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2018 Nanometrics Centaur Digitizer Evaluation

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2018 Nanometrics Digitizer Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated two Nanometrics Centaur digitizers. The Centaur 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 Centaur 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 Nanometrics for providing the Centaur 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 Centaur digitizers, developed by Nanometrics.

Figure 1 Nanometrics Centaur Digitizers

The Nanometrics Centaur 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 Centaur 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 Nanometrics Centaur digitizers, serial numbers 5001 and 5002 shown in the figure above, was performed to compare their performance to the manufacturer's specifications and CTBTO requirements.

The two digitizers were the Centaur CTR4-3A indicating that they are the 4th generation Centaur with 3 recording channels and include data authentication. The digitizers were operating with the Nanometrics firmware revision 4.3.14 installed. The digitizers were recording continuously on all 3 channels at sample rates of 20 Hz and 80 Hz on one of the digitizers and 40 Hz and 100 Hz on the other digitizer. They were configured to simultaneously record data locally on an internal memory card and stream data over Ethernet to a computer using a CD1.1 data receiver. The digitizers were configured to time synchronize to their internal GPS module and maintain an active GPS lock continuously.

TECHNICAL SPECIFICATIONS CENTAUR (CTR4 SERIES)

Specifications subject to change without notice

SENSOR INPUTS

Channels: Available with 3 or 6 channel inputs
Sampling: Simultaneous on all 3 or 6 channels
Resolution: 24 bits per channel, full 24-bit range to clip level
Input voltage range (Peak-to-peak differential):
- 40 V, 20 V, 10 V, 4 V, 2 V, 1 V (standard)
- 10 V, 5 V, 2.5 V, 1 V, 0.5 V, 0.25 V (high-gain)

Input Impedance: 40 kΩ (standard digitizer)
1.8 MΩ (high-gain digitizer)

SENSOR COMPATIBILITY

Sensor Types: Broadband seismometers, short period geophones, and microbarometers
Control Lines: 6 per connector – typically used for calibration enable, mass center, mass lock/unlock, XYZ/UVW select
Sensor Power:
- Supply power pass-through to sensor (9-36 VDC, 1A)
- Over-current and surge protected

Auto Mass Centering: Configurable thresholds, intervals, retries
Serial Interface: Supports digital management of Nanometrics sensors and connectivity to weather stations

DIGITIZER PERFORMANCE & CAPABILITIES

Type: True 24-bit ADC per channel
Accuracy: Nominal gain accuracy within ±0.5%
Dynamic Range: 142 dB @ 100 sps, 135 dB @ 500 sps (full-scale peak to RMS shorted-input noise)
Preamp Gain:
- Standard: 1x, 2x, 4x, 10x, 20x, 40x
- High Gain: 4x, 8x, 16x, 40x, 80x, 160x

Sample Rates: 1, 2, 5, 10, 20, 40, 50, 80, 100, 125, 200, 250, 500, 1000, 2000, 5000 sps
Dual Sample Rates: A second sample rate can be selected from the sample rates above
Decimation Anti-Aliasing Filter:
- Selectable linear phase (noncausal) or minimum phase (causal)
- -140 dB (linear phase) or -120 dB (minimum phase) at Nyquist frequency, 0 dB at 80% Nyquist

Digital Filters:
- User-configurable low-pass and high-pass
- 1st to 5th order, 0.1 mHz to Nyquist
- Different filters may be configured for primary and secondary sample rates and Sensor A and B

Orientation Correction: User configurable onboard 3-D data rotation for correcting azimuth and tilt

RECORDING (CONTINUOUS)

Formats: MiniSEED
Internal Memory: 8 GB flash memory (32 or 64 GB options available)
Removable Media: SD Card up to 64 GB

RECORDING (EVENTS)

Triggers: Bandpassed STA/LTA, threshold
Captured Data: MiniSEED, ASCII
Data Products: Peak Ground Motion (i.e PGA, PGV, PGD) statistics calculated on the instrument

CALIBRATION

Signal Source: 16-bit DAC with 30 ksps output
Calibration Mode
- Voltage source, 1% accuracy from ±10V to ±5mV
- Current source, 1% accuracy from ±30mA to ±30uA

Waveforms: Synthesized sine, PRB signals
Playback user defined calibration files
User controllable amplitude, frequency, pulse width, duration, lead-in and lead-out silence

STATE-OF-HEALTH INPUTS

Channels: 3 singled-ended inputs, ±5 V range, 50 kΩ input impedance
Sampling Interval: Configurable from 1 to 3600 seconds
Accuracy: 18 bits effective resolution
Tamper Detection: Case tamper switch (CTR4-3A) or 3 external switches via SOH connector

DATA RETRIEVAL

File Transfer: Via Ethernet, optional WiFi or Ethernet-connected DSL, VSAT, cellular, radio
Media Exchange: SD card field-swappable during continuous recording with no loss of data
Response Metadata: Generate and download full digitizer/sensor response files in RESP or Dataless SEED format

DATA STREAMING

Continuous: Seismic data and State-of-Health data
Formats: SeedLink, Nanometrics NP, CD-1.1 (CTR4-3A)
Events: Triggered event data: email, secure file transfer, other options available

TIMING - GNSS & PRECISION NETWORK TIMING

Timing System: Internal DCXO clock disciplined to selectable timing source
Timing Source: Select from GNSS, PTP (Precision Timing Protocol), NTP or free-running
Timing Server: Serve PTP or NTP time to other Centaur, Titan SMA/EA or Meridian
Timing Accuracy: <5 μsec (GNSS Always on)
<100 μsec (GNSS duty cycled, PTP or local NTP)
GNSS Receiver: Internal 32 channel GNSS receiver
GNSS Power: Selectable: always on, duty cycled or off

LOCAL USER INTERFACE

Removable Media: SD card protected in waterproof media bay
External LEDs: System status, Ethernet link, time quality, media card status, sensor A & B
Buttons: WiFi wakeup, media eject, system shutdown

COMMUNICATIONS

Web-based Graphical UI: Supports standard PC, tablet and mobile devices. Used for waveform and state-of-health monitoring, configuration, maintenance, sensor management and calibration, downloading data and events.
Interfaces: 10/100 Base-T Ethernet, WiFi (optional), Serial via USB
IP Addressing: Static, dynamic (DHCP) or link-local IP
Protocols: UDP/IP unicast/multicast, HTTP data streaming

POWER

Power Supply: 9-36 VDC isolated input
Protection: Electronic resettable fuse design, lightning surge, reverse battery and short circuit protection
Battery Manager: User-configurable low voltage shutdown and restart thresholds

POWER USAGE (TYPICAL)

