power and incoherent noise across a range of input amplitudes.

3.17.2 Configuration

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

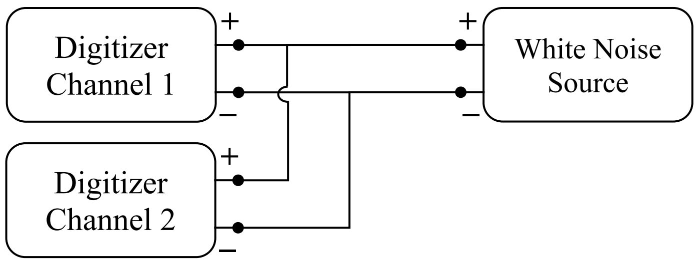

Figure 102 Modified Noise Power Ratio Configuration Diagram

Table 46 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal

The White Noise Source is configured to generate band-width limited white noise voltages with amplitudes spanning the full scale of the channel. One hour of data is recorded at each amplitude level.

3.17.3 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 ratio between the signal power and the noise power is computed at each of the amplitude levels and plotted on a scale with nominal reference lines (Merchant, 2011; McDonald 1994).

3.17.4 Result

A representative waveform time series plot is shown below for DAS-40565A channels Z and N sampled at 100 Hz.

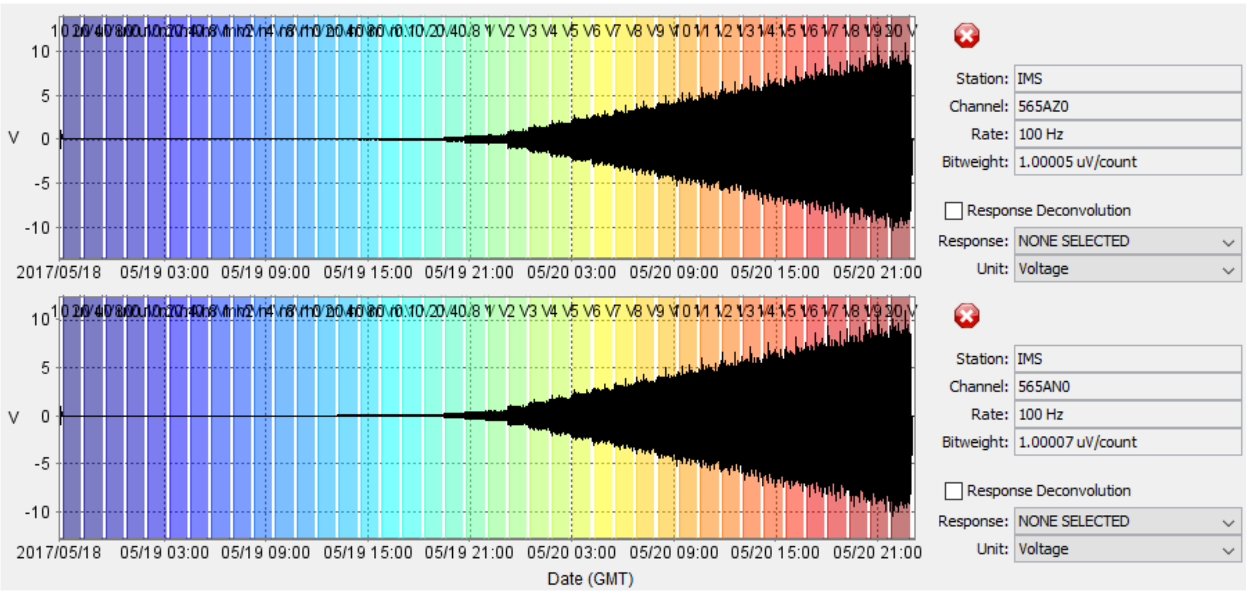

Figure 103 Modified Noise Power Ratio Time Series: DAS-40565A, Z and N, gain 1x

The Modified Noise Power Ratio is computed for both DAS-40565A and DAS-40565B at a sample rate of 100 Hz and at a gain of 1x. The amplitude and noise of the power spectra are integrated over 0.01 – 50 Hz. The figures and plot are shown below.

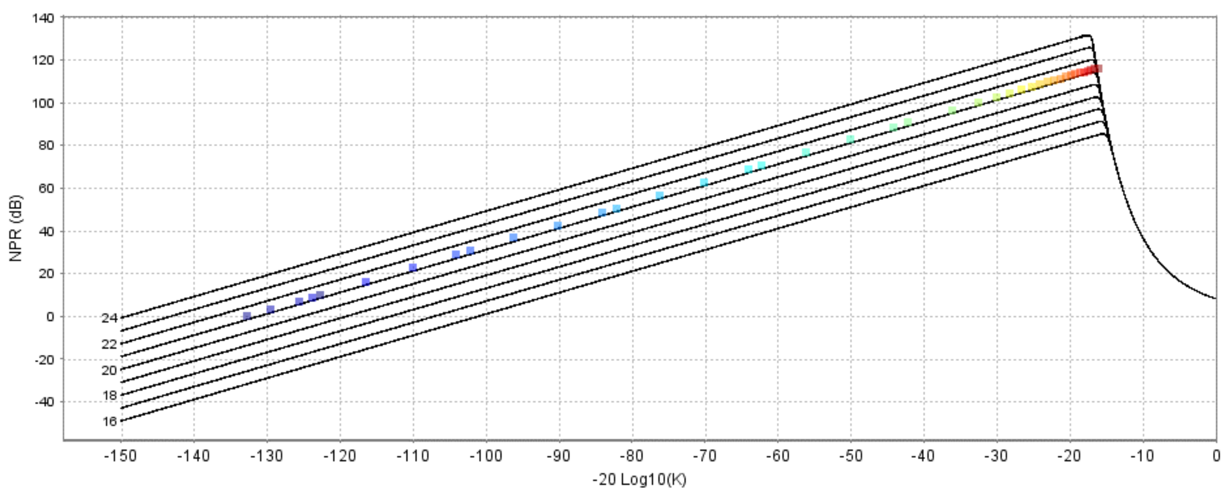

Figure 104 Modified Noise Power Ratio: DAS-40565A, Z and N, gain 1x

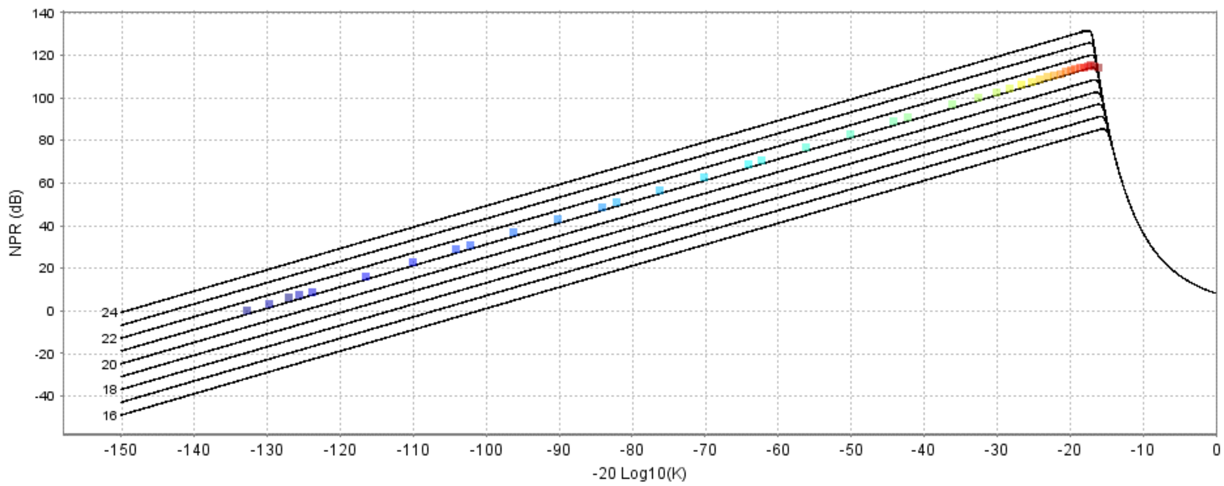

Figure 105 Modified Noise Power Ratio: DAS-40565A, E and C, gain 1x

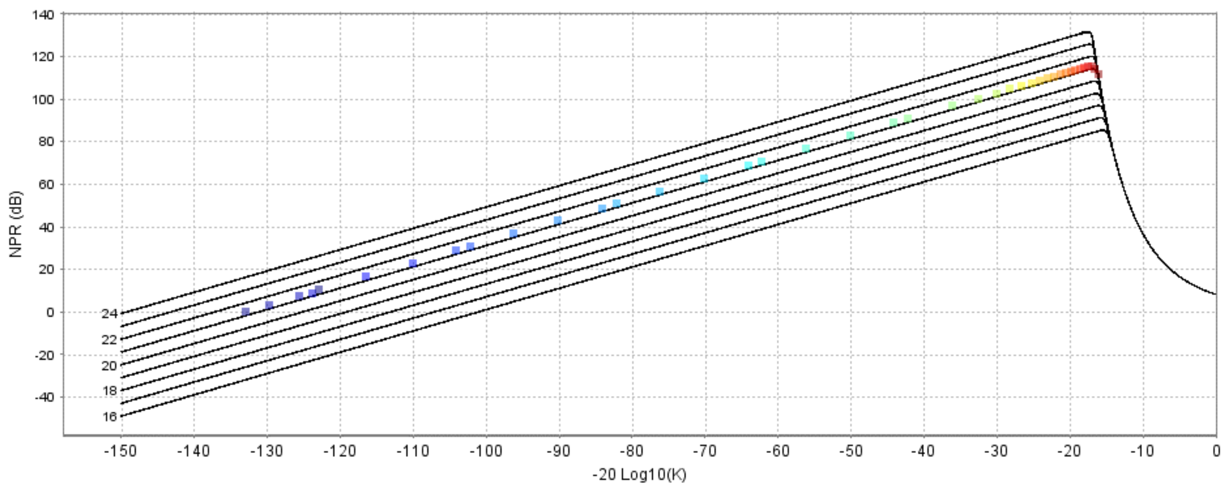

Figure 106 Modified Noise Power Ratio: DAS-40565B, Z and N, gain 1x

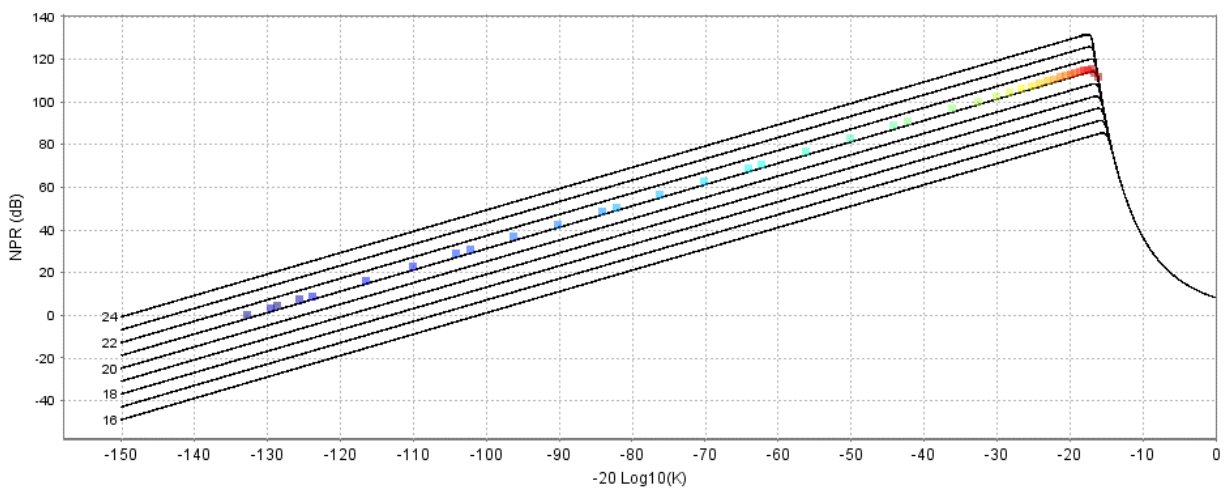

Figure 107 Modified Noise Power Ratio: DAS-40565B, E and C, gain 1x

Table 47 Modified Noise Power Ratio

			Noise Power Ratio			
Amplitude	RMS Amplitude	-20 log10(k)	DAS-40565A Z and N	DAS-40565A E and C	DAS-40565B Z and N	DAS-40565B E and C
20 uV	3.2596E-6 V rms	-132.75	0.32 dB	0.31 dB	0.28 dB	0.31 dB
40 uV	4.6628E-6 V rms	-129.64	3.19 dB	3.25 dB	3.26 dB	3.23 dB
80 uV	7.3814E-6 V rms	-125.65	7.17 dB	7.27 dB	7.32 dB	7.25 dB
0.1 mV	9.0258E-6 V rms	-123.90	8.94 dB	9.02 dB	9.03 dB	8.97 dB
0.2 mV	2.1156E-5 V rms	-116.50	16.30 dB	16.41 dB	16.49 dB	16.39 dB
0.4 mV	4.4097E-5 V rms	-110.12	22.68 dB	22.83 dB	22.85 dB	22.78 dB
0.8 mV	8.7802E-5 V rms	-104.14	28.69 dB	28.79 dB	28.86 dB	28.78 dB
1 mV	1.1000E-4 V rms	-102.19	30.64 dB	30.74 dB	30.81 dB	30.73 dB
2 mV	2.2000E-4 V rms	-96.19	36.64 dB	36.75 dB	36.80 dB	36.71 dB
4 mV	4.4000E-4 V rms	-90.16	42.65 dB	42.77 dB	42.83 dB	42.75 dB
8 mV	8.8000E-4 V rms	-84.14	48.67 dB	48.77 dB	48.85 dB	48.76 dB
10 mV	1.1000E-3 V rms	-82.20	50.58 dB	50.74 dB	50.79 dB	50.70 dB
20 mV	2.2000E-3 V rms	-76.17	56.63 dB	56.76 dB	56.81 dB	56.73 dB
40 mV	4.3900E-3 V rms	-70.16	62.67 dB	62.78 dB	62.85 dB	62.74 dB
80 mV	8.7800E-3 V rms	-64.14	68.67 dB	68.76 dB	68.84 dB	68.75 dB
0.1 V	0.0110 V rms	-62.20	70.60 dB	70.70 dB	70.78 dB	70.71 dB
0.2 V	0.0220 V rms	-56.18	76.62 dB	76.73 dB	76.82 dB	76.72 dB
0.4 V	0.0439 V rms	-50.16	82.63 dB	82.73 dB	82.80 dB	82.75 dB
0.8 V	0.0878 V rms	-44.14	88.65 dB	88.75 dB	88.83 dB	88.74 dB
1 V	0.1098 V rms	-42.20	90.59 dB	90.69 dB	90.76 dB	90.72 dB
2 V	0.2199 V rms	-36.17	96.63 dB	96.74 dB	96.81 dB	96.72 dB
3 V	0.3295 V rms	-32.65	100.14 dB	100.24 dB	100.30 dB	100.23 dB
4 V	0.4395 V rms	-30.15	102.64 dB	102.73 dB	102.80 dB	102.73 dB
5 V	0.5489 V rms	-28.22	104.55 dB	104.64 dB	104.72 dB	104.64 dB
6 V	0.6591 V rms	-26.63	106.11 dB	106.18 dB	106.31 dB	106.21 dB
7 V	0.7687 V rms	-25.29	107.43 dB	107.51 dB	107.64 dB	107.54 dB
8 V	0.8783 V rms	-24.14	108.59 dB	108.63 dB	108.80 dB	108.68 dB
9 V	0.9887 V rms	-23.11	109.59 dB	109.60 dB	109.83 dB	109.70 dB
10 V	1.0980 V rms	-22.20	110.48 dB	110.47 dB	110.72 dB	110.60 dB
11 V	1.2074 V rms	-21.37	111.28 dB	111.30 dB	111.53 dB	111.41 dB
12 V	1.3175 V rms	-20.62	112.02 dB	112.04 dB	112.29 dB	112.12 dB
13 V	1.4281 V rms	-19.92	112.68 dB	112.67 dB	112.94 dB	112.83 dB
14 V	1.5374 V rms	-19.27	113.31 dB	113.31 dB	113.58 dB	113.42 dB
15 V	1.6469 V rms	-18.68	113.90 dB	113.87 dB	114.16 dB	114.00 dB
16 V	1.7567 V rms	-18.12	114.43 dB	114.37 dB	114.69 dB	114.52 dB
17 V	1.8667 V rms	-17.59	114.95 dB	114.89 dB	115.22 dB	115.00 dB
18 V	1.9769 V rms	-17.09	115.40 dB	115.24 dB	115.40 dB	115.12 dB
19 V	2.0864 V rms	-16.62	115.81 dB	115.02 dB	113.96 dB	113.75 dB
20 V	2.1963 V rms	-16.18	116.09 dB	114.17 dB	111.47 dB	111.41 dB

The Modified Noise Power Ratio results indicate that the two digitizers perform similarly without any observable non-linearity across their amplitude ranges. Note that Modified Noise Power Ratio on DAS-40565A is slightly higher than on DAS-40565B at peak amplitudes above 19 V. However, both are consistent with what would be expected from an idealized digitizer with approximately 21.25 effective bits.

3.18 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.

3.18.1 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.

3.18.2 Configuration

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

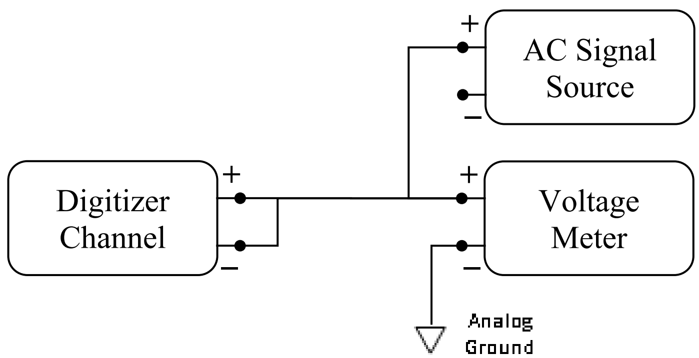

Figure 108 Common Mode Rejection Configuration Diagram

Since the digitizer input channels are differential and the positive and negative legs 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 48 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	MY45048371	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.

3.18.3 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:

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

3.18.4 Result

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

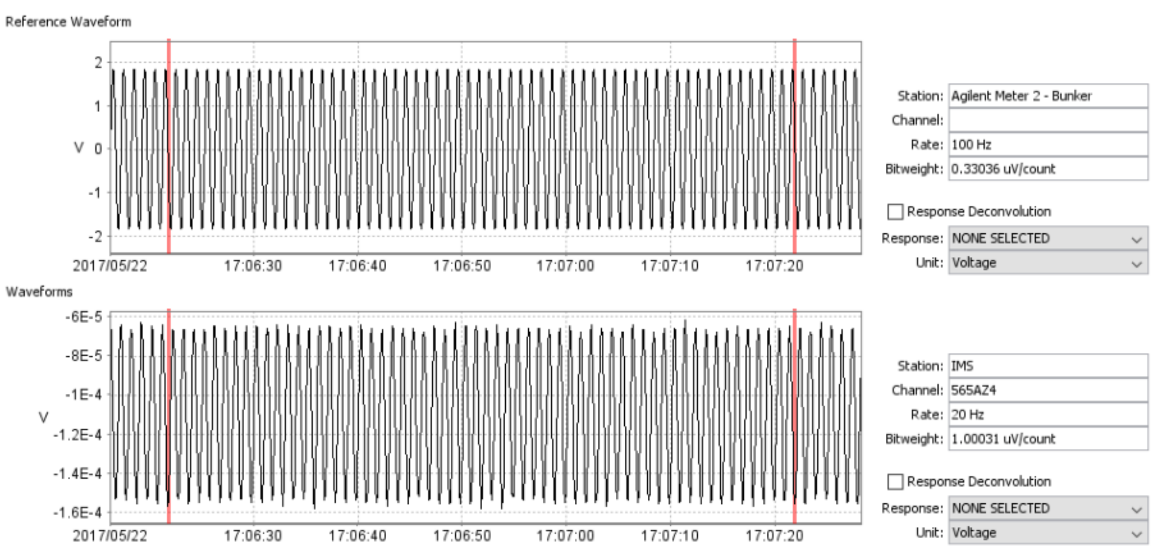

Figure 109 Common Mode Rejection Time Series

The following tables contains the computed common mode noise rejection ratio.