3 chan. (standard): 850 mW
6 chan. (standard): 1.2 W
Ethernet: Add 0.2 W for 10 Base-T, 0.3 W for 100 Base-T
High Gain: Add 0.2 W for every 3 high-gain channels
Authentication: Add 1.2 W if enabled (CTR4-3A)

CONNECTORS

Sensor: 26-pin Mil. circular, shell size 16, female
Power: 3-pin Mil. circular, shell size 8, male
Ethernet: Watertight RJ-45
USB: 2.0 Type A receptacle behind media bay door
GNSS Antenna: TNC (female) with 3.3V supply for active antenna
State-of-Health: 4-pin Mil. circular, shell size 8, female

PHYSICAL CHARACTERISTICS

Housing: Aluminum
Weather Resistance: Rated to IP68 with connectors mated
Humidity: 0 to 100%
Operating Temperature: -20°C to +60°C (Ultra-low temperature option available. Please contact Nanometrics.)
Storage Temperature: -40°C to +70°C
Weight: 1.9 kg (3-channel), 2.0 kg (6-channel)
Size: 196 mm (L) x 137 mm (W) x 88 mm (H)

CENTAUR WITH AUTHENTICATION (CTR4-3A)

Streaming: CD1.1 format
Digital Signature:
Hardware authentication provides
- Digital Signature Algorithm (DSA, SHA-1) and
- Elliptic Curve Digital Signature Algorithm (ECDSA P-256, SHA-224)

Tamper: Case tamper detection

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Figure 2 Nanometrics Centaur Specification (Nanometrics 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).

Most of the digitizer testing, except for 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 13 Volts.

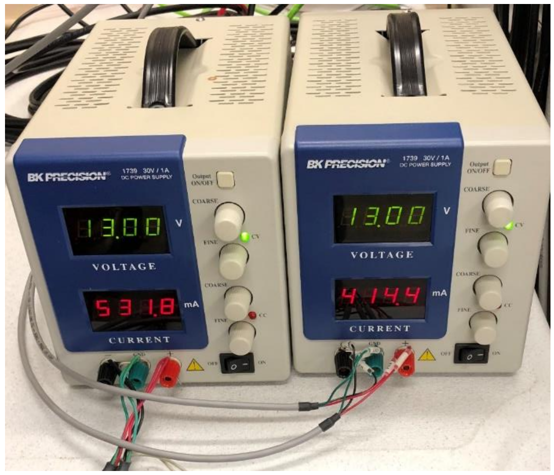

Figure 4 Power Supplies and Temperature Controller

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
Time Tag Accuracy
Time Tag Drift
Calibrator
Sensor Compatibility Verification
CD1 Status Flag Verification

2.3 Timeline

Most of the digitizer testing was performed at Sandia National Laboratories between April 9 - 26, 2018. Testing was performed using two digitizers, so that different tests could be performed on each digitizer simultaneously. Additional testing of the temperature extreme performance was performed in early July 2018. The following schedule of testing was followed:

Table 2 Timeline of Testing

Day	Time	Centaur 5001 (40 Hz and 100 Hz)	Centaur 5002 (20 Hz and 80 Hz)
April 10, 2018		Terminated Self-Noise, gain 1x	Terminated Self-Noise, gain 1x
April 11, 2018		Terminated Self-Noise, gain 1x	Terminated Self-Noise, gain 1x
April 12, 2018		Terminated Self-Noise, gain 2x	Terminated Self-Noise, gain 2x
April 13, 2018		Terminated Self-Noise, gain 4x	Terminated Self-Noise, gain 4x
April 14, 2018		Terminated Self-Noise, gain 10x	Terminated Self-Noise, gain 10x
Monday April 16, 2018	Morning	Equipment setup and checkout 1x, 2x, 4x, 10x, 20x, 40x gains: Power Consumption Input Impedance	Equipment setup and checkout 1x, 2x, 4x, 10x, 20x, 40x gains: Power Consumption Input Impedance
	Lunch	10x and 20x gain: Analog Bandwidth Relative Transfer Function Response Incoherent Noise	1x and 2x gain: Analog Bandwidth Relative Transfer Function Response Incoherent Noise
	Afternoon	1x, 2x, 4x, 10x, 20x, 40x gains: DC Accuracy AC Accuracy AC Full Scale AC Clip	1x, 2x, 4x, 10x, 20x, 40x gains: DC Accuracy AC Accuracy AC Full Scale AC Clip
Tuesday April 17, 2018	Morning	1x gain: Crosstalk 1x, 2x, 4x, 10x, 20x, 40x gains: Common Mode	1x gain: Crosstalk 1x, 2x, 4x, 10x, 20x, 40x gains: Common Mode
	Lunch	40x gain: Analog Bandwidth Relative Transfer Function Response Incoherent Noise	4x gain: Analog Bandwidth Relative Transfer Function Response Incoherent Noise
	Afternoon	1x gain: GPS Timing Accuracy	1x gain: PTP Timing Accuracy
	Overnight	1x gain: GPS Timing Drift	1x gain: PTP Timing Drift
Wednesday April 18, 2018	Morning	1x gain: GPS Timing Recovery	1x gain: PTP Timing Recovery

Day	Time	Centaur 5001 (40 Hz and 100 Hz)	Centaur 5002 (20 Hz and 80 Hz)
	Lunch	20, 40, 100 Hz at gain 8 Total Harmonic Distortion	20, 40, 100 Hz at gain 8 Total Harmonic Distortion
	Afternoon	Calibrator Signal Outputs	
Thursday April 19, 2018	Morning	CD1 Status Flags	CD1 Status Flags
	Lunch	10x gain: Total Harmonic Distortion	1x gain: Total Harmonic Distortion
	Afternoon	Sensor Application Tests	Sensor Application Tests
	Overnight	Sensor Application Tests	Sensor Application Tests
Friday April 20, 2018	Morning	20x gain: Total Harmonic Distortion	2x gain: Total Harmonic Distortion
	Lunch	Sensor Application Tests	Sensor Application Tests
	Afternoon	40x gain: Total Harmonic Distortion Sensor Application Tests	4x gain: Total Harmonic Distortion Sensor Application Tests
April 25, 2018		10x gain: MNPR	1x gain: MNPR
April 26, 2018		Terminated Self-Noise, gain 20x	Terminated Self-Noise, gain 20x
June 15, 2018		Terminated Self-Noise, gain 40x	Terminated Self-Noise, gain 40x
July 5 – 9, 2018		Temperature Self-Noise Tests, gain 10x	Temperature Self-Noise Tests, gain 1x

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.