Table 49 Common Mode Rejection: DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z) - 20 Hz	92.32 dB	92.38 dB	92.38 dB	92.28 dB
Channel 1 (Z) - 40 Hz	92.33 dB	92.39 dB	92.38 dB	92.28 dB
Channel 1 (Z) - 100 Hz	92.32 dB	92.39 dB	92.38 dB	92.28 dB
Channel 2 (N) - 20 Hz	113.25 dB	110.65 dB	108.89 dB	108.16 dB
Channel 2 (N) - 40 Hz	113.29 dB	110.64 dB	108.91 dB	108.14 dB
Channel 2 (N) - 100 Hz	113.27 dB	110.65 dB	108.90 dB	108.15 dB
Channel 3 (E) - 20 Hz	99.52 dB	99.59 dB	99.47 dB	99.31 dB
Channel 3 (E) - 40 Hz	99.52 dB	99.59 dB	99.47 dB	99.32 dB
Channel 3 (E) - 100 Hz	99.53 dB	99.59 dB	99.47 dB	99.32 dB
Channel 4 (X/C) - 20 Hz	107.29 dB	107.58 dB	108.07 dB	108.94 dB
Channel 4 (X/C) - 40 Hz	107.28 dB	107.57 dB	108.08 dB	108.94 dB
Channel 4 (X/C) - 100 Hz	107.26 dB	107.58 dB	108.09 dB	108.94 dB

Table 50 Common Mode Rejection: DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z) - 20 Hz	95.33 dB	94.76 dB	94.36 dB	94.22 dB
Channel 1 (Z) - 40 Hz	95.33 dB	94.76 dB	94.36 dB	94.22 dB
Channel 1 (Z) - 100 Hz	95.33 dB	94.76 dB	94.36 dB	94.22 dB
Channel 2 (N) - 20 Hz	110.22 dB	111.26 dB	111.73 dB	111.02 dB
Channel 2 (N) - 40 Hz	110.22 dB	111.26 dB	111.73 dB	111.03 dB
Channel 2 (N) - 100 Hz	110.21 dB	111.28 dB	111.74 dB	111.03 dB
Channel 3 (E) - 20 Hz	103.23 dB	102.72 dB	102.41 dB	102.12 dB
Channel 3 (E) - 40 Hz	103.24 dB	102.72 dB	102.41 dB	102.12 dB
Channel 3 (E) - 100 Hz	103.24 dB	102.72 dB	102.41 dB	102.12 dB
Channel 4 (X/C) - 20 Hz	98.50 dB	98.57 dB	98.51 dB	98.68 dB
Channel 4 (X/C) - 40 Hz	98.50 dB	98.57 dB	98.50 dB	98.68 dB
Channel 4 (X/C) - 100 Hz	98.50 dB	98.57 dB	98.51 dB	98.68 dB

The observed common mode rejection was typically between 92 and 113 dB. Also noted is that, as expected, the common mode value was unique to the physical recording channel and was not observed to change significantly with sample rate or gain level.

3.19 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.

3.19.1 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.

3.19.2 Configuration

The digitizer is connected to a AC signal source and a meter configured to measure voltage as shown in the diagram below. One channel is terminated with a resistor while the remaining channels record an AC signal.

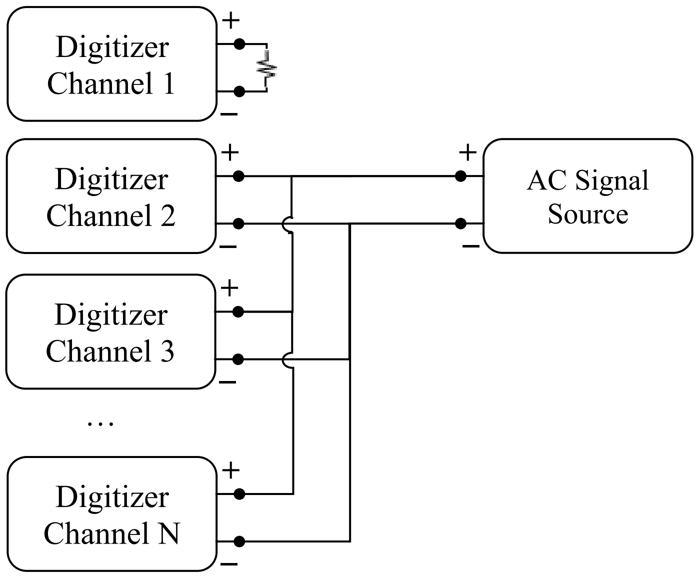

Figure 110 Crosstalk Configuration Diagram

Table 51 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.

3.19.3 Analysis

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

$x[n]$

The PSD is computed (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:

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

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:

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

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

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

3.19.4 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 segments of data used for analysis.

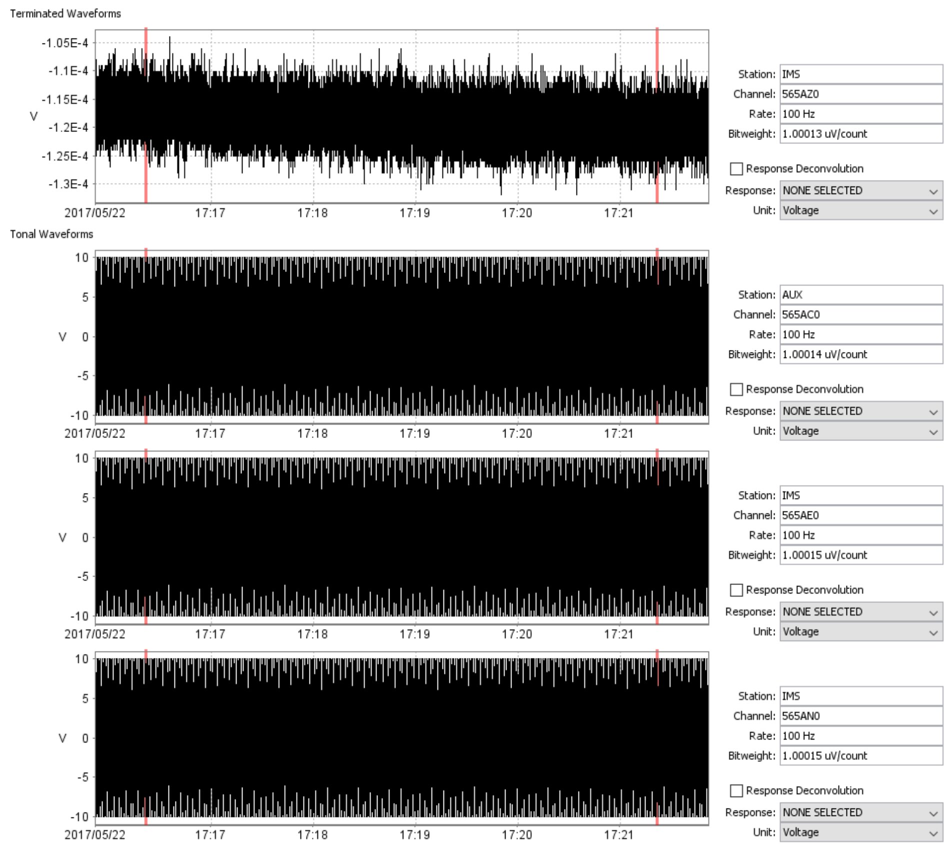

Figure 111 Crosstalk Representative Waveform Time Series

The figures below show a representative power spectra of the terminated and tonal channels for a 100 Hz sample rate and at gains of 1x and 8x. All of the results were similar to the power spectra shown below.

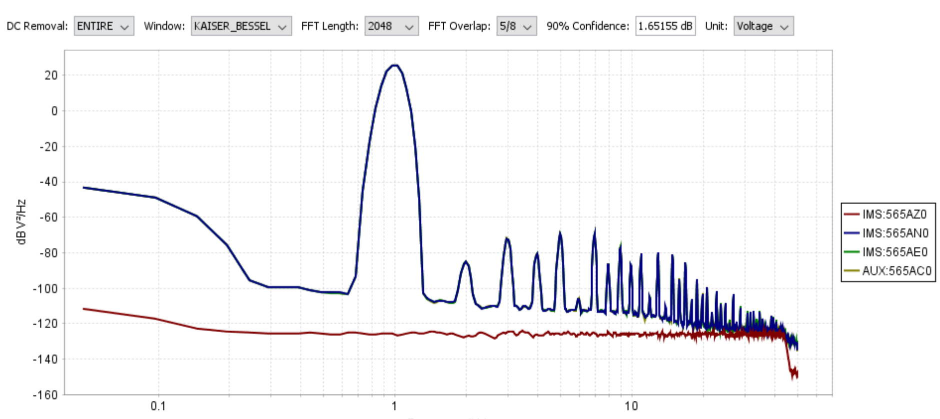

Figure 112 Crosstalk Power Spectra, 100 Hz, Gain 1

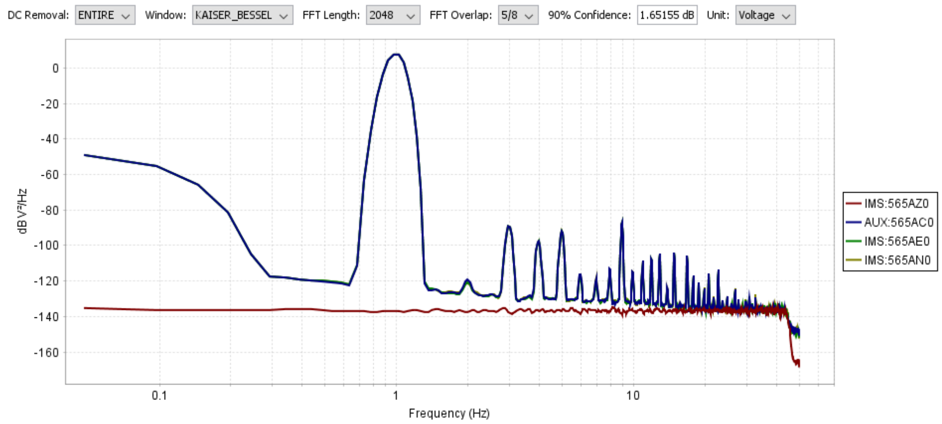

Figure 113 Crosstalk Power Spectra, 100 Hz, Gain 8

Table 52 Crosstalk: DAS-40565A

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z)	-150.37 dB	-149.34 dB	-147.22 dB	-143.27 dB
Channel 2 (N)	-150.59 dB	-144.65 dB	-147.79 dB	-143.62 dB
Channel 3 (E)	-149.73 dB	-148.90 dB	-147.15 dB	-143.25 dB
Channel 4 (X/C)	-150.11 dB	-150.15 dB	-147.21 dB	-144.09 dB

Table 53 Crosstalk: DAS-40565B

	Gain 1x	Gain 2x	Gain 4x	Gain 8x
Channel 1 (Z)	-146.62 dB	-149.61 dB	-147.73 dB	-142.56 dB
Channel 2 (N)	-150.15 dB	-149.79 dB	-147.23 dB	-142.82 dB
Channel 3 (3)	-150.81 dB	-149.54 dB	-147.45 dB	-143.06 dB
Channel 4 (X/C)	-150.19 dB	-149.43 dB	-146.62 dB	-143.76 dB

The computed levels of crosstalk were all between -142 and -150 dB. Crosstalk levels are only being reported for the 100 Hz sample rate. An examination of the other sample rates for equivalent channels and gain settings revealed identical results.

Note that the spectra of the terminated channel did not contain a peak indicating the presence of crosstalk in any of the tests. Therefore, the calculated values represent the maximum possible level of crosstalk that may be present. Note that the decrease in the maximum possible level of crosstalk observed with increasing gain is associated with the slight increase in the digitizer noise-floor at those gain levels and not any actual amount of observable crosstalk.

In addition, tests were performed of the level of crosstalk between the primary and auxiliary recording channels of the Affinity digitizer. In the first sequence, a 1 Hz sinusoid was recorded on several of the auxiliary channels while the primary channels were terminated with a 50 ohm resistor while at a gain of 1x. A representative power spectra figure is shown below.

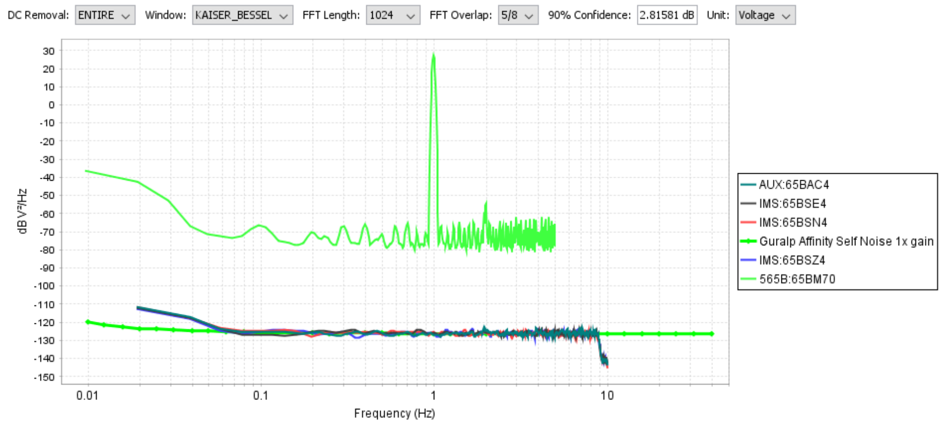

Figure 114 Crosstalk Power Spectra, Auxiliary to Primary, DAS-40565A

Table 54 Crosstalk, Auxiliary to Primary

	DAS-40565A	DAS 40565B
Channel 1 (Z)	-147.27 dB	-149.04 dB
Channel 2 (N)	-148.19 dB	-148.32 dB
Channel 3 (3)	-149.62 dB	-147.97 dB
Channel 4 (X/C)	-148.06 dB	-148.65 dB

The computed levels of crosstalk were between -149 and -147 dB. There was no indication of crosstalk visible on the primary channels, therefore the computed values represent the maximum possible level of crosstalk that is possible.

In the second sequence of auxiliary crosstalk tests, a 1 Hz sinusoid was recorded on several of the primary channels while the auxiliary channels were terminated with a 50 ohm resistor to ground. The power spectra figures are shown below.

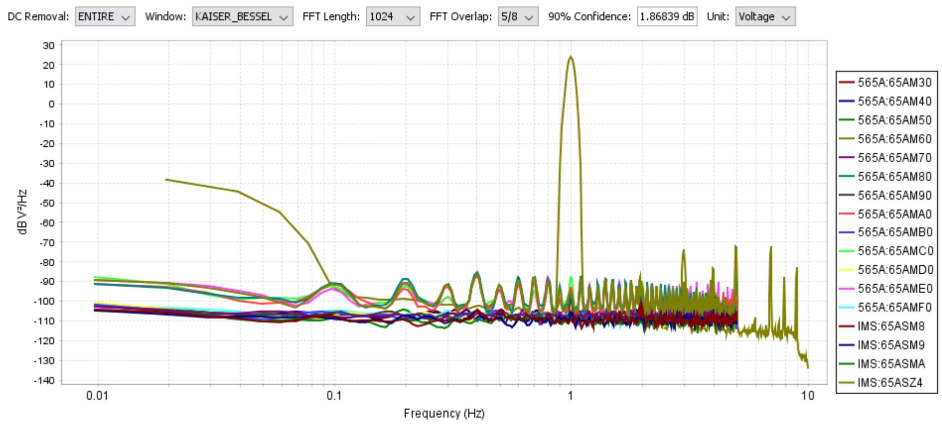

Figure 115 Crosstalk Power Spectra, Primary to Auxiliary, DAS-40565A

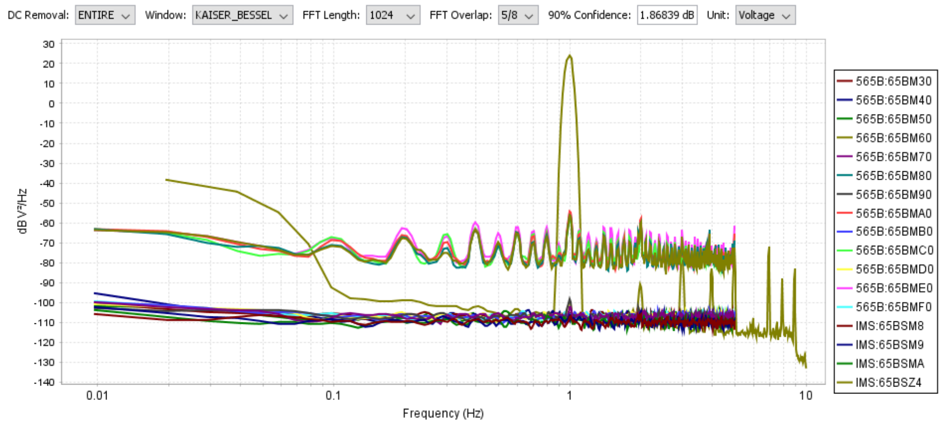

Figure 116 Crosstalk Power Spectra, Primary to Auxiliary, DAS-40565B

Table 55 Crosstalk, Auxiliary to Primary

Channel	DAS-40565A	DAS-40565B
565A:65AM30	-135.01 dB	-133.23 dB
565A:65AM40	-130.76 dB	-130.78 dB
565A:65AM50	-134.44 dB	-133.01 dB
565A:65AM60	-119.35 dB	-82.87 dB
565A:65AM70	-132.89 dB	-127.62 dB
565A:65AM80	-122.73 dB	-83.00 dB
565A:65AM90	-124.90 dB	-124.92 dB
565A:65AMA0	-119.24 dB	-81.09 dB
565A:65AMB0	-131.62 dB	-131.70 dB
565A:65AMC0	-114.36 dB	-84.24 dB
565A:65AMD0	-126.51 dB	-125.23 dB
565A:65AME0	-119.10 dB	-81.70 dB
565A:65AMF0	-132.75 dB	-131.27 dB
IMS:65ASM8	-130.58 dB	-131.24 dB
IMS:65ASM9	-133.13 dB	-132.94 dB
IMS:65ASMA	-130.67 dB	-131.35 dB

There was very little evidence of crosstalk coupling from the primary channels to the auxiliary channels. Typical crosstalk levels were between -133 dB and -114 dB. Note that on DAS-40565B, some of the auxiliary channels had a noticeably higher noise floor, which resulted in the higher crosstalk levels between -84 dB and -81 dB. The harmonics observed in some of the auxiliary channels began when the channel was terminated to ground with a resistor, most likely due to noise coupling through the ground connection.

3.20 GPS 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 with a GPS timing source.

3.20.1 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.

3.20.2 Configuration

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

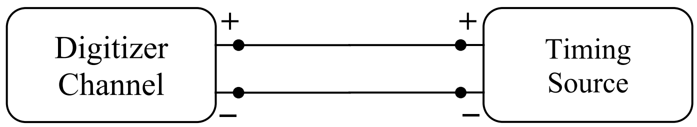

Figure 117 GPS Time Tag Accuracy Configuration Diagram

Table 56 GPS Time Tag Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Quanterra Supertonal	123669	GPS PPM Output
Digitizer Timing Lock	Supplied GPS Antenna	N/A	N/Af

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 to identify a time tag.