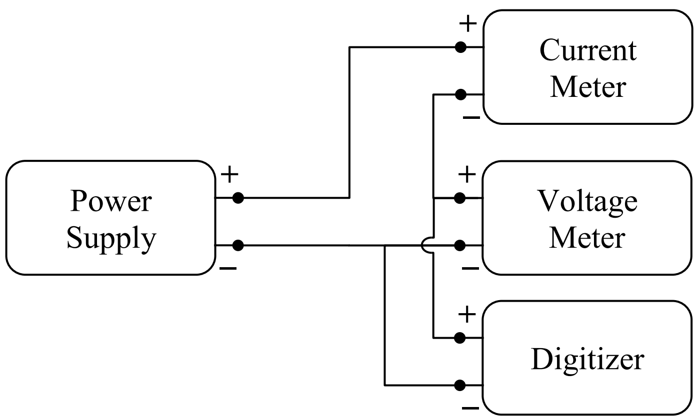

Figure 7 Power Consumption Configuration Diagram

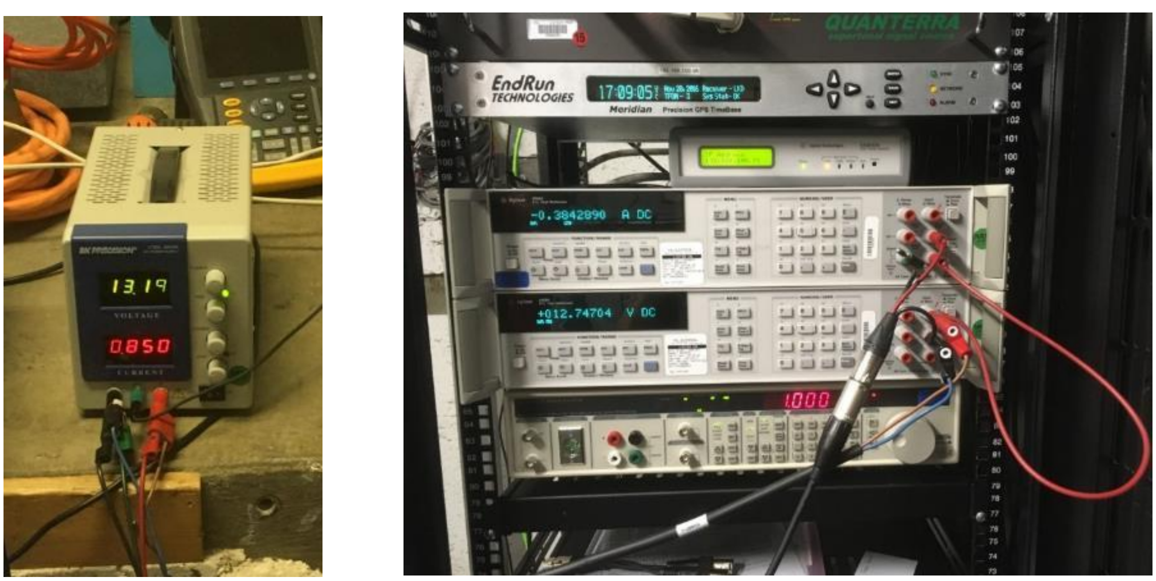

Figure 8 Power Consumption Configuration Picture

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.

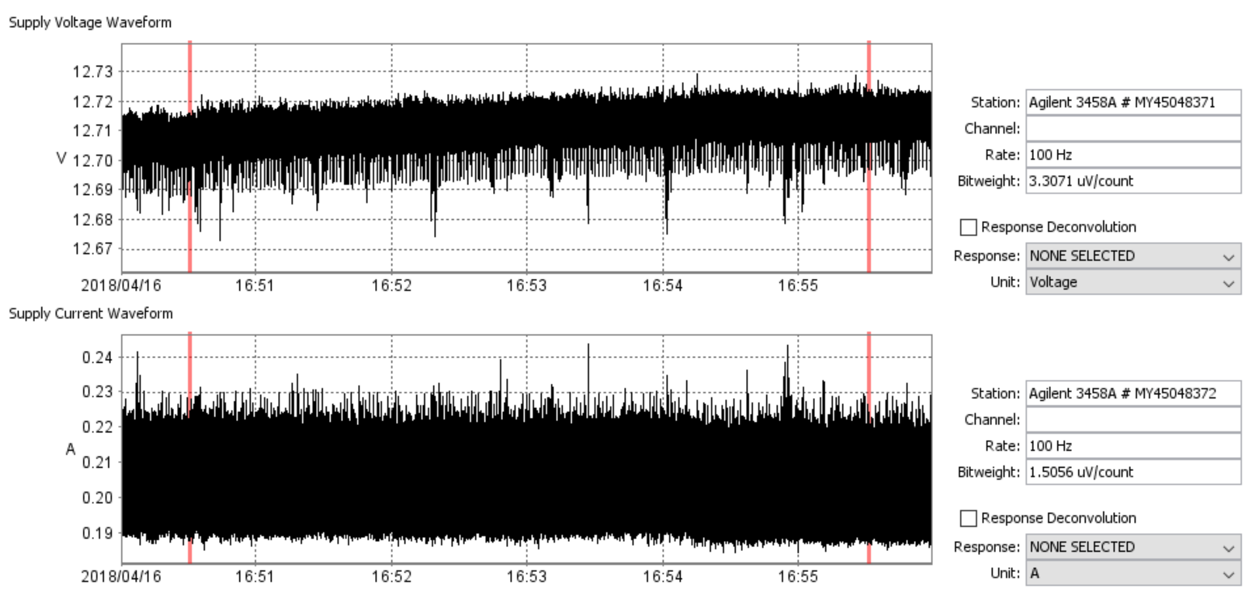

Figure 9 Power Consumption Voltage and Current Time Series

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

Table 4 Power Consumption Results: Centaur 5001, 40 and 100 Hz Sampling

	Supply Voltage		Supply Current		Power Consumption	
	Mean	SD	Mean	SD	Mean	SD
Gain 1x	12.71 V	6.825 mV	0.1966 A	8.663 mA	2.499 W	0.1115 W
Gain 1x*	12.65 V	61.37 mV	0.1839 A	8.693 mA	2.325 W	0.1217 W
Gain 2x	12.68 V	7.327 mV	0.1962 A	8.567 mA	2.489 W	0.1102 W
Gain 4x	12.69 V	7.143 mV	0.1982 A	8.641 mA	2.516 W	0.1112 W
Gain 10x	12.64 V	8.504 mV	0.1995 A	8.611 mA	2.522 W	0.1106 W
Gain 20x	12.67 V	20.30 mV	0.2009 A	9.181 mA	2.545 W	0.1206 W
Gain 40x	12.68 V	7.790 mV	0.2077 A	8.709 mA	2.632 W	0.1121 W

* Tested while configured for 10 Base-T Ethernet rather than 100 Base-T.