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 average time tag error is computed over a minimum of an hour.

3.20.4 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.

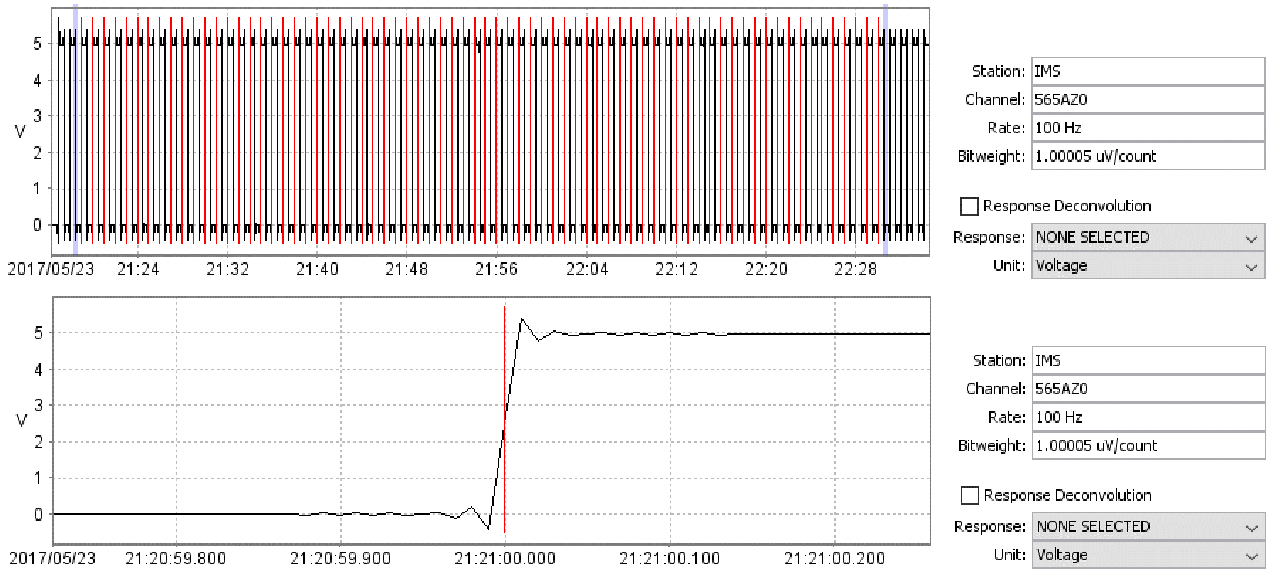

Figure 118 Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets.

Table 57 Time Tag Accuracy

	DAS-40565A (gain 1x)	DAS-40565B (gain 1x)
Channel 1 (Z) - 20 Hz	2.62 uS	2.27 uS
Channel 1 (Z) - 40 Hz	2.62 uS	2.41 uS
Channel 1 (Z) - 100 Hz	2.62 uS	2.16 uS
Channel 2 (N) - 20 Hz	2.42 uS	2.32 uS
Channel 2 (N) - 40 Hz	2.38 uS	2.41 uS
Channel 2 (N) - 100 Hz	2.38 uS	2.16 uS
Channel 3 (E) - 20 Hz	2.62 uS	2.30 uS
Channel 3 (E) - 40 Hz	2.61 uS	2.42 uS
Channel 3 (E) - 100 Hz	2.61 uS	2.16 uS
Channel 4 (X/C) - 20 Hz	2.40 uS	2.15 uS
Channel 4 (X/C) - 40 Hz	2.38 uS	2.38 uS
Channel 4 (X/C) - 100 Hz	2.38 uS	2.11 uS

The measured time tag accuracy values were consistent for all of the recording channels on each digitizer and found to be less than 2.62 uS. The sampling rate did not affect the timing accuracy.

In addition, there was very little scatter in the results from the 60 PPM signals that were analyzed, as shown in the histogram plot below.

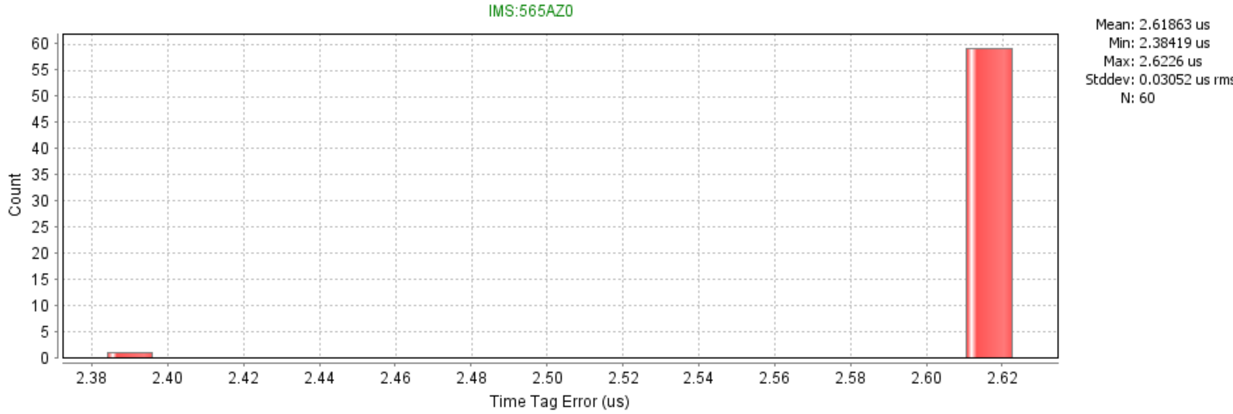

Figure 119 GPS Time Tag Accuracy PPM Time Distribution

Measurement of the GPS Time Tag Accuracy was performed by splitting the time synchronized PPM signal source simultaneously to all 8 channels at once. Since this configuration introduces the potential for additional time delay due to the combined loading of multiple channels, a separate test was performed in which the PPM signal was being split to all of the channels at once for an hour immediately followed by the PPM only being recorded by a single channel for an hour. At the time at which this follow-on test was performed, this resulted in a consistent 1.5 uS timing error while the PPM was split and 0 uS of error when only a single channel was recording the PPM. Therefore, the measured results above may in fact be 1.5 uS lower than the 2.16 to 2.62 uS that was reported. Correcting for this configuration bias results in the Affinity digitizers having a timing accuracy at or better than 1 uS.

Note that the Affinity digitizer supports GNSS time synchronization from multiple satellite constellations including GPS and GLONASS. The signal repeater in use for the testing only supports GPS frequencies, therefore only GPS time synchronization was demonstrated in this evaluation.

3.21 GPS 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 using a GPS timing source.

3.21.1 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.

3.21.2 Configuration

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

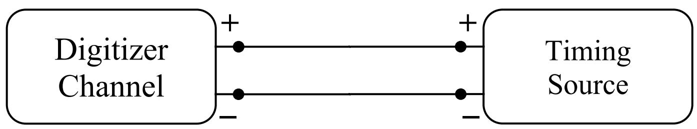

Figure 120 GPS Timing Drift Configuration Diagram

Table 58 GPS Timing Drift Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Quanterra Supertonal	123669	GPS PPM Output
Digitizer Timing Lock	Supplied GPS Antenna	N/A	N/A

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 to identify a time tag.

The digitizer clock is allowed to stabilize before the GPS antenna is covered 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.

In order for the Affinity GPS to lose reception, it was necessary to wrap the GPS antennas in metal foil and place them inside of a metal cabinet, as shown in the pictures below.

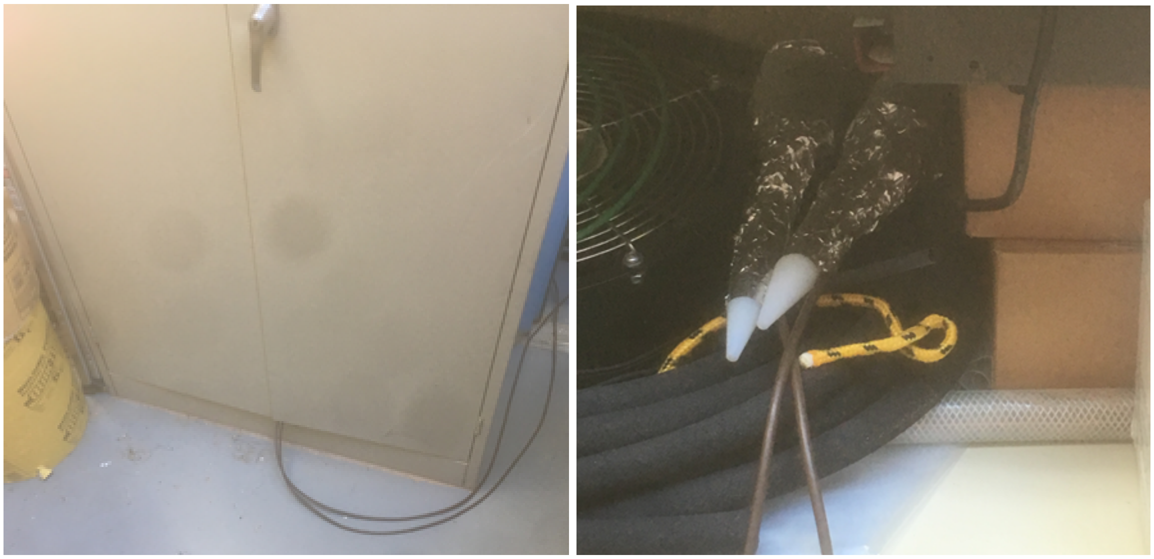

Figure 121 GPS Timing Drift Antenna picture

3.21.3 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.

3.21.4 Result

The figures below show the timing offsets over time as the digitizer channels drift and recover.

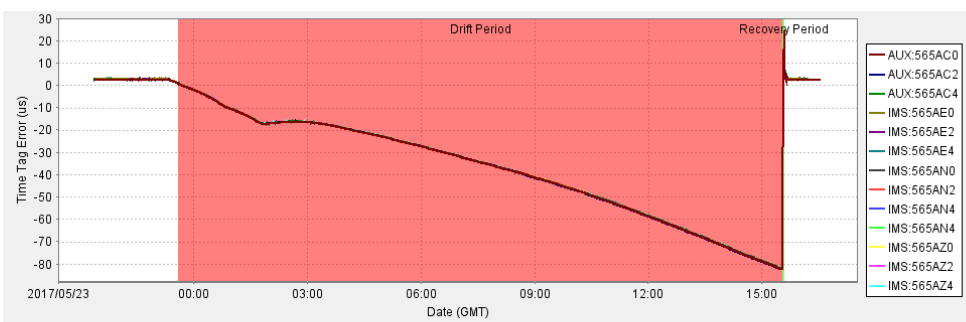

Figure 122 Time Tag Drift, DAS-40565A

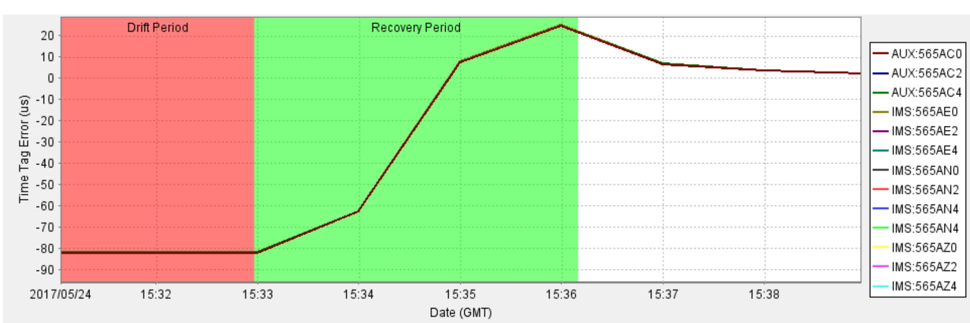

Figure 123 Time Tag Recovery, DAS-40565A

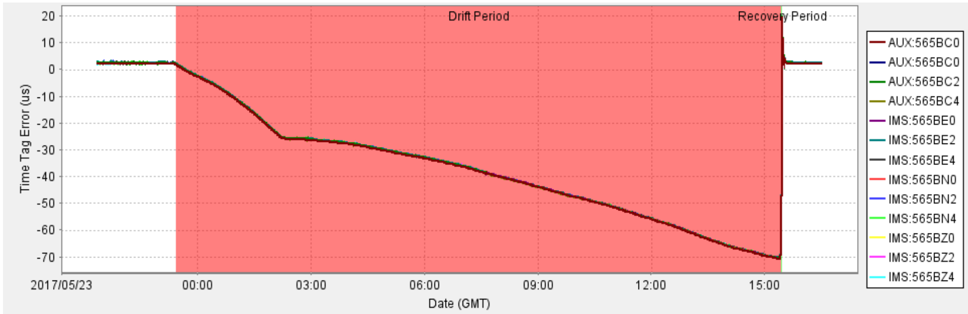

Figure 124 Time Tag Drift, DAS-40565B

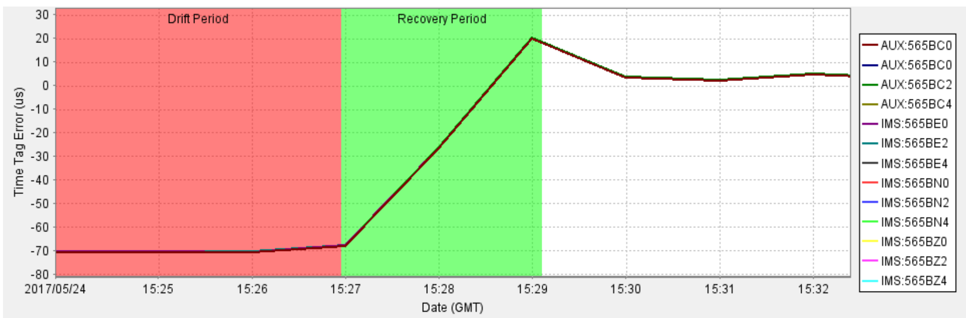

Figure 125 GPS Time Tag Recovery, DAS-40565B

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 59 GPS Time Tag Drift and Recovery

	DAS-40565A	**DAS-40565B**
Lock Level	2.5 us	2.5 us
Drift Rate	5.28 us/hr	4.56 us/hr
Drift Level (16 hrs)	-82 us	-70.5 us
Recovery Time	3 minutes	2 minutes
Stabilized Recovery Level	2.5 us	2.5 us

Both Affinity digitizers, DAS-40565A and DAS-40565B, drifted similarly once the GPS antenna had been covered at rates of 5.28 and 4.56 us/hr, respectively. Once timing lock was regained, they both recovered very quickly, within 2-3 minutes, back to levels of approximately 2.5 microseconds. The GPS timing drift test was performed at a gain of 1x. All channels and sample rates performed similarly.

3.22 PTP 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 with a PTP network timing source.

3.22.1 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.

3.22.2 Configuration

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

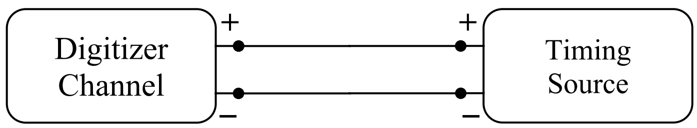

Figure 126 PTP Time Tag Accuracy Configuration Diagram

Figure 127 PTP Time Server

The PTP Time Server was placed outdoors and connected to the local network using a power over Ethernet connection.

Table 60 PTP Time Tag Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Quanterra Supertonal	123669	GPS PPM Output
Digitizer Timing Lock	PTP Time Server	N/A	N/A

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 to identify a time tag.

3.22.3 Analysis

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

3.22.4 Result

The tests of PTP timing were only performed on the DAS-40565A digitizer channels N and E as the Z channel was being used for recording from an MB3a infrasound sensor and the Auxiliary port was being used for recording meteorological sensors. DAS-40565B was being used at this time for temperature input terminated noise testing.

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.

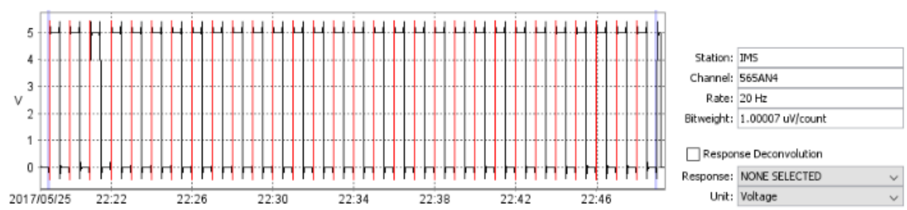

Figure 128 Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets averaged from 30 minutes of PPM signals:

Table 61 Time Tag Accuracy

	DAS-40565A (gain 1x)
Channel 2 (N) - 20 Hz	3.05 us
Channel 2 (N) - 40 Hz	0.21 us
Channel 2 (N) - 100 Hz	-2.25 us
Channel 3 (E) - 20 Hz	3.05 us
Channel 3 (E) - 40 Hz	0.26 us
Channel 3 (E) - 100 Hz	-2.19 us

The measured time tag accuracy values were found to have more differences in their result when using PTP than when using the GPS. However, results were still within single digits of microsecond timing error.

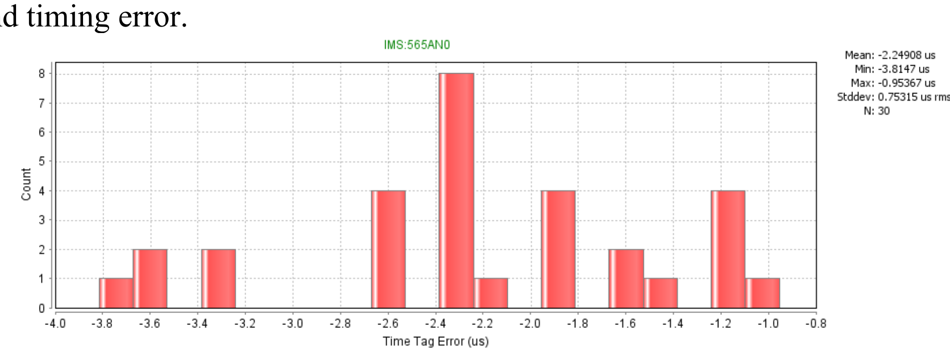

Figure 129 PTP Time Tag Accuracy PPM Time Distribution

There was considerably more variability in the distribution of PPM results when using a PTP server than what had been observed using the GPS, as shown histogram above.

3.23 PTP 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 using a PTP timing source.

3.23.1 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.

3.23.2 Configuration

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

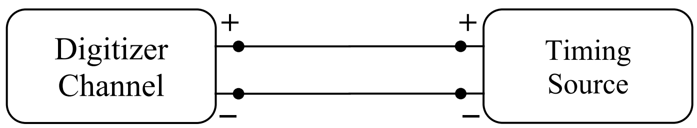

Figure 130 Timing Drift Configuration Diagram

Table 62 Timing Drift Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Quanterra Supertonal	123669	GPS PPM Output
Digitizer Timing Lock	PTP Time Server	N/A	N/A

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 PTP servers GPS antenna is covered resulting in the digitizer to lose timing lock. The digitizer is allowed to drift before the PTP server's antenna is uncovered and allowed to regain its timing lock.

In order for the PTP server to lose reception, it was necessary to wrap the PTP antenna in metal foil and place it indoors, as shown in the picture below.

Figure 131 PTP Timing Drift Antenna picture

3.23.3 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.

3.23.4 Result

The tests of PTP timing were only performed on the DAS-40565A digitizer channels N and E as the Z channel was being used for recording from an MB3a infrasound sensor and the Auxiliary port was being used for recording meteorological sensors. DAS-40565B was being used at this time for temperature input terminated noise testing.

Due to a combination of circumstances, the initial PTP drift period was performed at the same time as running a long duration calibration into an MB3a infrasound sensor on the same DAS-40565A digitizer. A feature of the Affinity, requested by the PTS, is that timing lock not be updated or maintained during a calibration cycle. Therefore, the over-night drift period did not yield valid results. However, after the calibration completed, the Affinity re-locked its timing to the PTP server, which was not locked to GPS and had been drifting. The figures below show the timing offsets over time as the digitizer channels drift and recover.

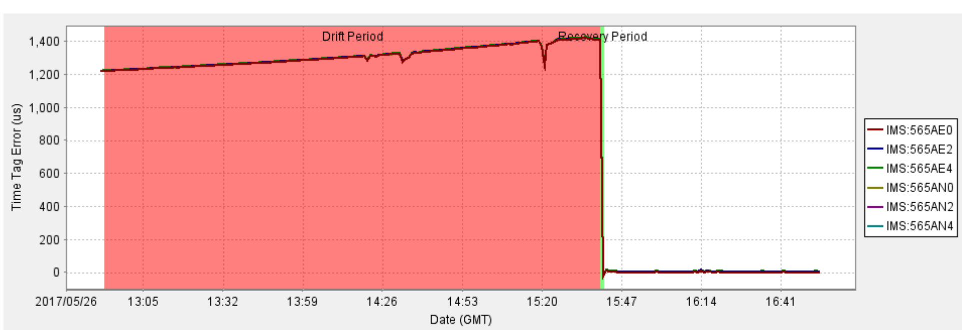

Figure 132 PTP Time Tag Drift, DAS-40565A

The Affinity remained locked to the PTP server the entire time that the PTP server was drifting and reported a valid time lock during this time. Apparently, the PTP server either was not relaying, or the Affinity was not monitoring, any information indicating that the PTP server did not have GPS lock. The observed drift is entirely due to the GPS receiving within the PTP server.

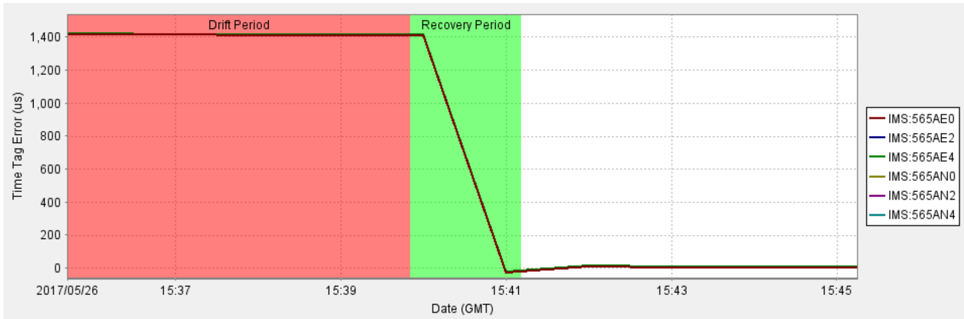

Figure 133 PTP Time Tag Recovery, DAS-40565A

Once the PTP server GPS antenna was uncovered, the PTP server quickly regained lock within 1 minute and the Affinity corrected its timing offset.

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 63 Time Tag Drift and Recovery

	DAS-40565A with PTP server
Lock Level	-2 us
Drift Rate	88 us/hr
Drift Level (16 hrs)	1410 us
Recovery Time	1 minute
Stabilized Recovery Level	0.5 us

It is apparent that the PTP server drifted more rapidly than the Affinity would when relying on its own internal clock. This may be due to higher drift rate in the clock implementation within the PTP server that was used or the fact that it was operating in a less temperature stable environment than the Affinity. In either case, it may be advisable for the Affinity to have a configuration that would allow it revert to its own internal clock in the event that a PTP server is able to report that it has lost GPS lock.

Additional tests were performed to continue measuring the Affinity timing accuracy with a PTP server while attempting to increase the amount of network data traffic. Data rates of approximately 1.5 Megabytes/second were started on May 26, 2017 at 18:36 UTC on the local 100 Mbit network that continued for several hours. The plot of timing error versus time below show the impact of the data traffic.

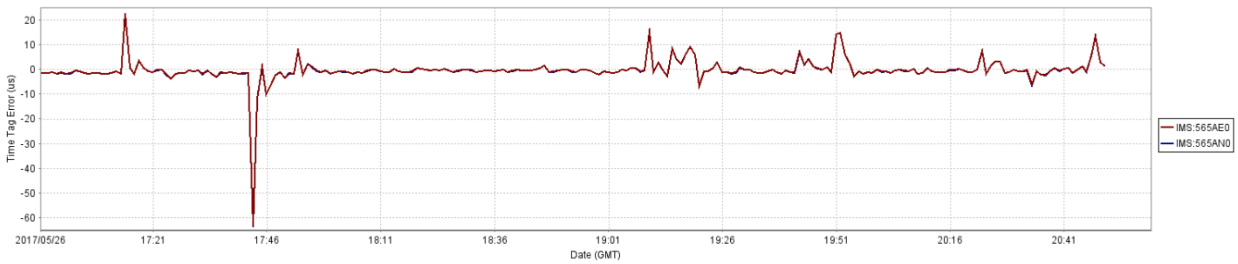

Figure 134 PTP Timing Accuracy with data traffic

The digitizer timing accuracy did not appear to be affected by the imposed data rates on the local wired Ethernet network. The variability in the timing accuracy does not appear to change significantly. Note that it is possible that a more remote network topology or higher latency network connections, such as a wireless link, may have more of an affect.

3.24 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.

3.24.1 Measurand

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

3.24.2 Configuration

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

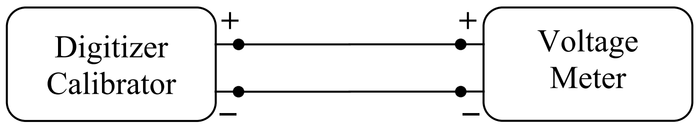

Figure 135 Calibrator Configuration Diagram

Table 64 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.

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.

3.24.3 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.

3.24.4 Result

The calibrator performance was demonstrated on the Affinity DAS-40565A digitizer. The figures and tables below show the reference meter recording of the calibrator output.

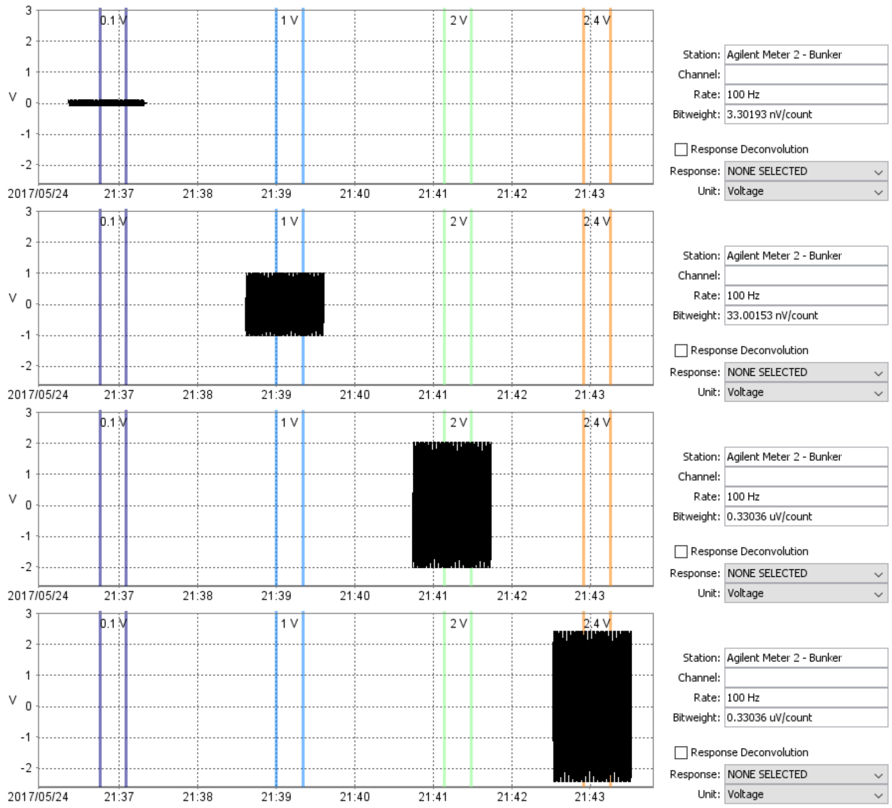

Figure 136 Calibrator Sine Amplitude at 1 Hz

Table 65 Calibrator Sine Amplitude at 1 Hz

Programmed Amplitude	Measured Amplitude	Percent Difference
0.1 V	0.1011 V	1.08%
1.0 V	1.0107 V	1.07%
2.0 V	2.0216 V	1.08%
2.4 V	2.4259 V	1.08%

The calibrator sinusoid amplitudes were measured to be approximately 1.08% higher than the values programmed into the digitizer.

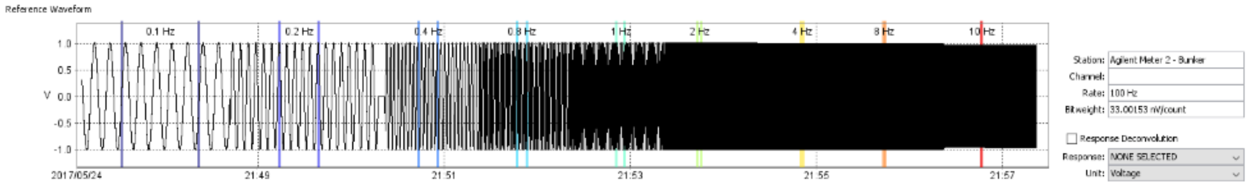

Figure 137 Calibrator Sine Frequency at 1 V

Table 66 Calibrator Sine Frequency at 1 V

Programmed Frequency	Measured Frequency	Percent Difference
0.1 Hz	0.09999 Hz	-0.0141%
0.2 Hz	0.20000 Hz	0.0000%
0.4 Hz	0.40000 Hz	0.0000%
0.8 Hz	0.80001 Hz	0.0012%
1.0 Hz	1.00001 Hz	0.0010%
2.0 Hz	2.00002 Hz	0.0010%
4.0 Hz	4.00004 Hz	0.0010%
8.0 Hz	8.00008 Hz	0.0010%
10.0 Hz	10.00010 Hz	0.0010%

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

In addition, the loopback to the calibration recording channel was monitored and the Affinity channel that was designated to recorded the calibration signal was observed to have a bit-weight of 0.29776 uV/count during the calibration cycle, regardless of that channel's original gain setting.

3.25 Sensor Compatibility Verification

The Affinity digitizers were connected to several example sensors to demonstrate compatibility and functionality. Each sensor was operated sufficiently to determine that it was performing properly. In addition, where possible, an instrument calibration was performed.

3.25.1 Geotech GS13

The Affinity DAS-40565B was connected to a Geotech GS13 Seismometer via a Guralp 40x preamplifier intended for a GS13.

Figure 138 Affinity DAS-40565B and GS13 Seismometer

The GS13 was operated to collect site background noise, a sine calibration, and a broadband calibration as described in the following sections.

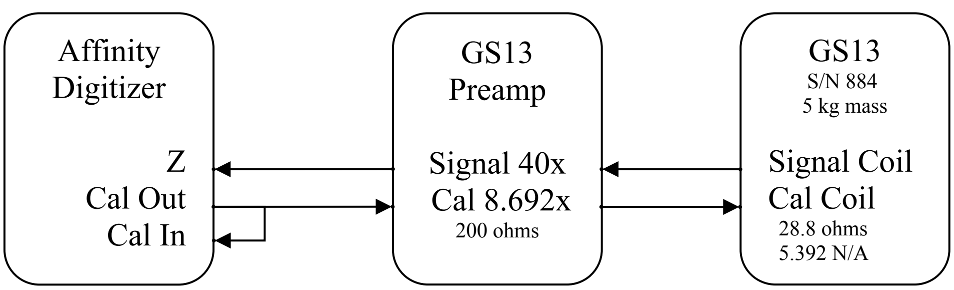

Figure 139 Geotech GS13 Demonstration Configuration

The recorded calibration input amplitude is scaled to determine the amount of acceleration imparted to the seismometer through its calibration coil:

$$A_{gs13} = \frac{V_{cal} * G_{preamp\ cal}}{R_{preamp} + R_{gs13\ calcoil}} * \frac{G_{cal\ coil}}{M}$$

Where

A_{gs13}	Acceleration imparted to the GS13 Seismometer Mass
V_{cal}	Calibration voltage input to the preamplifier
$G_{preamp\ cal}$	Calibration gain factor of the preamplifier, nominally 8.692x
R_{preamp}	Output impedance of the preamplifier calibration line, nominally 200 ohm
$R_{gs13\ calcoil}$	GS13 calibration coil impedance, 28.8 ohm from S/N 884 datasheet
$G_{cal\ coil}$	GS13 coil motor constant, 5.392 N/Ampere from S/N 884 datasheet
M	GS13 mass, 5 kg

This results in a theoretical calibration sensitivity of 0.04097 (m/s^2)/V or 24.41 V/(m/s^2).

3.25.1.1 Site Background

The GS13 seismometer and Affinity digitizer collected background signal as shown in the power spectra plot below:

Figure 140 GS13 Background Power Spectra

The power spectra properly represents the local site noise, indicating that the Affinity is collecting valid data from the GS13.

3.25.1.2 Sine Calibration

A sine calibration was performed using the Affinity digitizer to generate a 1 Hz sinusoid. The amplitude was reduced to a level of 0.010 V peak that would not produce clipping on the output.

The Affinity automatically loops back the calibration signal and records on an additional calibration recording channel. The time series of the calibration signal and the sensor output are shown in the figures below.

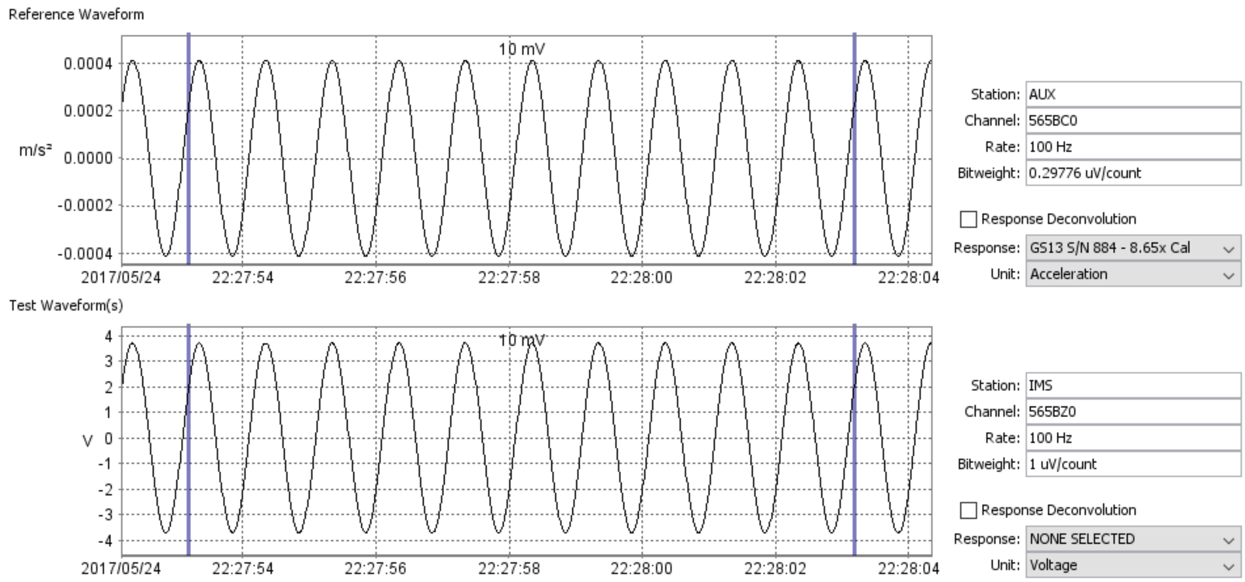

Figure 141 GS13 Sine Calibration Time Series

Using the specification sheet for the GS13 calibrator combined with the Guralp 40x preamplifier, the calibration signal shown above was converted to approximately 0.00041 m/s^2 of acceleration. Converting the calibration acceleration to a velocity at 1 Hz results in a velocity of 66.6e-5 m/s. Computing the ratio of the sensor voltage output and the calibration velocity results in an observed GS13 seismometer sensitivity at 1 Hz of 56,555 V/(m/s). Note that this includes the approximate 40x gain of the amplifier being used. Removing the 40x gain results in a GS13 sensor sensitivity of 1414 V/(m/s). This corresponds very closely to the theoretical GS13 sensitivity at 1 Hz of 1415 V/(m/s).

The results of the sine calibration indicate that the Affinity, operating through the Guralp 40x preamplifier box, was able to generate a calibration signal that matched very closely with the theoretical GS13 response at 1 Hz.

3.25.1.3 Broadband Calibration

A broadband white noise calibration was performed using the Affinity digitizer. The Affinity automatically loops back the calibration signal and records on an additional calibration recording channel. The time series, power spectra, coherence, and amplitude and phase response are shown in the figures below.

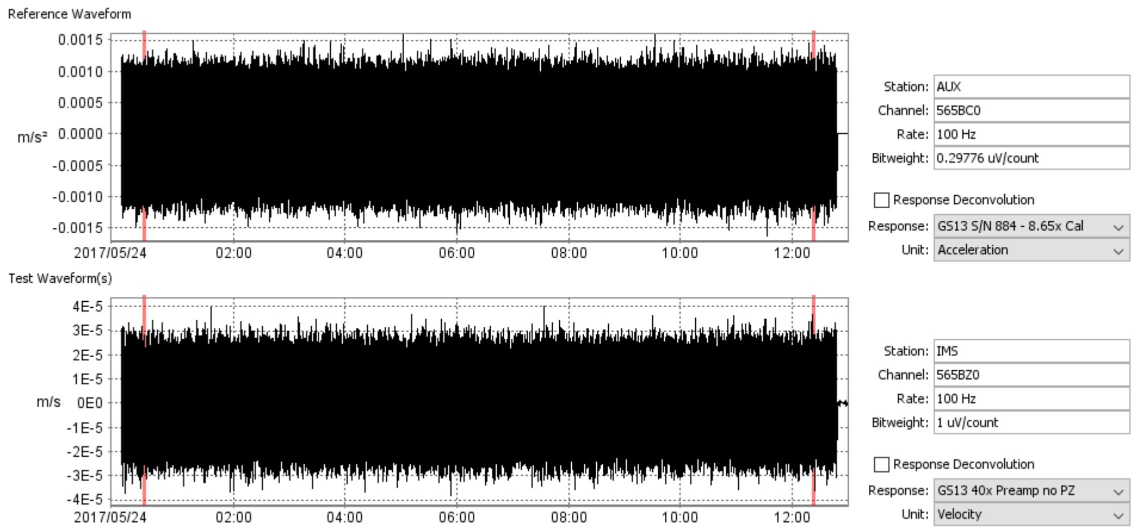

Figure 142 GS13 Calibration Time Series

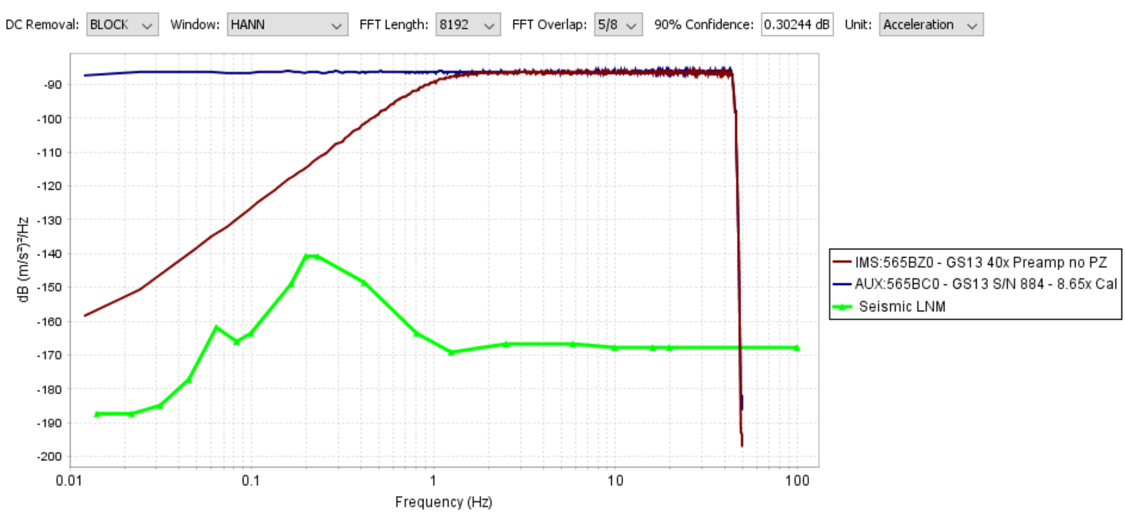

Figure 143 GS13 Calibration Power Spectra

The power spectra plot above shows the calibration signal in blue recorded on the Affinity loopback channel, converted to an equivalent acceleration. The sensor output voltage is corrected for the GS13 and 40x preamplifier sensitivity, but not poles and zeros, and converted to an equivalent acceleration. Note that the two power spectra overlay above 2 Hz, indicating agreement between the two signals. Below 2 Hz the sensor output is observed to roll off, consistent with the 1 Hz corner of the GS13 response.