Table 5 Power Consumption Results: Centaur 5002, 20 and 80 Hz Sampling

	Supply Voltage		Supply Current		Power Consumption	
	Mean	SD	Mean	SD	Mean	SD
Gain 1x	12.77 V	5.994 mV	0.1968 A	8.412 mA	2.513 W	0.1086 W
Gain 2x	12.76 V	5.904 mV	0.1953 A	8.308 mA	2.492 W	0.1072 W
Gain 4x	12.76 V	5.615 mV	0.1973 A	8.415 mA	2.517 W	0.1085 W
Gain 10x	12.70 V	23.97 mV	0.1992 A	8.494 mA	2.529 W	0.1128 W
Gain 20x	12.70 V	23.97 mV	0.1992 A	8.494 mA	2.529 W	0.1128 W
Gain 40x	12.67 V	12.58 mV	0.2074 A	9.158 mA	2.628 W	0.1187 W

The Centaur digitizers were observed to consume between 2.5 and 2.63 watts of power during operation with a standard deviation of approximately 110 mW. There does appear to be an increase in power consumption of approximately 130 mW between a gain of 1x and 40x. In addition, for the 5001 digitizer at a gain of 1x, the power consumption was measured with both a 10 and 100 Base-T Ethernet configuration and found to have 175 mW less power consumption at the slower Ethernet configuration.

The Centaur CTR4 datasheet specifies that the expected power consumption is 850 mW for a baseline 3 channel configuration. The digitizers as configured included an additional 300 mW for a 100 Base-T Ethernet, 1.2 W for CD1.1 data authentication (CTR4-3A), and 350 mW for continuous rather than duty-cycled GPS for a total expected power consumption of 2.7 W. The observed 2.5 W to 2.63 W was less than expected from the documentation.

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.

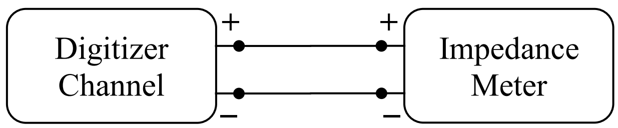

Figure 10 Input Impedance Configuration Diagram

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 measured impedance for each of the digitizer channels and their percent difference from the nominal 40 kohm impedance are shown in the tables below.

Table 7 Input Impedance Results: Centaur 5001

	Channel 1 (Z)		Channel 2 (N)		Channel 3 (E)	
1x Gain	40.048 kohm	0.12%	40.04 kohm	0.11%	40.05 kohm	0.11%
2x Gain	40.05 kohm	0.12%	40.04 kohm	0.10%	40.05 kohm	0.11%
4x Gain	40.04 kohm	0.11%	40.04 kohm	0.10%	40.04 kohm	0.11%
10x Gain	40.04 kohm	0.11%	40.04 kohm	0.10%	40.04 kohm	0.11%
20x Gain	40.05 kohm	0.11%	40.04 kohm	0.10%	40.04 kohm	0.11%
40x Gain	38.89 kohm	-2.79%	38.85 kohm	-2.88%	38.83 kohm	-2.94%

Table 8 Input Impedance Results: Centaur 5002

	Channel 1 (Z)		Channel 2 (N)		Channel 3 (E)	
1x Gain	40.043 kohm	0.11%	40.041 kohm	0.10%	40.05 kohm	0.11%
2x Gain	40.042 kohm	0.11%	40.040 kohm	0.10%	40.05 kohm	0.11%
4x Gain	40.040 kohm	0.10%	40.037 kohm	0.09%	40.04 kohm	0.11%
10x Gain	40.040 kohm	0.10%	40.038 kohm	0.09%	40.04 kohm	0.11%
20x Gain	40.040 kohm	0.10%	40.038 kohm	0.09%	40.04 kohm	0.11%
40x Gain	39.410 kohm	-1.48%	39.371 kohm	-1.57%	38.83 kohm	-2.94%

The measured input impedance of the digitizer channels was within 0.1 % - 0.12% of the nominal 40 kohm, with the exception of a 40x gain. At a 40x gain, the measured impedances were between -3% and -1.5% of the nominal 40 kohm.

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.

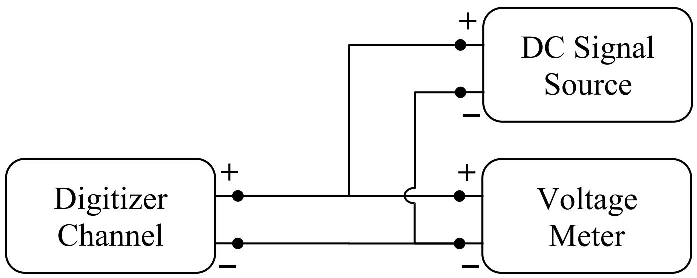

Figure 11 DC Accuracy Configuration Diagram

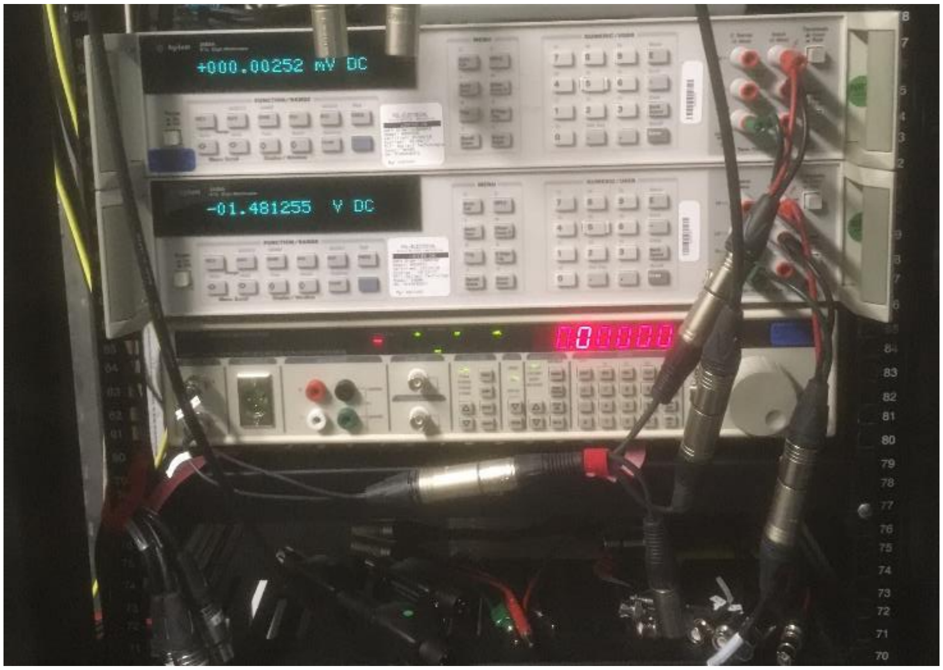

Figure 12 DC Accuracy Configuration Picture

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 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:

$$V_{pos} \text{ and } V_{neg}$$

The average of each of the positive and negative segments are computed from the digitizer channel in counts:

$$C_{pos} \text{ and } C_{neg}$$

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.