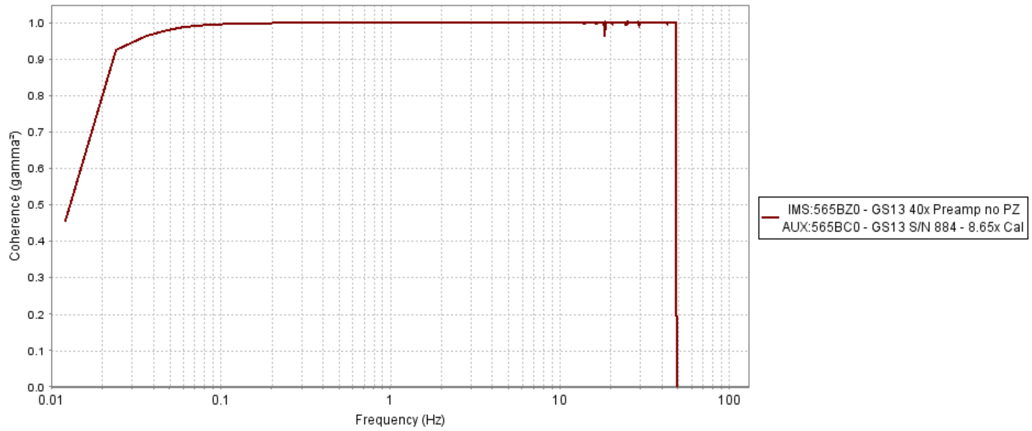

Figure 144 GS13 Calibration Coherence

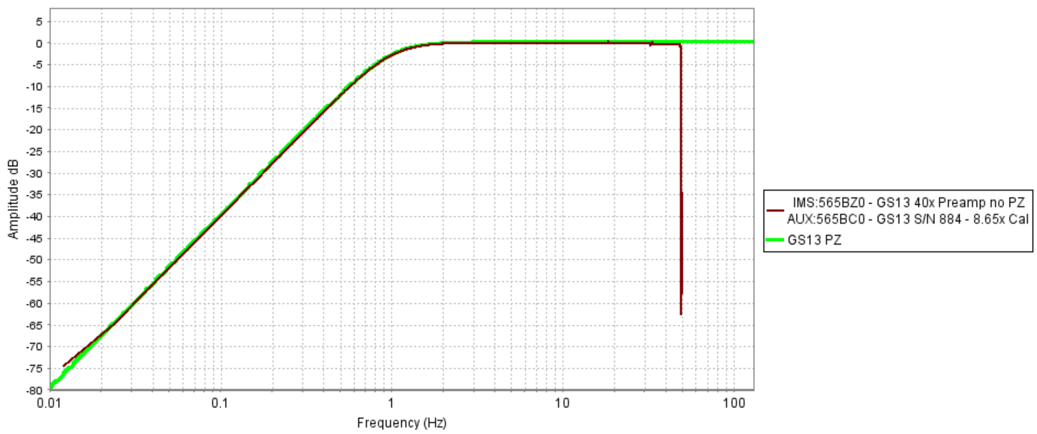

Figure 145 GS13 Calibration Amplitude Response

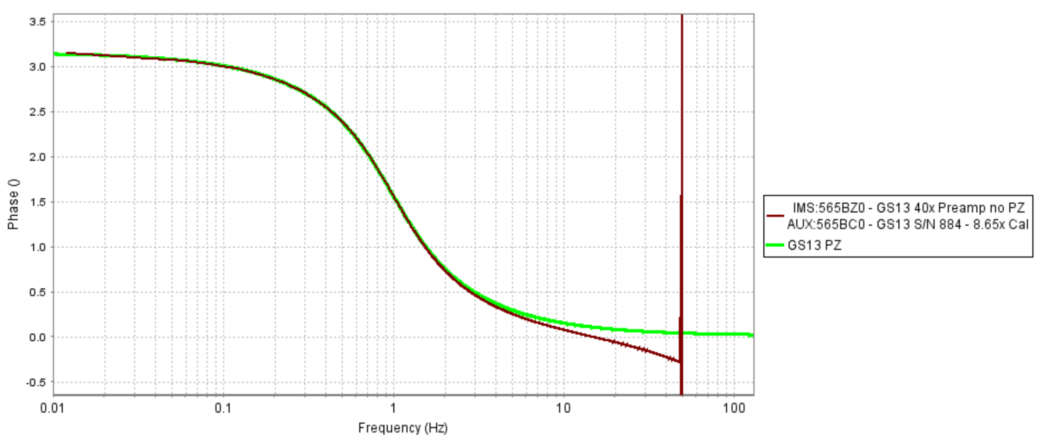

Figure 146 GS13 Calibration Phase Response

The results of the calibration indicate that the Affinity, operating through the Guralp GS13 40x Preamp box, was able to generate a calibration signal that was well above the site noise with excellent coherence and that the recorded GS13 amplitude and phase response, relative to the calibration signal, match very closely with the theoretical GS13 poles and zeros, shown in green in the figures above.

3.25.2 Kinemetrics STS-2

The Affinity DAS-40565B was connected to a Kinemetrics STS-2 high gain seismometer.

Figure 147 Affinity DAS-40565B and STS-2 Seismometer

The STS2 was operated to collect site background noise, a sine calibration, and a broadband calibration as described in the sections below.

3.25.2.1 Site Background

The STS-2 seismometer and Affinity digitizer collected background signal as shown in the power spectra plot below:

Figure 148 STS-2 Background Power Spectra

The power spectra properly reflects the local site noise, indicating that the Affinity is collecting valid data from the STS-2.

3.25.2.2 Sine Calibration

A sine calibration was performed using the Affinity digitizer to generate a 1 Hz sinusoid. The amplitude was reduced to a level of 0.1 V peak that would not produce clipping on the output.

The Affinity automatically loops back the calibration signal and records on an additional calibration recording channel. The time series of the calibration signal and the sensor output are shown in the figures below.

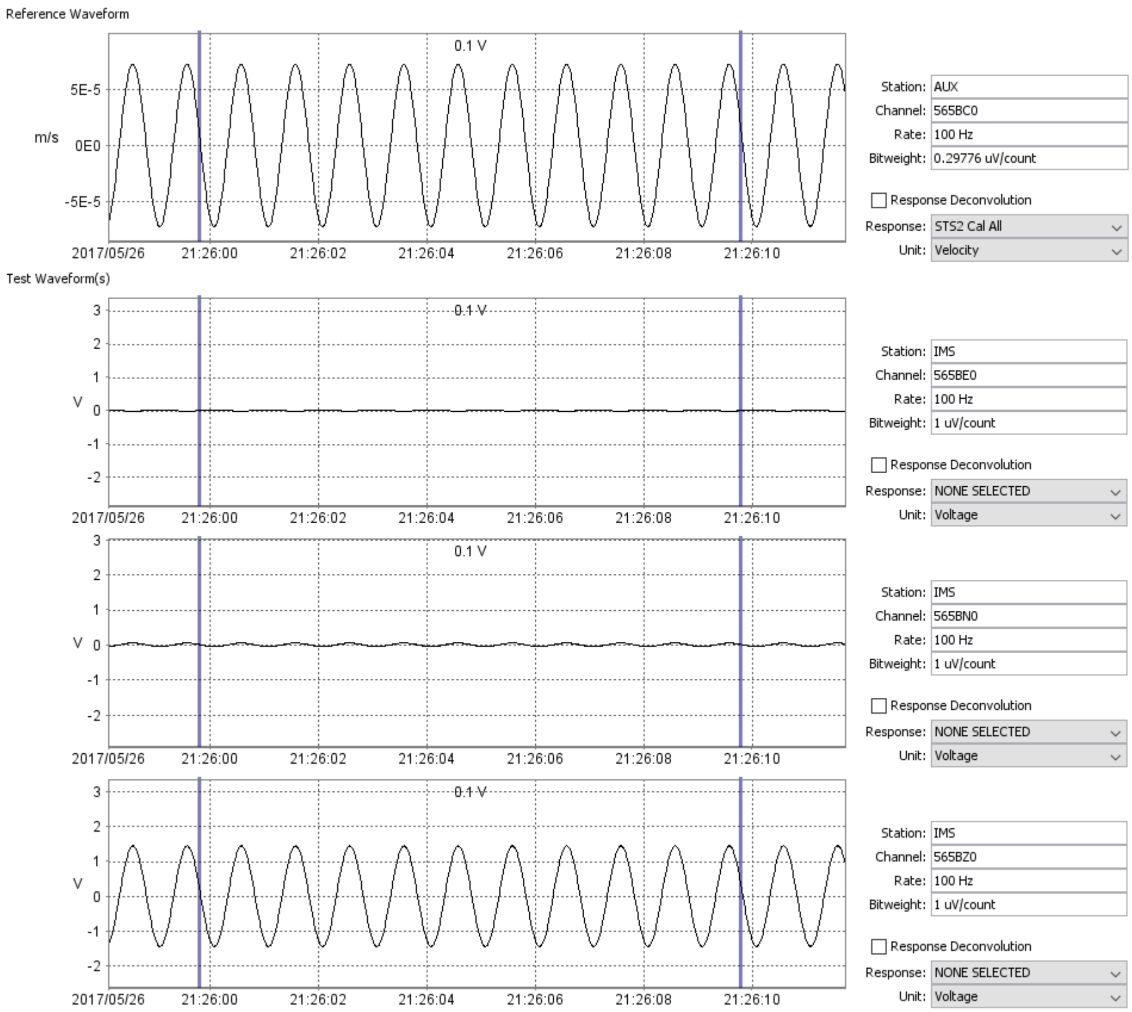

Figure 149 STS-2 Sine Calibration Time Series

Using the specification sheet for the STS2 calibrator, the recorded calibration signal was converted from voltage to acceleration. Converting the calibration acceleration then to a velocity and computing the ratio of the sensor voltage output and the calibration velocity results in an observed STS-2 seismometer sensitivity at 1 Hz of 19,989 V/(m/s). This corresponds very closely to the theoretical STS-2 high gain sensitivity at 1 Hz of 20,000 V/(m/s).

The results of the sine calibration indicate that the Affinity was able to generate a calibration signal that matched very closely with the theoretical STS-2 high gain response at 1 Hz.

3.25.2.3 Broadband Calibration

A broadband white noise calibration was performed using the Affinity digitizer. The Affinity automatically loops back the calibration signal and records on an additional calibration recording channel. The calibration was performed on all (U, V, and W) channels of the STS-2 simultaneously for 300 seconds. The time series, power spectra, coherence, and amplitude and phase response are shown in the figures below.

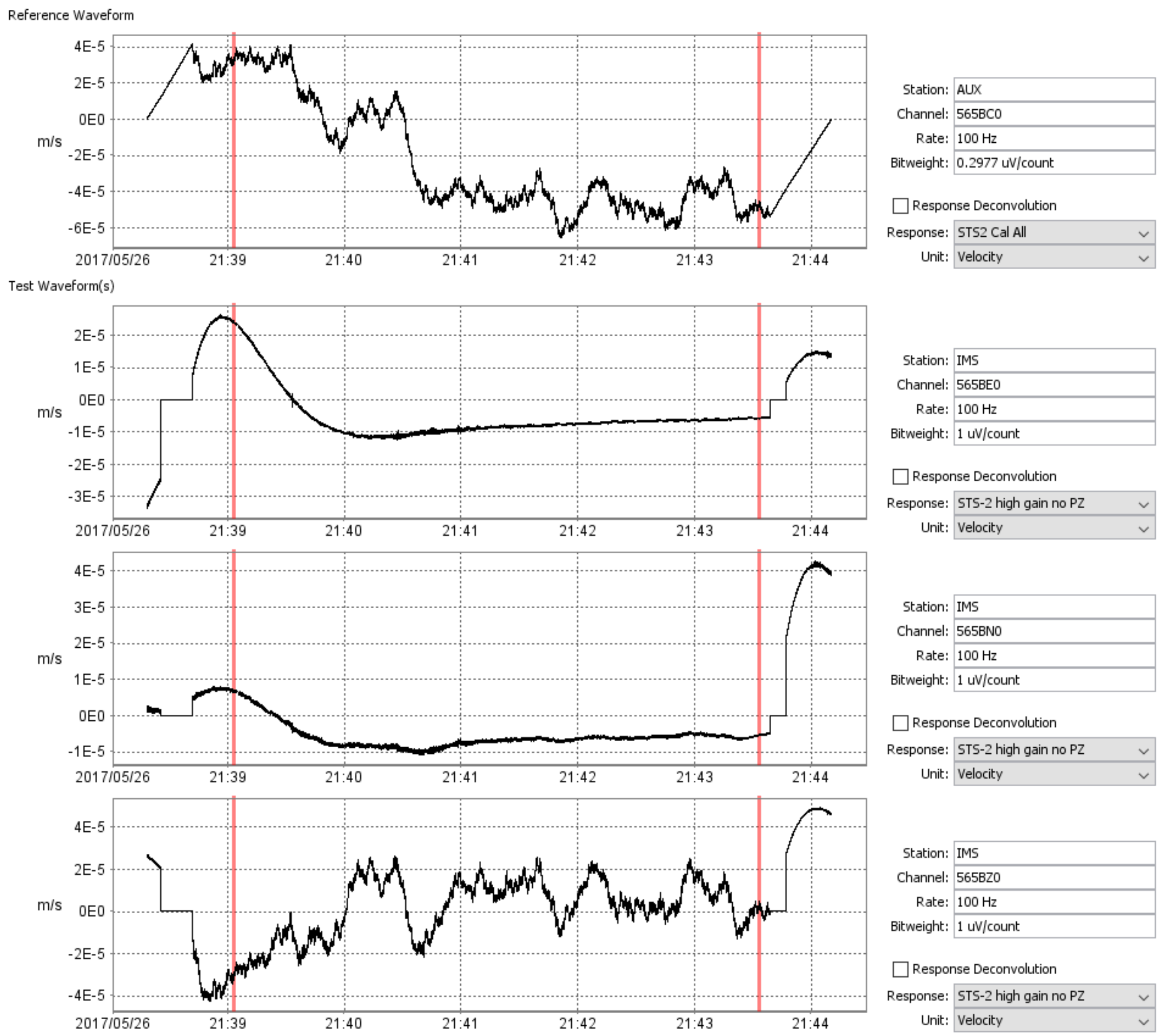

Figure 150 STS-2 Calibration Time Series

As expected from performing a calibration on all U, V, and W channels simultaneously, the output is principally on the STS-2 Z output channel. The horizontal channels have minimal output.

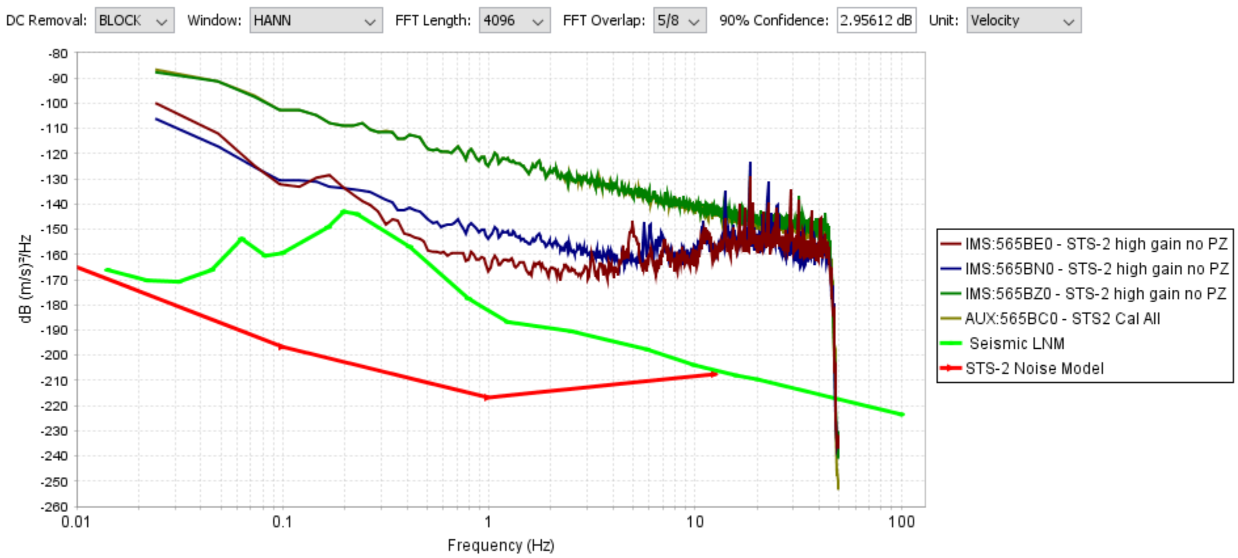

Figure 151 STS-2 Calibration Power Spectra

The power spectra plot above shows the calibration signal in beige, overlaid by the green line, recorded on the Affinity loopback channel, converted to an equivalent acceleration. The sensor output voltage is corrected for the STS-2 sensitivity, but not poles and zeros, and converted to an equivalent acceleration. Note that the two power spectra overlay above 2 Hz, indicating agreement between the two signals. Below 2 Hz the sensor output is observed to roll off.