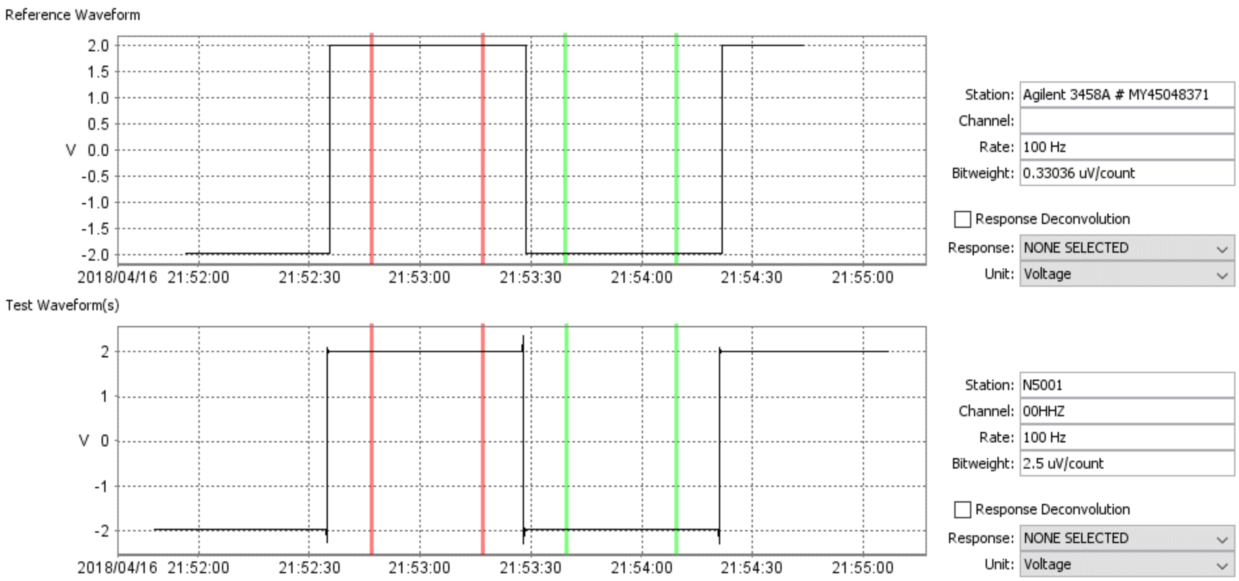

Figure 13 DC Accuracy Time Series

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

Table 10 DC Accuracy Bit-weight: Centaur 5001

	Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Voltage	1.9876 V	0.99273 V	0.49646 V	0.19860 V	99.274 mV	49.654 mV
Z - 40 Hz	2.4996 uV/cnt	1.2499 uV/cnt	0.62491 uV/cnt	0.24996 uV/cnt	0.12499 uV/cnt	62.497 nV/cnt
N - 40 Hz	2.4996 uV/cnt	1.2499 uV/cnt	0.62491 uV/cnt	0.24997 uV/cnt	0.12499 uV/cnt	62.498 nV/cnt
E - 40 Hz	2.4995 uV/cnt	1.2498 uV/cnt	0.62490 uV/cnt	0.24996 uV/cnt	0.12498 uV/cnt	62.496 nV/cnt
Z - 100 Hz	2.4996 uV/cnt	1.2499 uV/cnt	0.62491 uV/cnt	0.24996 uV/cnt	0.12499 uV/cnt	62.497 nV/cnt
N - 100 Hz	2.4996 uV/cnt	1.2499 uV/cnt	0.62491 uV/cnt	0.24997 uV/cnt	0.12499 uV/cnt	62.498 nV/cnt
E - 100 Hz	2.4995 uV/cnt	1.2498 uV/cnt	0.62490 uV/cnt	0.24996 uV/cnt	0.12498 uV/cnt	62.496 nV/cnt
Nominal	2.5000 uV/cnt	1.2500 uV/cnt	0.62500 uV/cnt	0.25000 uV/cnt	0.12500 uV/cnt	62.500 nV/cnt
Maximum Difference	0.020%	0.016%	0.016%	0.016%	0.016%	0.006%

Table 11 DC Accuracy Bit-weight: Centaur 5002

	Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Voltage	1.9876 V	0.99273 V	0.49646 V	0.19860 V	99.274 mV	49.654 mV
Z - 20 Hz	2.4998 uV/cnt	1.2499 uV/cnt	0.62496 uV/cnt	0.24999 uV/cnt	0.12500 uV/cnt	62.506 nV/cnt
N - 20 Hz	2.4999 uV/cnt	1.2500 uV/cnt	0.62500 uV/cnt	0.25001 uV/cnt	0.12501 uV/cnt	62.516 nV/cnt
E - 20 Hz	2.4996 uV/cnt	1.2498 uV/cnt	0.62493 uV/cnt	0.24998 uV/cnt	0.12499 uV/cnt	62.503 nV/cnt
Z - 80 Hz	2.4998 uV/cnt	1.2499 uV/cnt	0.62496 uV/cnt	0.24999 uV/cnt	0.12500 uV/cnt	62.506 nV/cnt
N - 80 Hz	2.4999 uV/cnt	1.2500 uV/cnt	0.62500 uV/cnt	0.25001 uV/cnt	0.12501 uV/cnt	62.516 nV/cnt
E - 80 Hz	2.4996 uV/cnt	1.2498 uV/cnt	0.62493 uV/cnt	0.24998 uV/cnt	0.12499 uV/cnt	62.503 nV/cnt
Nominal	2.5000 uV/cnt	1.2500 uV/cnt	0.62500 uV/cnt	0.25000 uV/cnt	0.12500 uV/cnt	62.500 nV/cnt
Maximum Difference	0.016%	0.016%	0.011%	0.008%	0.008%	0.026%

The nominal bit-weights provided by Nanometrics were specified to be 2.5 uV/count, 1.25 uV/count, 0.625 uV/count, 0.25 uV/count, 0.125 uV/count, and 62.5 nV/count for gains of 1, 2, 4, 10, 20, and 40, respectively. The measured DC bit-weights were found to be most consistent with the nominal values to within better than 0.011 % to 0.026 %.

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.

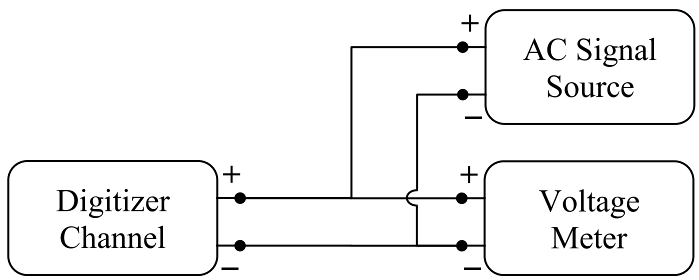

Figure 14 AC Accuracy Configuration Diagram

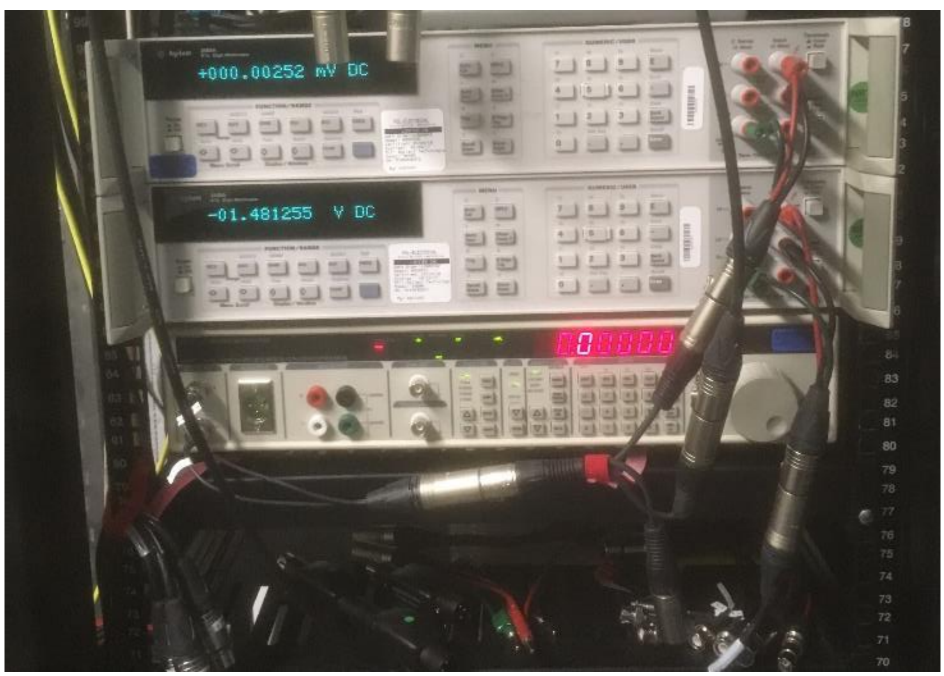

Figure 15 AC Accuracy Configuration Picture

Table 12 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 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:

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

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

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.

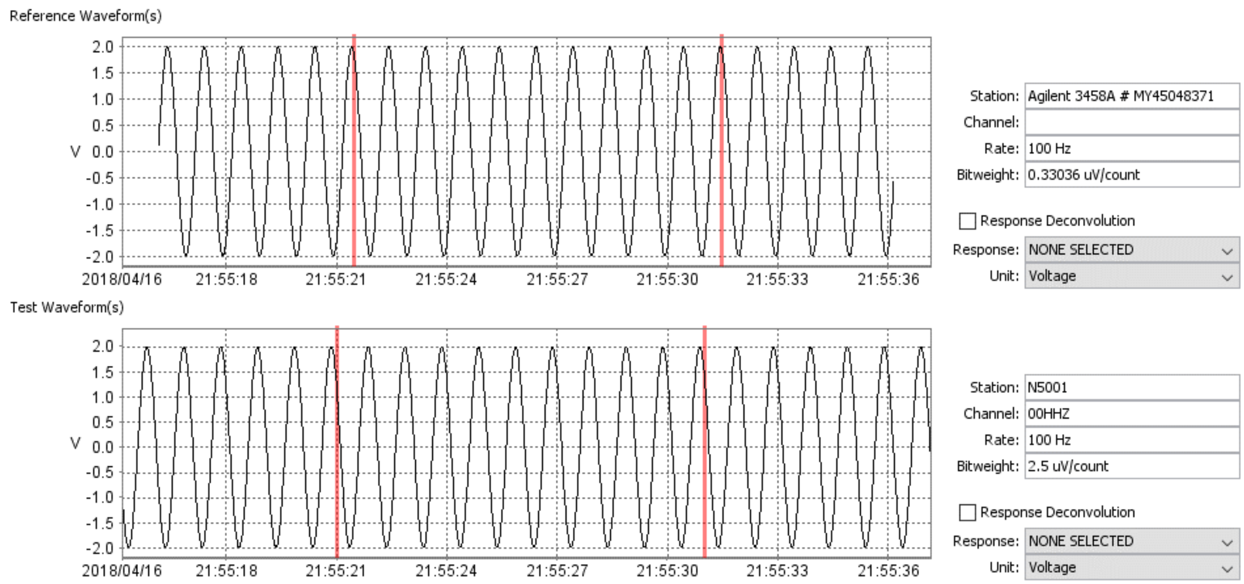

Figure 16 AC Accuracy Time Series

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

Table 13 AC Accuracy Bit-weight: 5001

	Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Voltage	1.9864 V	0.99227 V	0.49614 V	0.19856 V	99.222 mV	49.616 mV
Z - 40 Hz	2.4993 uV/cnt	1.2497 uV/cnt	0.62483 uV/cnt	0.24993 uV/cnt	0.12497 uV/cnt	62.490 nV/cnt
N - 40 Hz	2.4993 uV/cnt	1.2497 uV/cnt	0.62483 uV/cnt	0.24993 uV/cnt	0.12497 uV/cnt	62.491 nV/cnt
E - 40 Hz	2.4992 uV/cnt	1.2496 uV/cnt	0.62480 uV/cnt	0.24992 uV/cnt	0.12496 uV/cnt	62.488 nV/cnt
Z - 100 Hz	2.4993 uV/cnt	1.2497 uV/cnt	0.62483 uV/cnt	0.24993 uV/cnt	0.12497 uV/cnt	62.490 nV/cnt
N - 100 Hz	2.4993 uV/cnt	1.2497 uV/cnt	0.62483 uV/cnt	0.24993 uV/cnt	0.12497 uV/cnt	62.491 nV/cnt
E - 100 Hz	2.4992 uV/cnt	1.2496 uV/cnt	0.62480 uV/cnt	0.24992 uV/cnt	0.12496 uV/cnt	62.488 nV/cnt
Nominal	2.5000 uV/cnt	1.2500 uV/cnt	0.62500 uV/cnt	0.25000 uV/cnt	0.12500 uV/cnt	62.500 nV/cnt
Maximum Difference	0.032%	0.032%	0.032%	0.032%	0.032%	0.019%