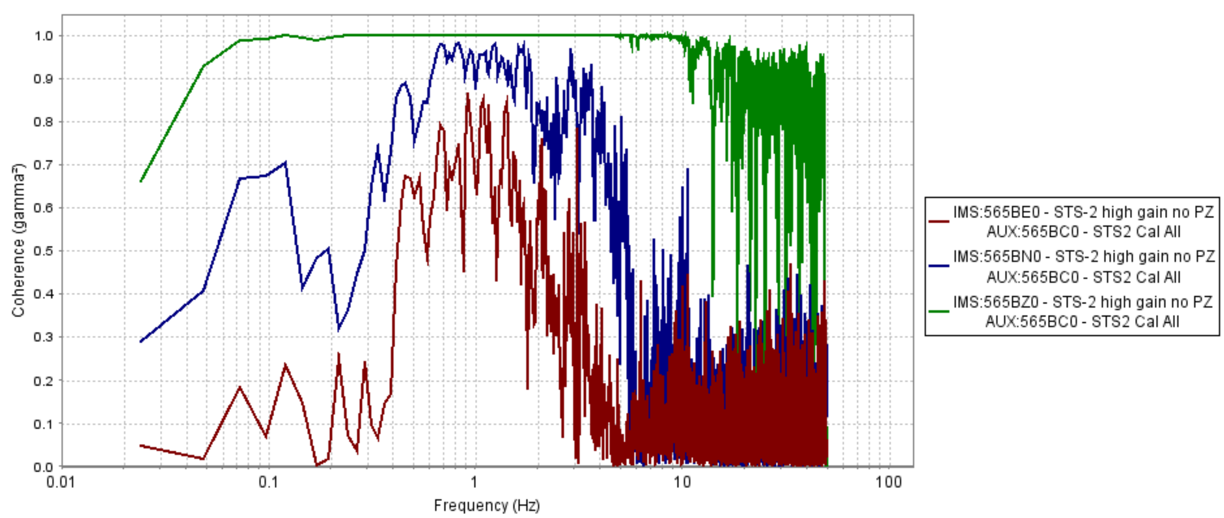

Figure 152 STS-2 Calibration Coherence

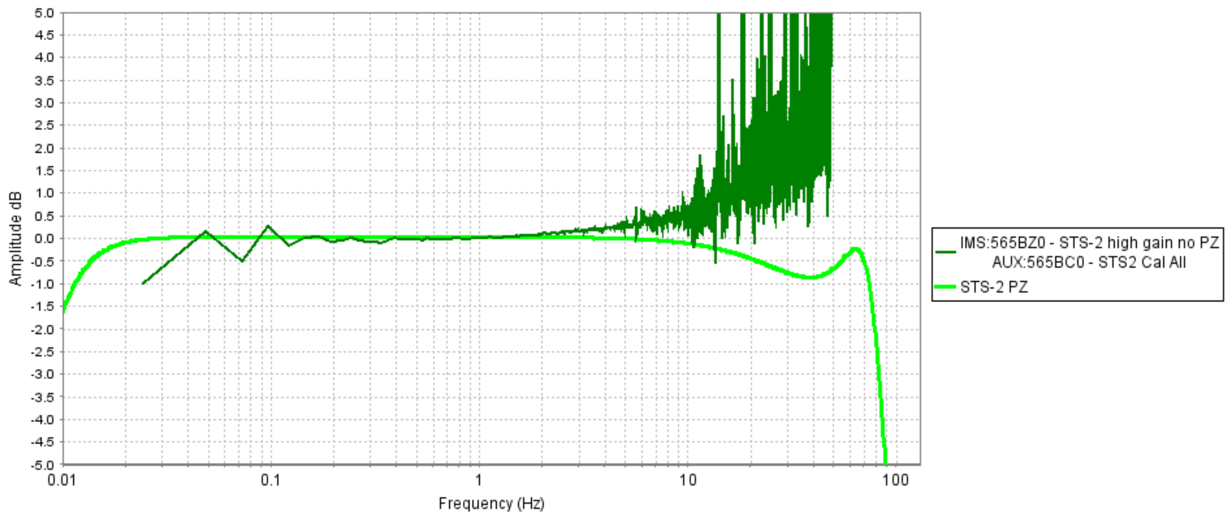

Figure 153 STS-2 Calibration Amplitude Response

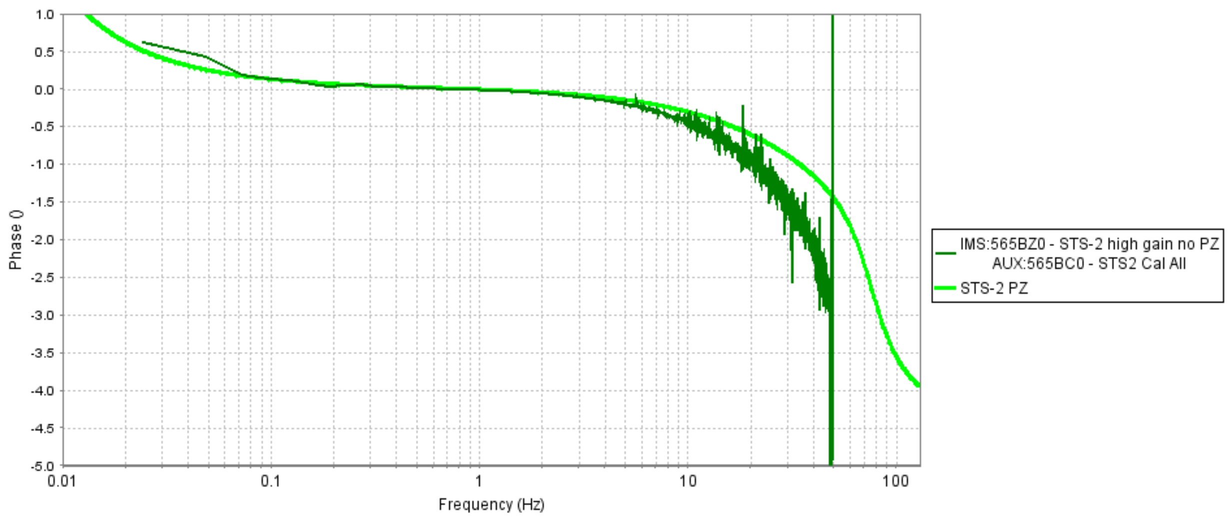

Figure 154 STS-2 Calibration Phase Response

The results of the calibration indicate that the Affinity was able to generate a calibration signal that was above the site noise with acceptable coherence over 0.1 to 10 Hz and that the recorded STS-2 amplitude and phase response, relative to the calibration signal, match with the theoretical STS-2 poles and zeros, shown in green in the figures above.

3.25.3 MB3a

The Affinity DAS-40565A was connected to an MB3a infrasound sensor, as shown in the figure below.

Figure 155 Affinity DAS-40565A and MB3a infrasound sensor

The MB3a was operated to collect site background noise, a sine calibration, and a broadband calibration as described in the sections below.

3.25.3.1 Site Background

The MB3a and Affinity digitizer collected background signals with the sensor ports open and plugged as shown in the power spectra plots below:

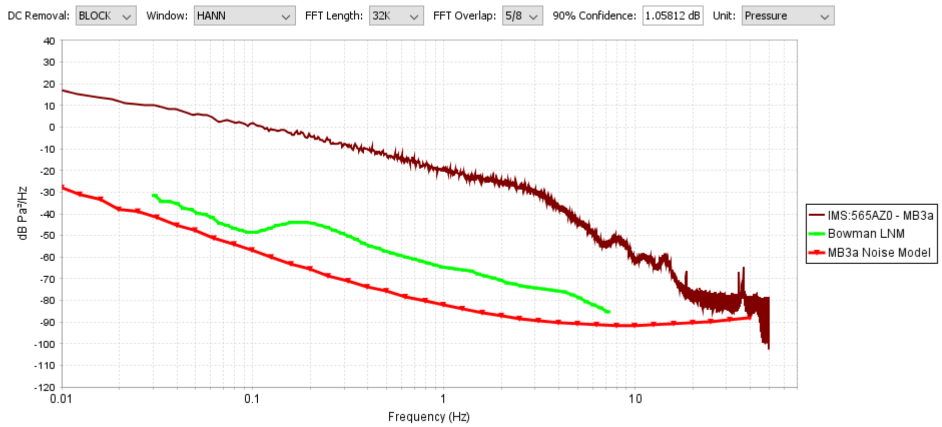

Figure 156 MB3a Open Background Power Spectra

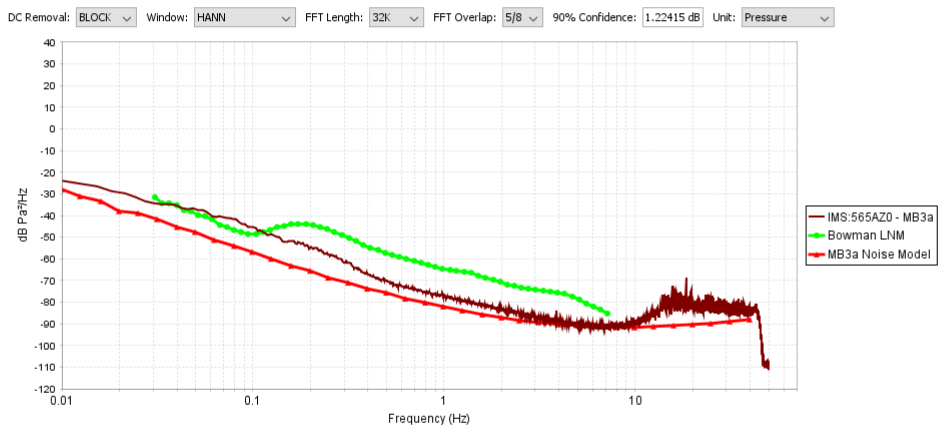

Figure 157 MB3a Plugged Background Power Spectra

The Affinity was able to resolve the MB3a output as being close to its self-noise model when capped, as the MB3a system noise plots suggested. Note that the site background noise is much higher than the Bowman Low Noise Model when the MB3a ports are open as it is not connected to a wind noise reduction system.

3.25.3.2 Sine Calibration

A sine calibration was performed using the Affinity digitizer to generate a 1 Hz sinusoid. The amplitude was increased to its maximum output level of 2.4 V peak to maximize the signal to noise ratio.

The Affinity automatically loops back the calibration signal and records on an additional calibration recording channel. The time series of the calibration signal and the sensor output are shown in the figures below.

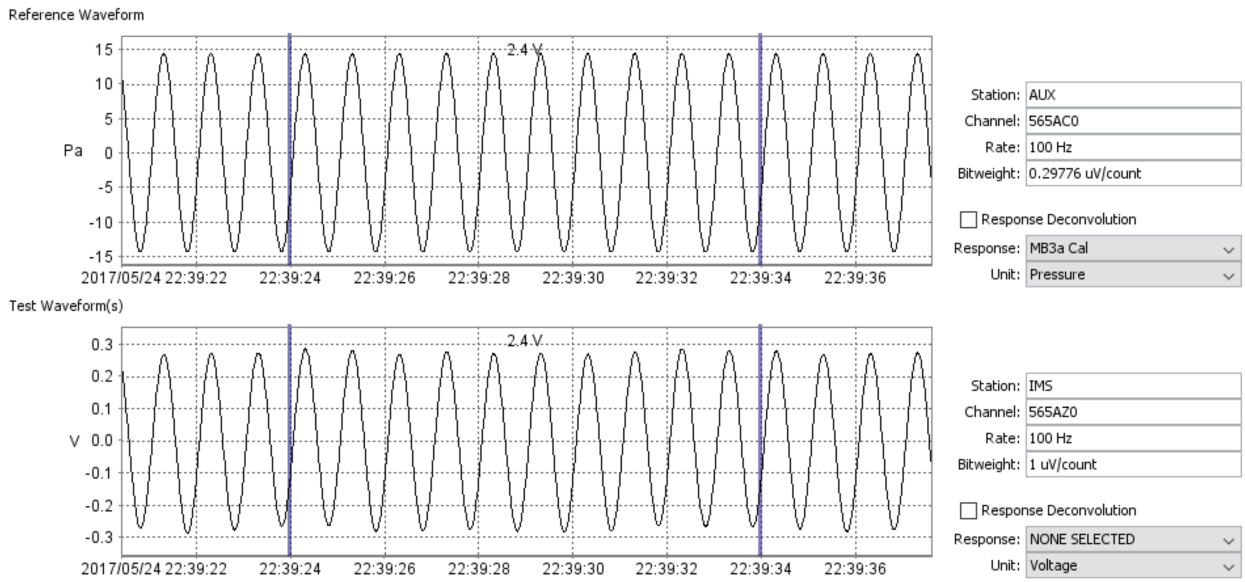

Figure 158 MB3a Sine Calibration Time Series

The MB3a calibrator sensitivity of 6 Pa/V (or 0.1667 V/Pa) was applied to the input calibration single to convert it from voltage to a pressure. Computing the ratio of the sensor voltage output and the calibration pressure results in an observed MB3a sensitivity at 1 Hz of 19.2 mV/Pa. This corresponds very closely to the theoretical MB3a sensitivity at 1 Hz of 20 mV/Pa.

The results of the sine calibration indicate that the Affinity was able to generate a calibration signal that matched very closely with the theoretical MB3a response at 1 Hz.

3.25.3.3 Broadband Calibration

A broadband noise calibration was performed using the Affinity digitizer. Note that the calibration of the MB3a must be performed with the ports open, otherwise the results will be affected by the restrained volume internal to the MB3a.

The Affinity was programmed to generate brown noise at its maximum voltage output of 2.4 V during an overnight test. 7 hours of data was used for comparing the calibration response, once the local site noise had reduced during the overnight period. The Affinity automatically loops back the calibration signal and records on an additional calibration recording channel. The time series, power spectra, and amplitude and phase response are shown in the figures below.

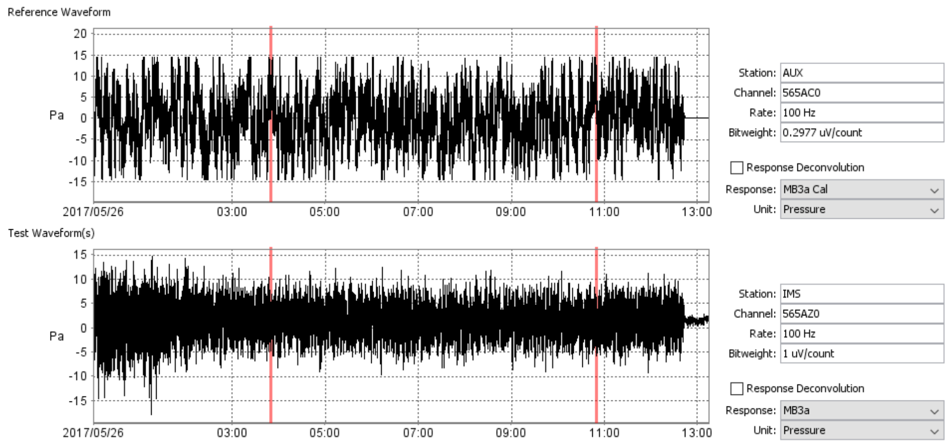

Figure 159 MB3a Calibration Time Series

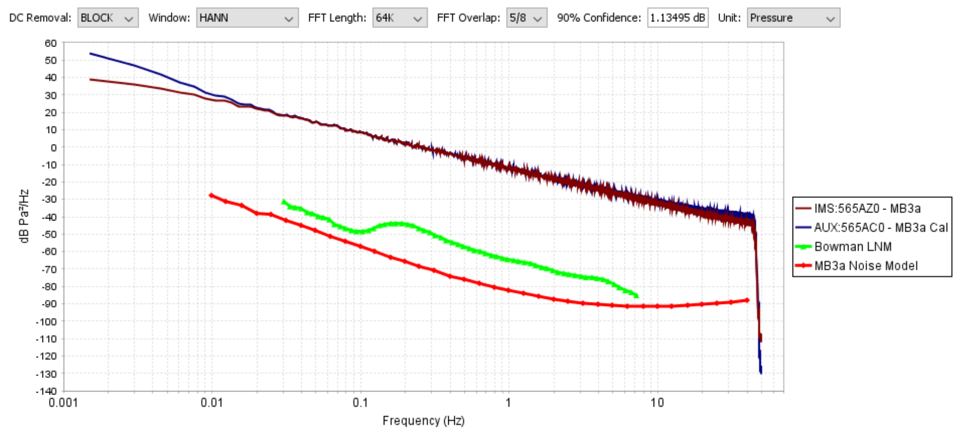

Figure 160 MB3a Calibration Power Spectra

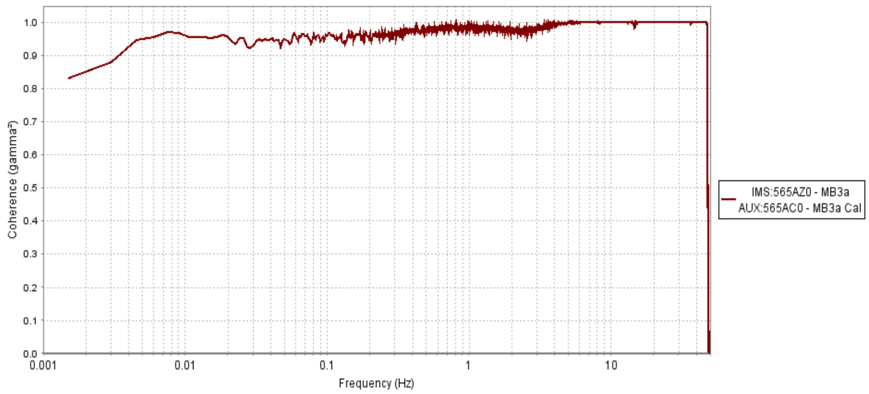

Figure 161 MB3a Calibration Coherence

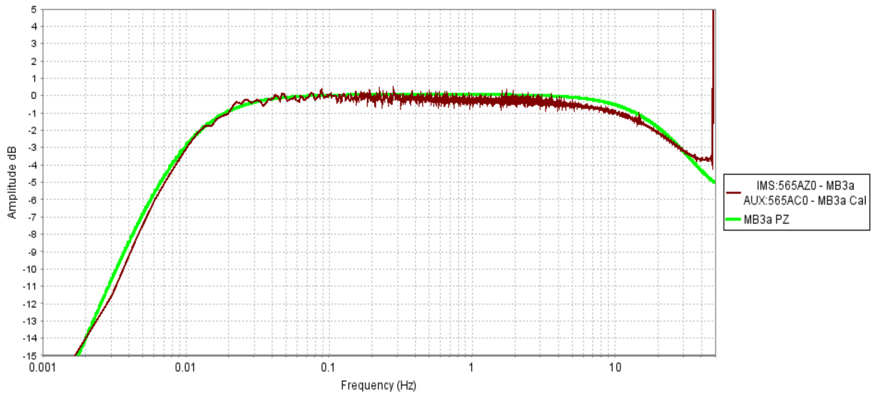

Figure 162 MB3a Calibration Amplitude Response

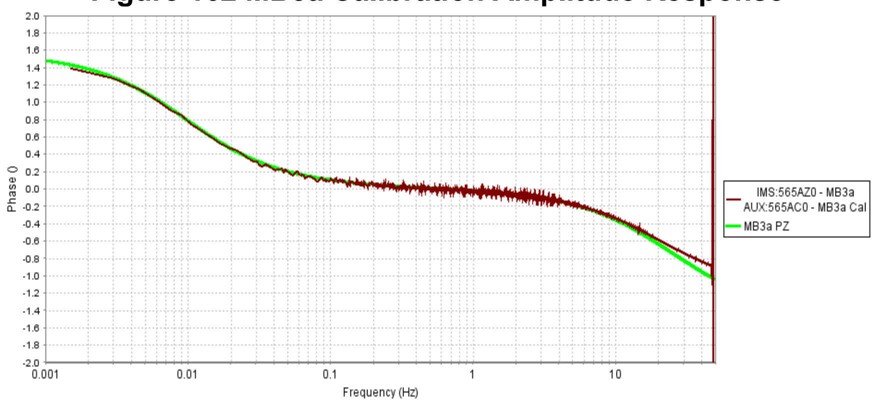

Figure 163 MB3a Calibration Phase Response

The results of the calibration indicate that the Affinity was able to generate a broadband calibration signal that was slightly above the background site noise at the time of the test. The measured amplitude and phase response, relative to the calibration signal, match very closely with the theoretical MB3a poles and zeros, shown in green in the figures above. However, the background noise present on the MB3a was sufficiently high to cause the reductions in coherence and increased scatter in the amplitude and phase response.