Table 14 AC Accuracy Bit-weight: 5002

	Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Voltage	1.9864 V	0.99226 V	0.49613 V	0.19856 V	99.222 mV	49.616 mV
Z - 20 Hz	2.4995 uV/cnt	1.2497 uV/cnt	0.62488 uV/cnt	0.24996 uV/cnt	0.12498 uV/cnt	62.499 nV/cnt
N - 20 Hz	2.4996 uV/cnt	1.2498 uV/cnt	0.62491 uV/cnt	0.24997 uV/cnt	0.12500 uV/cnt	62.508 nV/cnt
E - 20 Hz	2.4993 uV/cnt	1.2496 uV/cnt	0.62484 uV/cnt	0.24994 uV/cnt	0.12498 uV/cnt	62.496 nV/cnt
Z - 80 Hz	2.4995 uV/cnt	1.2497 uV/cnt	0.62488 uV/cnt	0.24996 uV/cnt	0.12498 uV/cnt	62.499 nV/cnt
N - 80 Hz	2.4996 uV/cnt	1.2498 uV/cnt	0.62491 uV/cnt	0.24997 uV/cnt	0.12500 uV/cnt	62.508 nV/cnt
E - 80 Hz	2.4993 uV/cnt	1.2496 uV/cnt	0.62484 uV/cnt	0.24994 uV/cnt	0.12498 uV/cnt	62.496 nV/cnt
Nominal	2.5000 uV/cnt	1.2500 uV/cnt	0.62500 uV/cnt	0.25000 uV/cnt	0.12500 uV/cnt	62.500 nV/cnt
Maximum Difference	0.028%	0.032%	0.026%	0.024%	0.016%	0.013%

The nominal bit-weights provided by Nanometrics were specified to be 2.5 uV/count, 1.25 uV/count, 0.625 uV/count, 0.25 uV/count, 0.125 uV/count, and 62.5 nV/count for gains of 1, 2, 4, 10, 20, and 40, respectively. The measured AC bit-weights were found to be most consistent with the nominal values to within better than 0.016 % to 0.032 %.

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.

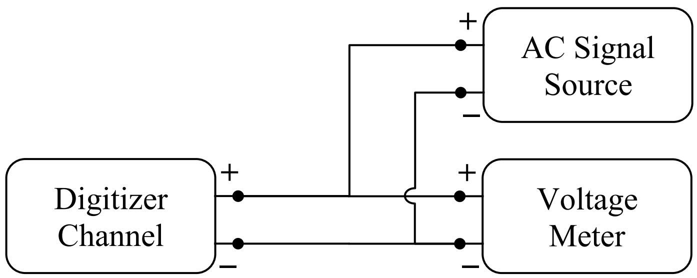

Figure 17 AC Full Scale Configuration Diagram

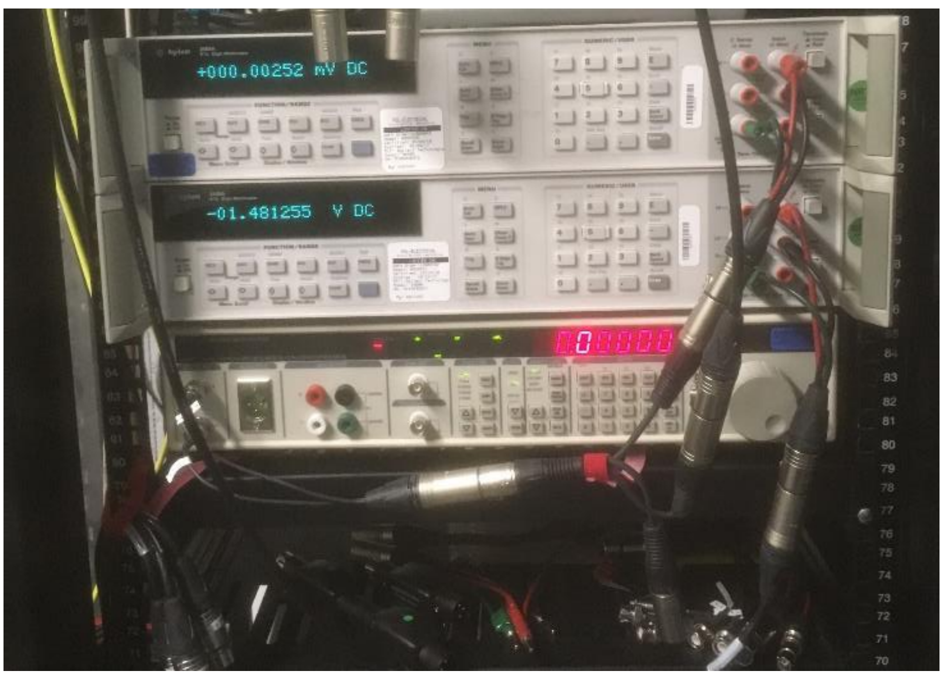

Figure 18 AC Full Scale Configuration Picture

Table 15 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 100% FS
Voltage Meter	Agilent 3458A	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:

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

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 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.