In noisier site conditions, it may be difficult to conduct a broadband calibration with an Affinity and an MB3a. It is possible that an increase in the Affinity's maximum voltage output, an increase in the MB3a calibration sensitivity, or an intermediate preamplifier may be sufficient to generate larger calibration signals.

3.26 CD1 Status Flag Verification

During the evaluation of the Affinity digitizer, the status flags on the CD1 stream were examined to verify whether they were passing status flags for events such as calibration underway, loss of GPS lock, and timing drift too large.

Verification of CD1 status flags was performed using DAS-40565A. As a baseline, the CD1 status flags being reported during normal operation were observed to be:

```
Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x13 0x43 "2017305 17:25:56.000" 0
      vault door opened
```

Indicating that the relay for the vault door was not connected to anything and that the GPS was locked with 0 micro-seconds of offset.

3.26.1 Calibration underway

A calibration was initiated from the webpage of the Affinity DAS-40565A on November 1, 2017 at 17:32 (UTC) to generate a sine calibration signal for 300 seconds. The following was observed on the CD1 status:

```
Channel status: 32/0x01 0x08 0x04 0x07 0x00 0x4a 0x14 0x43 "2017305 17:32:58.000" 193938
      calibration underway
      vault door opened
      clock differential too large
      GPS receiver off
      GPS receiver unlocked
```

The proper *calibration underway* flag was set. However, it should be noted that the Affinity was also reporting during calibration that the GPS was receiver was off, unlocked, and that the clock differential was too large.

At the completion of the calibration cycle, the CD1 status flags reverted to the baseline condition:

```
Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x13 0x43 "2017305 17:40:28.000" 6
      vault door opened
```

Note that the status messages indicated a very slight amount of timing offset of less than 10 microseconds for a few minutes after the calibration completed. This would appear to be consistent with the timing resynchronizing with the GPS receiver locked.

3.26.2 GPS Unlocked

The Affinity DAS-40565A GPS antenna was covered with metal foil and placed within a steel cabinet, without disconnecting the antenna from the digitizer, in order to recreate conditions in which the GPS antenna did not have reception. After several minutes, the Affinity did report in the CD1 log that the GPS receiver was unlocked:

```
Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x4a 0x14 0x44 "2017305 18:04:07.000" 0
      vault door opened
      GPS receiver unlocked
```

However, within the next data frame, the CD1 status log also reported that the GPS receiver was off. There was initially a very large reported timing offset that was corrected by the next frame.

```
Channel status: 32/0x01 0x00 0x04 0x06 0x00 0x4a 0x13 0x44 "2017305 18:04:18.000" 4294967294
      vault door opened
      GPS receiver off
      GPS receiver unlocked
```

```
Channel status: 32/0x01 0x00 0x04 0x06 0x00 0x4a 0x13 0x44 "2017305 18:04:28.000" 1
      vault door opened
      GPS receiver off
      GPS receiver unlocked
```

Note that even though the CD1 status log indicated that the GPS receiver was off, detailed examination of the Affinity status webpages reported that the GPS receiver was actually powered on and that serial communication with the GPS receiver was active. The GPS receiver did not report seeing any satellite within view.

In discussion with Guralp, it was identified that the GPS receiver was entering a low power mode and transmitting serial messages back to the Affinity less frequently, once every 4 seconds, rather than once per second. The Affinity was then intermittently reporting the GPS receiver as being off due to the messages not being received as expected. Guralp has reportedly corrected this in a firmware revision to require that no messages be received within a 20 second period before declaring the GPS to be off. Note that this change has not been independently verified by Sandia.

3.26.3 GPS Drift

The Affinity DAS-40565A was allowed to drift over-night with the GPS antenna unlocked. The CD1 status continued to report that the GPS receiver was both off and unlocked. The Affinity accumulated a worst-case timing drift that was reported in the channel status. The estimated timing drift increased continuously and once it exceeded 1 millisecond the CD1 status updated to indicate a *clock differential too large* message:

```
Time stamp: "2017306 01:01:20.000" [1509584480.000000 2017/11/02 01:01:20.000000]
Authentication offset (bytes): 540
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [40.000000]
Authentication switch: 1 [on]
Compression: 1 [Canadian before signing]
Sensor type: 0 [Seismic]
Calibration factor (nm/count): 1.591549e+08
Calibration period (sec): 1.000000
Site/Channel/Location names: 565A/BHZ/
Channel status: 32/0x01 0x00 0x04 0x07 0x00 0x4a 0x14 0x46 "2017305 18:04:28.000" 1002
      vault door opened
      clock differential too large
      GPS receiver off
      GPS receiver unlocked
```

It took just under 5 hours with the GPS antenna covered for the Affinity to report that 1002 microseconds of drift had occurred, indicating an assumed drift rate of 200 us/hr. The assumed drift rate is much higher than the previously measured GPS drift rate of between 4.56 and 5.28 us/hr that was observed under thermally stable temperatures.

The digitizer clock was allowed to drift for a total of two days by the end of which it had reported an assumed drift of 6922 microseconds:

```
Time stamp: "2017307 18:08:30.000" [1509732510.000000 2017/11/03 18:08:30.000000]
Authentication offset (bytes): 660
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [40.000000]
Authentication switch: 1 [on]
Compression: 1 [Canadian before signing]
Sensor type: 0 [Seismic]
Calibration factor (nm/count): 1.591549e+08
Calibration period (sec): 1.000000
Site/Channel/Location names: 565A/BHZ/
Channel status: 32/0x01 0x00 0x04 0x07 0x00 0x4a 0x14 0x47 "2017305 18:04:28.000" 6922
      vault door opened
      clock differential too large
      GPS receiver off
      GPS receiver unlocked
```

The GPS antenna was uncovered and placed back where it would have reception. Once the GPS receiver regained lock, the CD1 status flags of *clock differential too large*, *GPS receiver off*, and *GPS receiver unlocked* all cleared and the reported time differential reverted back to near zero:

```
Time stamp: "2017307 18:13:50.000" [1509732830.000000 2017/11/03 18:13:50.000000]
Authentication offset (bytes): 688
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [40.000000]
Authentication switch: 1 [on]
Compression: 1 [Canadian before signing]
Sensor type: 0 [Seismic]
Calibration factor (nm/count): 1.591549e+08
Calibration period (sec): 1.000000
Site/Channel/Location names: 565A/BHZ/
Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x14 0x46 "2017307 18:13:54.000" 5
      vault door opened
```

3.27 CD1 Frame Alignment Verification

During the evaluation of the Affinity digitizer, the frame alignment of the CD1 stream was checked to verify that data packets from channels with different sample rates were being properly packaged in the same CD1 frame.

Verification of CD1 frame alignment was performed using DAS-40565A. The three primary channels were being transmitted at 40 Hz sample rate and three auxiliary channels were being transmitted at a 10 Hz sample rate. Below are sections of the output for two successive frames, showing only channels 1, a 10 second 10 Hz data frame, and 4, a 10 second 40 Hz data frame.

Inspection of the data frames reveal that each channel subframe contains the correct number of samples to make up 10 seconds, 100 samples for the 10 Hz data and 400 samples for the 40 Hz data. In addition, the start times of the channel subframes are all consistent with the overall start time of the data frame.

```
**** Data Frame received ****
Bytes received: [2836]
Frameset: DAS565A/0/303745
Trailer offset: 2780
Authentication Key ID: 8690
Authentication size (bytes): 40
Received at: [1510862604.712040 2017/11/16 20:03:24.712039]
Placed at offset: [0x98d50 (626000) in DAS565A.20171116.1924.11bin]
Receive span (sec): [0.000304]
Authentication summary: [Unknown]
Frame signature check: [Unknown]
Frame parsing code: [0x0]
Additional info: [Data frame received]
Number of Channels: 6
Channel mask: [111111]
Frame Time Length (mS): 10000
Nominal start time: "2017320 20:03:20.000" [1510862600.000000 2017/11/16 20:03:20.000000]
Nominal delay (sec): [4.712040]
Channel string count: 60
Channel Sub-Frame information:
Channel # [1]:
     Channel parsing code: [0x0]
     Channel offset (bytes): [128]
     Packet length (bytes): 352
     Number of samples: 100
     Time stamp: "2017320 20:03:20.000" [1510862600.000000 2017/11/16 20:03:20.000000]
     Authentication offset (bytes): 308
     Subframe Time Length (mS): 10000
     Nominal sample rate (s/sec): [10.000000]
     Authentication switch: 1 [on]
     Compression: 1 [Canadian before signing]
     Sensor type: 3 [Weather]
     Calibration factor (nm/count): 1
     Calibration period (sec): 1.000000
     Site/Channel/Location names: 565A/MB/
     Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x13 0x3e "2017320 20:03:18.000" 0
          vault door opened
     Data format: s4
     Data size (bytes): 204
     Subframe count: 0
     Authentication Key ID: 8690
     Authentication size (bytes): 40
     Diff from nominal time (sec): [0.000000]
     Data offset (bytes): [228]
     Signature check: [Unknown]

     ...
Channel # [4]:
     Channel parsing code: [0x0]
     Channel offset (bytes): [1224]
     Packet length (bytes): 708
     Number of samples: 400
     Time stamp: "2017320 20:03:20.000" [1510862600.000000 2017/11/16 20:03:20.000000]
     Authentication offset (bytes): 664
     Subframe Time Length (mS): 10000
     Nominal sample rate (s/sec): [40.000000]
     Authentication switch: 1 [on]
     Compression: 1 [Canadian before signing]
     Sensor type: 4 [Other]
     Calibration factor (nm/count): 1.591549e+08
     Calibration period (sec): 1.000000
     Site/Channel/Location names: 565A/BHZ/
     Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x13 0x3e "2017320 20:03:18.000" 0
          vault door opened
     Data format: s4
     Data size (bytes): 560
     Subframe count: 0
     Authentication Key ID: 8690
     Authentication size (bytes): 40
     Diff from nominal time (sec): [0.000000]
     Data offset (bytes): [1324]
     Signature check: [Unknown]
```

Figure 164 CD1 Frame Alignment – Frame 1

```
**** Data Frame received ****
Bytes received: [2844]
Frameset: DAS565A/0/303746
Trailer offset: 2788
Authentication Key ID: 8690
Authentication size (bytes): 40
Received at: [1510862614.724187 2017/11/16 20:03:34.724186]
Placed at offset: [0x99864 (628836) in DAS565A.20171116.1924.11bin]
Receive span (sec): [0.000011]
Authentication summary: [Unknown]
Frame signature check: [Unknown]
Frame parsing code: [0x0]
Additional info: [Data frame received]
Number of Channels: 6
Channel mask: [111111]
Frame Time Length (mS): 10000
Nominal start time: "2017320 20:03:30.000" [1510862610.000000 2017/11/16 20:03:30.000000]
Nominal delay (sec): [4.724187]
Channel string count: 60
Channel Sub-Frame information:
Channel # [1]:
      Channel parsing code: [0x0]
      Channel offset (bytes): [128]
      Packet length (bytes): 340
      Number of samples: 100
      Time stamp: "2017320 20:03:30.000" [1510862610.000000 2017/11/16 20:03:30.000000]
      Authentication offset (bytes): 296
      Subframe Time Length (mS): 10000
      Nominal sample rate (s/sec): [10.000000]
      Authentication switch: 1 [on]
      Compression: 1 [Canadian before signing]
      Sensor type: 3 [Weather]
      Calibration factor (nm/count): 1
      Calibration period (sec): 1.000000
      Site/Channel/Location names: 565A/MB/
      Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x13 0x3e "2017320 20:03:18.000" 0
            vault door opened
      Data format: s4
      Data size (bytes): 192
      Subframe count: 0
      Authentication Key ID: 8690
      Authentication size (bytes): 40
      Diff from nominal time (sec): [0.000000]
      Data offset (bytes): [228]
      Signature check: [Unknown]

        ...
Channel # [4]:
      Channel parsing code: [0x0]
      Channel offset (bytes): [1240]
      Packet length (bytes): 704
      Number of samples: 400
      Time stamp: "2017320 20:03:30.000" [1510862610.000000 2017/11/16 20:03:30.000000]
      Authentication offset (bytes): 660
      Subframe Time Length (mS): 10000
      Nominal sample rate (s/sec): [40.000000]
      Authentication switch: 1 [on]
      Compression: 1 [Canadian before signing]
      Sensor type: 4 [Other]
      Calibration factor (nm/count): 1.591549e+08
      Calibration period (sec): 1.000000
      Site/Channel/Location names: 565A/BHZ/
      Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x4a 0x13 0x3e "2017320 20:03:18.000" 0
            vault door opened
      Data format: s4
      Data size (bytes): 556
      Subframe count: 0
      Authentication Key ID: 8690
      Authentication size (bytes): 40
      Diff from nominal time (sec): [0.000000]
      Data offset (bytes): [1340]
      Signature check: [Unknown]
```

Figure 165 CD1 Frame Alignment – Frame 2

4 SUMMARY

Power Consumption
The Affinity digitizer was found to consume 2.2 watts of power in general operation. Power consumption was not observed to vary with gain level. This power consumption is elevated above the datasheet specification of 1.55 W, consistent with the presence of a Spyrus data authentication card internal to the digitizer.

Input Impedance
The Affinity digitizer channels were found to have an input impedance that was approximately 113.5 kOhms, within 0.4 % of the 113 kOhm nominal, across all gains and sample rates.

DC Accuracy
The Affinity digitizer channels were found to have bit-weights that were to consistent with the nominal values to within 0.009 %, 0.062 %, 0.1 %, and 0.104 % at gains of 1x, 2x, 4x, and 8x, respectively. The auxiliary multiplexed channels were found to have bit-weights that were consistent with the nominal 1 uV/count to within 0.075 %.

AC Accuracy
The Affinity digitizer channels were found to have bit-weights that were to consistent with the nominal values to within 0.035 %, 0.088 %, 0.128 %, and 0.128 % at gains of 1x, 2x, 4x, and 8x, respectively. The auxiliary multiplexed channels were found to have bit-weights that were consistent with the nominal 1 uV/count to within 0.027 % on DAS-40565A and 0.274% on DAS-40565B.

AC Full Scale
The Affinity digitizer channels were able to fully resolve peak-to-peak amplitudes at or about their full scale of +/- 20V, +/- 10 V, +/- 5 V, and +/- 2.5 V at gains settings of 1, 2, 4, and 8, respectively, at sample rates of 20 Hz, 40 Hz, and 100 Hz.

AC Over Scale
The Affinity 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, 40, and 100 Hz.

Input Shorted Offset
The Affinity digitizer channels were found to have a DC offset that was between -125 uV and -10 uV. No relationship between gain level and offset was observed.

Self-Noise
The Affinity digitizers were observed to have noise free bits at a gain of 1x of 22.8 bits, 22.3 bits, and 21.6 bits at sample rates of 20 Hz, 40 Hz, and 100 Hz, respectively. Increasing gain levels from 1x to 2x, 4x, and 8x resulted in reductions in the effective number of bits of 0.2 bits, 0.5 bits, and 1.2 bits, respectively.

Dynamic Range
The Affinity digitizers exhibited a dynamic range at a gain of 1x of approximately 133 dB for a passband of 50 Hz, 137 dB for a passband of 16 Hz, 143 dB for a passband of 4 Hz, and 143 dB for a passband of 1 Hz. Increasing gain levels from 1x to 2x, 4x, and 8x resulted in a dynamic range reduction of 1 dB, 3 dB, and 7 dB, respectively.

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.

Temperature Self-Noise
The Affinity digitizer channels exhibited no observable change in self-noise power spectra levels at temperatures of -10 C and 40 C. There was a small change in DC offset as a function of temperature. The digitizers continued to operate as expected at these temperature extremes.

Response Verification
The Affinity digitizer channels were found to all have an amplitude and phase response that was consistent from channel to channel. The relative amplitude response had no observable deviation and the relative phase response was linear, consistent with a slight timing skew.

Relative Transfer Function
The Affinity digitizer channels exhibited less than 0.2 microsecond of timing skew from channel to channel.

Analog Bandwidth
The Affinity digitizer channels exhibited a bandwidth of between 88.48% and 89.65% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, and 100 Hz. Bandwidth was not observed to vary with gain level.

Incoherent Noise
The Affinity digitizer channels exhibited incoherent noise while recording a white noise signal that was consistent with earlier measurements of input terminated noise, indicating a lack of non-linear effects at those amplitude levels.

Total Harmonic Distortion
The Affinity digitizer channels exhibited total harmonic distortion ranging between -126.05 dB and -121.81 dB at a gain of 1x, -125.23 dB and -120.37 dB at a gain of 2x, -124.89 dB and -118.06 dB at a gain of 4x, and -126.14 dB and -117.52 dB at a gain of 8x. The auxiliary multiplexed channels were found to have total harmonic distortion levels between -86.09 dB and -91.3 dB due to elevated noise on single-ended channels.

Modified Noise Power Ratio
The Affinity digitizer channels exhibited a modified noise power ratio, measured at a sample rate of 100 Hz and gain of 1x, indicating that both digitizers perform consistently with 21.25 effective bits and have limits on distortion at their full-scale range that are consistent with their clip levels.

Common Mode Rejection

The Affinity digitizer channels exhibited common mode rejection ratios of between 92 and 113 dB. As expected, the common mode levels were unchanged for each unique physical digitizer channel and did not vary with sample rate or gain.

Crosstalk

The Affinity digitizer channels exhibited crosstalk that was measured to be better than between -142 and -150 dB. The measurement was limited due to there being no observable crosstalk present on the channel self-noise. Measurement of crosstalk between the primary and auxiliary channels did not reveal any significant coupling.

GPS Time Tag Accuracy

The Affinity digitizers were measured to have time tag accuracy values that were at or better than 1 uS. Timing accuracy was very stable throughout the 60-minute measurement with almost no observable variation from one PPM measurement to the next.

GPS Time Tag Drift

The Affinity digitizers drifted by between 4.56 and 5.28 us/hour when GPS lock was lost. Over the 12 hour evaluation period, the GPS Time Tag Accuracy drifted to levels of between -80 and -70 microseconds. Both digitizers were able to recover back to their original time tag accuracy within minutes of regaining GPS lock.

PTP Time Tag Accuracy

The Affinity digitizers exhibited PTP time tag accuracy values that were accurate to better than +/- 3 uS. Unlike in the GPS Time Tag Accuracy, there was more variation from one PPM measurement to the next.

PTP Time Tag Drift

The PTP server drifted at a rate of 88 us/hr when GPS lock was lost. Over the 16 hour evaluation period, the PTP Time Tag Accuracy drifted to 1410 microseconds. The Affinity digitizer time tag followed the PTP server drift and reported that it maintained a time lock. In addition, introducing a moderation amount of local network traffic was unable to affect stability of the PTP timing lock.

Calibrator

The Affinity DAS-40565A digitizer demonstrated the ability to accurately generate sinusoids at amplitudes of 0.1, 1, 2, and 2.4 Volts with an amplitude accuracy of just over 1 %. Sinusoid with frequencies at 0.1, 0.2, 0.4, 0.8, 1, 2, 4, 8, and 10 Hz were generated with a frequency accuracy of better than 0.0141%. The Affinity calibrator recording channel was observed to have a bit-weight of 0.29776 uV/count during the calibration cycle.

Sensor Compatibility Verification

The Affinity digitizer was able to demonstrate the proper operation and calibration of a Geotech GS13 seismometer, a Kinemetrics STS-2 high gain seismometer, and an MB3a infrasound sensor. It was noted that there may be some issues with performing broadband calibrations of an

MB3a infrasound sensor in a noisy environment due to limitations on the maximum amplitude of the calibration signal.

CD1 Status Flag Verification
The Affinity digitizer was able to demonstrate the transmission of CD1 status flags for a calibration underway, GPS receiver unlocked, and clock differential too large. Note, however, that during calibration the Affinity reports unlocking from the GPS clock. Also, the Affinity appears to be reporting that the GPS receiver is off when it is only unlocked, although this has reportedly been corrected by Guralp.

CD1 Data Frame Verification
The Affinity digitizer was able to demonstrate the transmission of CD1 channel subframes that are correctly synchronized in time even when they contain waveform data with different sample rates.

REFERENCES

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4. Kromer, Richard P., Hart, Darren M. and J. Mark Harris (2007), *Test Definition for the Evaluation of Digital Waveform Recorders Version 1.0*, SAND2007-5037.

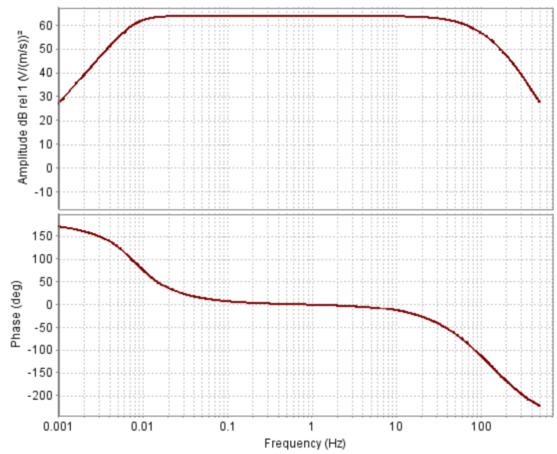
5. McDonald, Timothy S. (1994), *Modified Noise Power Ratio Testing of High Resolution digitizers*, SAND94-0221.

6. Merchant, B. John, and Darren M. Hart (2011), *Component Evaluation Testing and Analysis Algorithms*, SAND2011-8265.

7. Sleeman, R., Wettum, A., Trampert, J. (2006), *Three-Channel Correlation Analysis: A New Technique to Measure Instrumental Noise of Digitizers and Seismic Sensors*, Bulletin of the Seismological Society of America, Vol. 96, No. 1, pp. 258-271, February 2006.

APPENDIX A: RESPONSE MODELS

Guralp CMG-3T Seismometer (1500 V/(m/s) and 120 second corner)



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

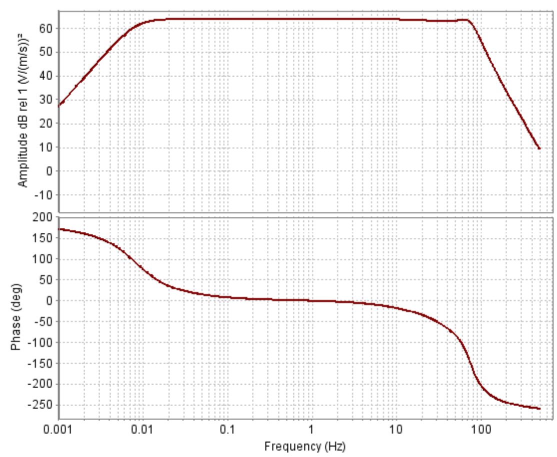
-1130.0	0.0
-1010.0	0.0
-503.0	0.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
861,208.00814 MV·s/m

Kinemetrics STS-2 Low Gain Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

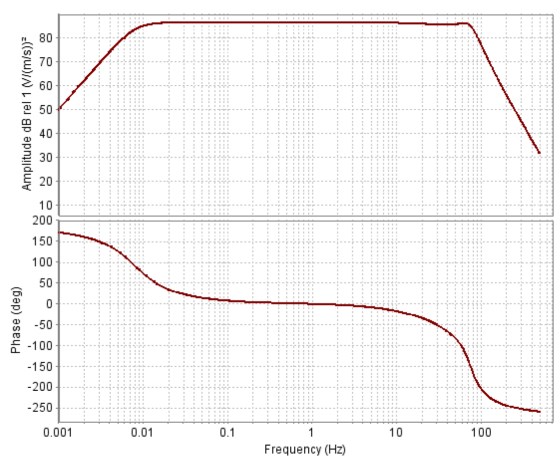
-251.0	0.0
-131.0	467.0
-131.0	-467.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
88,586.67303 MV·s/m

Kinemetrics STS-2 High Gain Seismometer



Sensitivity:
20 kV·s/m at 1.0 Hz

Poles:

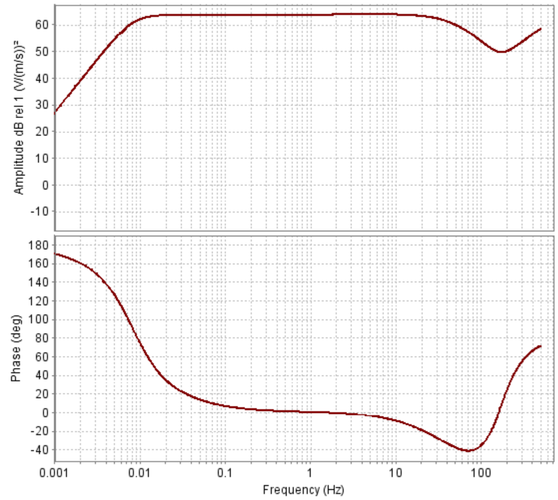
-251.33	0.0
-131.04	467.29
-131.04	-467.29
-0.035647	0.036879
-0.035647	-0.036879

Zeros:

0.0	0.0
0.0	0.0

A:
1.1841199E6 MV·s/m

Kinematrics STS-5A Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

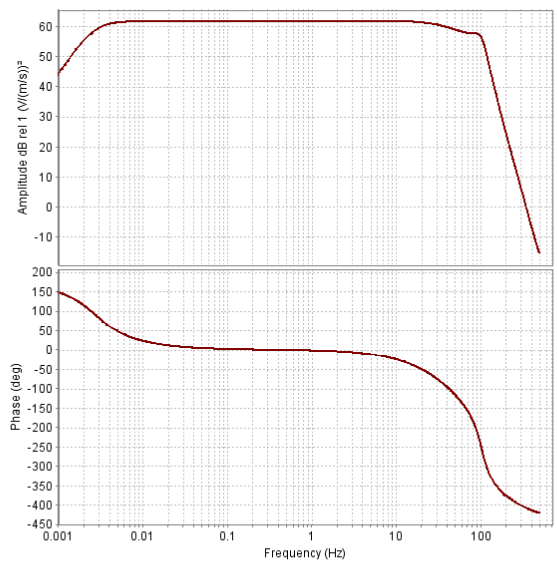
-961.0	0.0
-339.0	116.0
-339.0	-116.0
-16.0	0.0
-16.0	0.0
-0.037	-0.037
-0.037	0.037

Zeros:

-961.0	0.0
-605.0	0.0
-522.0	961.0
-522.0	-961.0
-15.7	0.0
-15.7	0.0
0.0	0.0
0.0	0.0

A:
0.27503 V·s/m

Kinematrics STS-6A Seismometer



Sensitivity:
1,200 V·s/m at 1.0 Hz

Poles:

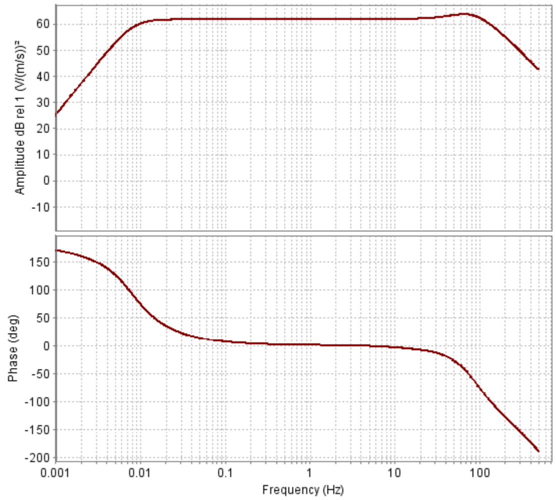
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-351.858	0.0
-121.58	647.231
-121.58	-647.231
-22.3068	0.0
-22.3068	0.0
-0.01231	0.01206
-0.01231	-0.01206

Zeros:

-605.071	0.0
-521.504	0.0
-521.504	0.0
-351.858	0.0
-21.9911	0.0
-21.9911	0.0
0.0	0.0
0.0	0.0

A:
51.422261E9 MV·s/m

Nanometrics Trillium 120 Seismometer



Sensitivity:
1,200 V·s/m at 1.0 Hz

Poles:

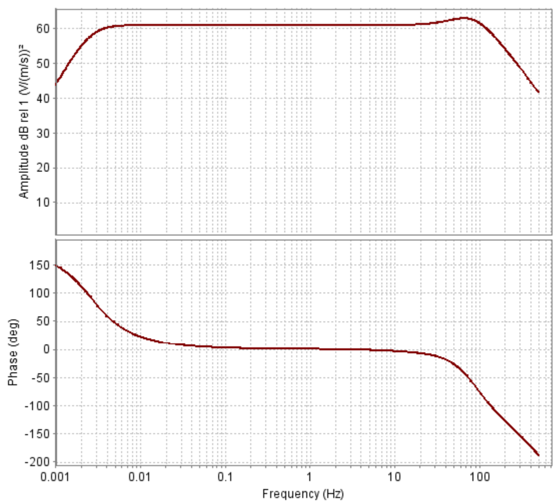
-7100.0	1700.0
-7100.0	-1700.0
-4900.0	5204.0
-4900.0	-5204.0
-1260.0	0.0
-364.0	404.0
-364.0	-404.0
-142.0	0.0
-32.55	0.0
-0.036614	0.037059
-0.036614	-0.037059

Zeros:

-3177.0	0.0
-350.0	0.0
-160.0	0.0
-31.63	0.0
0.0	0.0
0.0	0.0

A:
999.05912E12 MV·s/m

Nanometrics Trillium 360 Seismometer



Sensitivity:
1,100 V·s/m at 1.0 Hz

Poles:

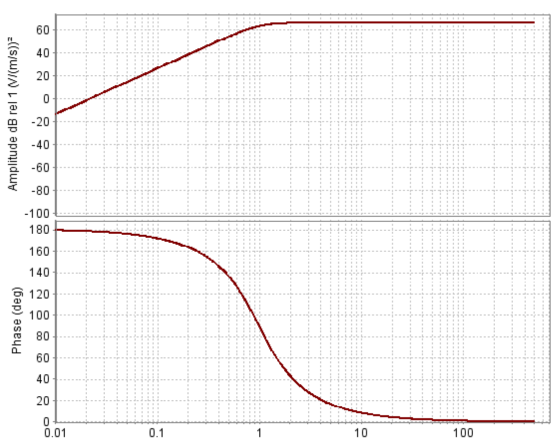
-7200.0	1700.0
-7200.0	-1700.0
-4900.0	5200.0
-4900.0	-5200.0
-1234.0	0.0
-360.0	405.0
-360.0	-405.0
-146.0	0.0
-0.01189	0.01189
-0.01189	-0.01189

Zeros:

-3079.0	0.0
-350.0	0.0
-160.0	0.0
0.0	0.0
0.0	0.0

A:
942.91505E12 MV·s/m

Geotech GS13 Seismometer



Sensitivity:
2,000 V·s/m at 5.0 Hz

Poles:

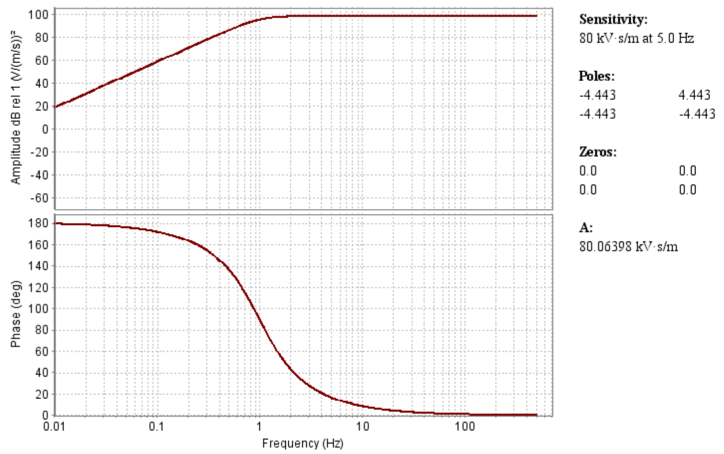
-4.443	4.443
-4.443	-4.443

Zeros:

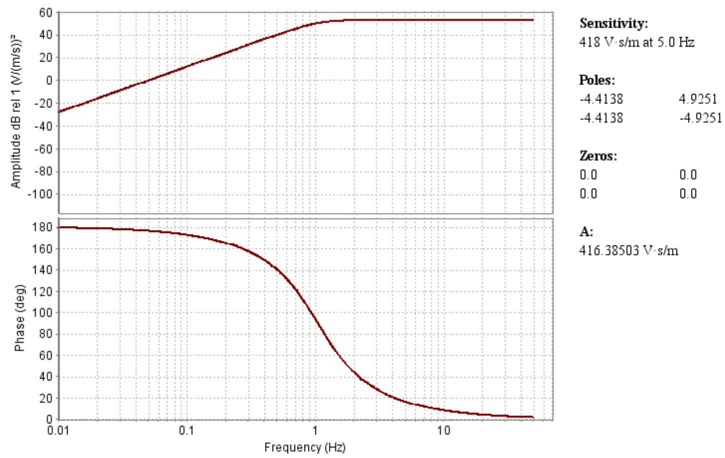
0.0	0.0
0.0	0.0

A:
2,001.59953 V·s/m

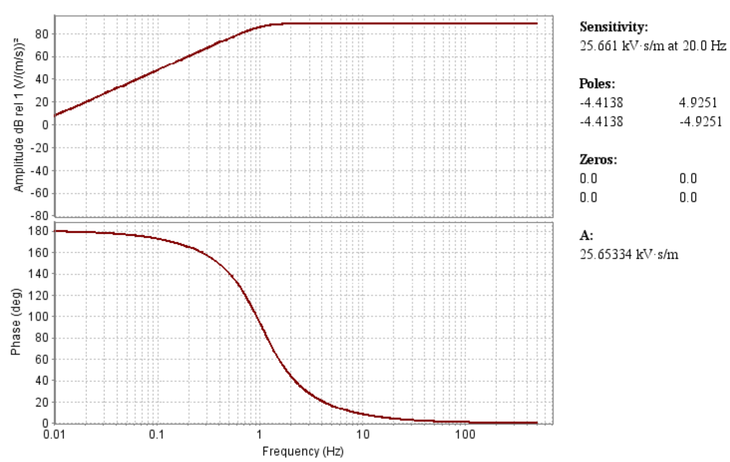
Geotech GS13 Seismometer and 40x Preamplifier



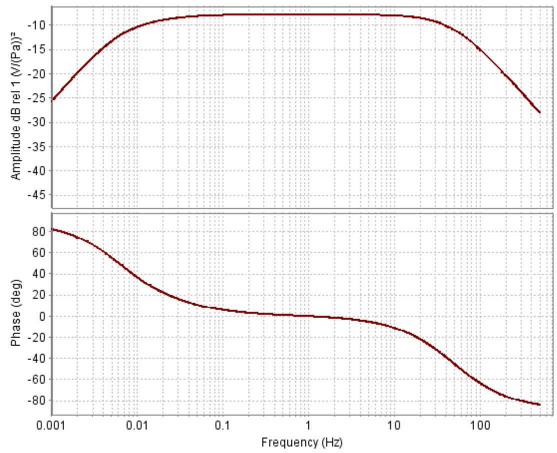
Geotech GS21 Seismometer



Geotech GS21 Seismometer and 61.39x Preamplifier



Chaparral 50A Infrasound Sensor



Sensitivity:
0.4 V/Pa at 1.0 Hz

Poles:

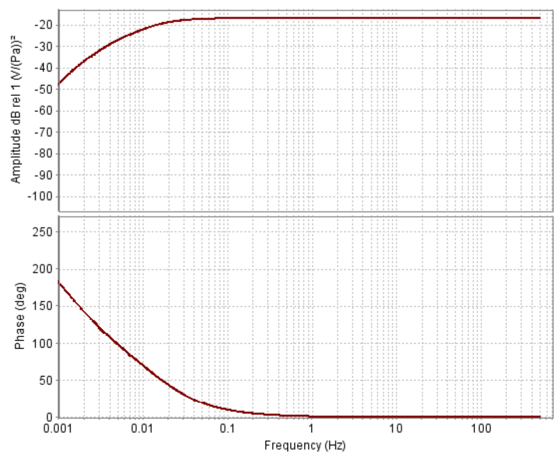
-314.0	0.0
-0.188	0.0
-0.044	0.0
0.0	0.0

Zeros:

-0.17	0.0
0.0	0.0
0.0	0.0

A:
125.63847 V/Pa

Hyperion 5000 Infrasound Sensor



Sensitivity:
0.14 V/Pa at 1.0 Hz

Poles:

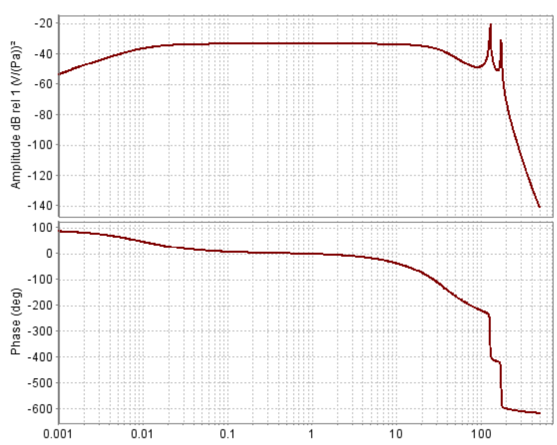
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
0.14003 V/Pa

MB2005 Infrasound Sensor



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

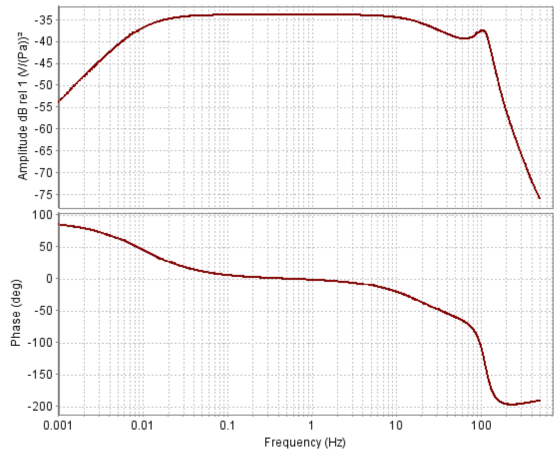
-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.06283	0.0

Zeros:

-468820.0	0.0
0.0	0.0

A:
466,949.57524 MV/Pa

MB3a Infrasound Sensor



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

APPENDIX B: 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

PRIMARY STANDARDS
LABORATORY

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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

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

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

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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	

PRIMARY STANDARDS LABORATORY

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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	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	

PRIMARY STANDARDS LABORATORY

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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	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	100.0129	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	100.0300	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;

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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.

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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

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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

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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

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	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

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Equipment (Standard) Used

Asset #	Description	Model	Expires
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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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4. Ratio(s) or other non-maintained standards established by either a self-calibration and/or a direct calibration technique;
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Authorization

Calibrated By:	Approved By:
Liddle, Brian David	Diana Kothmann
Metrologist	QA Representative

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