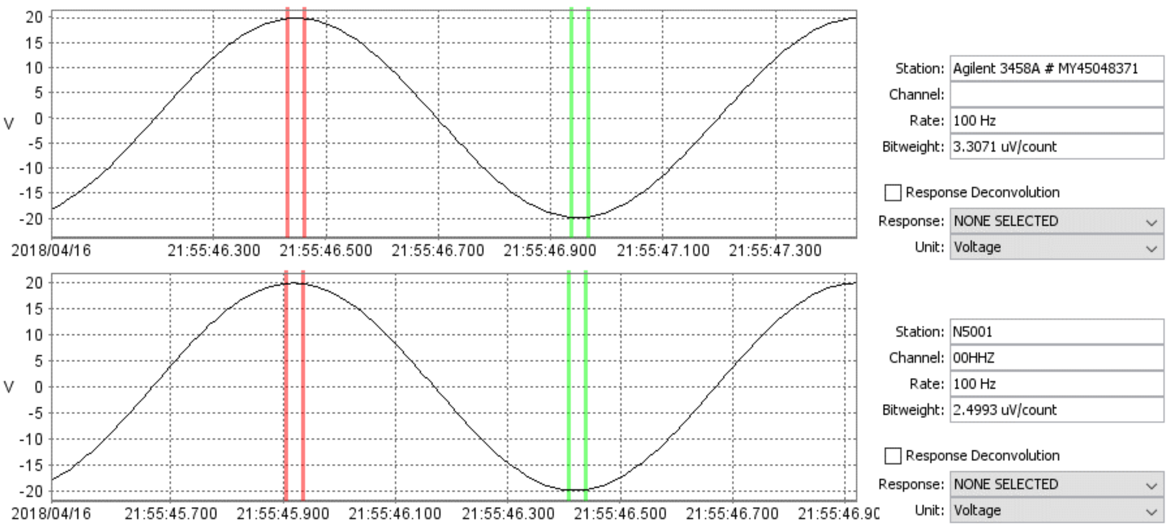

Figure 19 AC Full Scale Time Series

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

Table 16 AC Full Scale: Centaur 5001

		Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Reference	Max	19.816 V	9.9088 V	4.9533 V	1.9828 V	0.99100 V	0.49536 V
	Min	-19.864 V	-9.9327 V	-4.9668 V	-1.9885 V	-0.99343 V	-0.49654 V
Z - 40 Hz	Max	19.799 V	9.8804 V	4.9431 V	1.9832 V	0.99099 V	0.49483 V
	Min	-19.854 V	-9.9104 V	-4.9531 V	-1.9891 V	-0.99335 V	-0.49586 V
N - 40 Hz	Max	19.799 V	9.8804 V	4.9431 V	1.9832 V	0.99099 V	0.49482 V
	Min	-19.854 V	-9.9105 V	-4.9532 V	-1.9892 V	-0.99338 V	-0.49588 V
E - 40 Hz	Max	19.798 V	9.8796 V	4.9428 V	1.9831 V	0.99094 V	0.49480 V
	Min	-19.854 V	-9.9100 V	-4.9531 V	-1.9891 V	-0.99336 V	-0.49587 V
Z - 100 Hz	Max	19.815 V	9.9085 V	4.9535 V	1.9832 V	0.99099 V	0.49550 V
	Min	-19.865 V	-9.9338 V	-4.9669 V	-1.9891 V	-0.99335 V	-0.49677 V
N - 100 Hz	Max	19.815 V	9.9085 V	4.9535 V	1.9832 V	0.99099 V	0.49550 V
	Min	-19.866 V	-9.9340 V	-4.9671 V	-1.9892 V	-0.99338 V	-0.49678 V
E - 100 Hz	Max	19.814 V	9.9077 V	4.9533 V	1.9831 V	0.99094 V	0.49547 V
	Min	-19.865 V	-9.9334 V	-4.9669 V	-1.9891 V	-0.99336 V	-0.49678 V

Table 17 AC Full Scale: Centaur 5002

		Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Reference	Max	19.815 V	9.9089 V	4.9533 V	1.9828 V	0.99100 V	0.49536 V
	Min	-19.864 V	-9.9328 V	-4.9668 V	-1.9885 V	-0.99343 V	-0.49654 V
Z - 20 Hz	Max	19.685 V	9.8800 V	4.9359 V	1.9832 V	0.99094 V	0.49478 V
	Min	-19.718 V	-9.9104 V	-4.9519 V	-1.9892 V	-0.99343 V	-0.49594 V
N - 20 Hz	Max	19.686 V	9.8804 V	4.9361 V	1.9833 V	0.99101 V	0.49483 V
	Min	-19.717 V	-9.9098 V	-4.9516 V	-1.9891 V	-0.99333 V	-0.49586 V
E - 20 Hz	Max	19.684 V	9.8793 V	4.9356 V	1.9830 V	0.99087 V	0.49474 V
	Min	-19.717 V	-9.9100 V	-4.9517 V	-1.9892 V	-0.99340 V	-0.49592 V
Z - 80 Hz	Max	19.803 V	9.9091 V	4.9547 V	1.9831 V	0.99095 V	0.49532 V
	Min	-19.855 V	-9.9337 V	-4.9678 V	-1.9892 V	-0.99344 V	-0.49676 V
N - 80 Hz	Max	19.803 V	9.9094 V	4.9549 V	1.9832 V	0.99101 V	0.49538 V
	Min	-19.853 V	-9.9331 V	-4.9675 V	-1.9891 V	-0.99334 V	-0.49669 V
E - 80 Hz	Max	19.801 V	9.9084 V	4.9544 V	1.9830 V	0.99088 V	0.49529 V
	Min	-19.854 V	-9.9334 V	-4.9677 V	-1.9892 V	-0.99341 V	-0.49675 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.

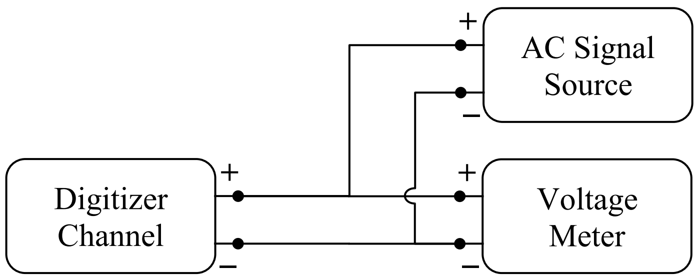

Figure 20 AC Over Scale Configuration Diagram

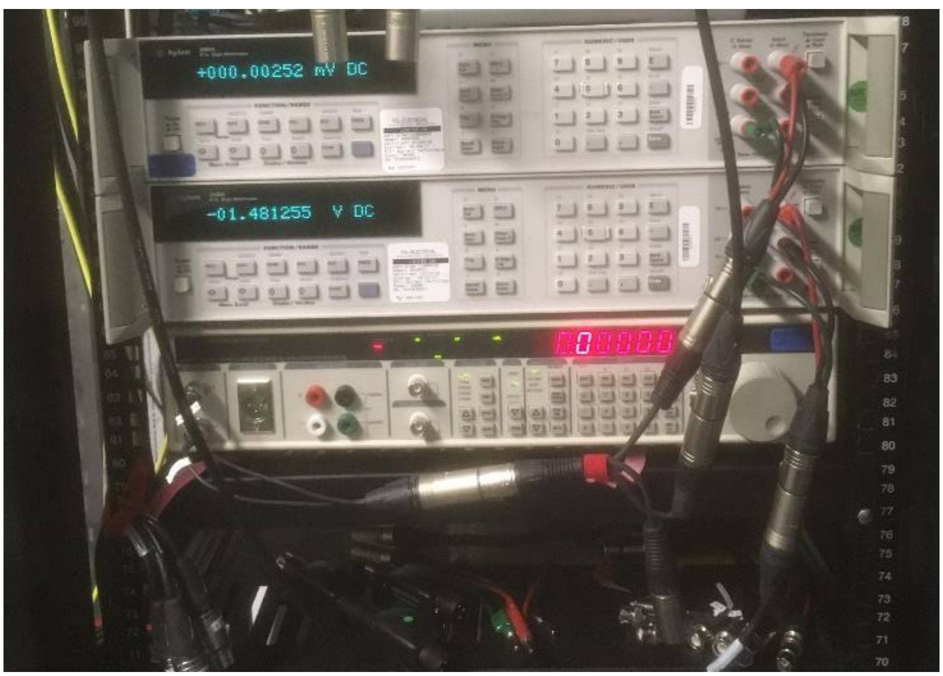

Figure 21 AC Over Scale Configuration Picture

Table 18 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 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 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:

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

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.

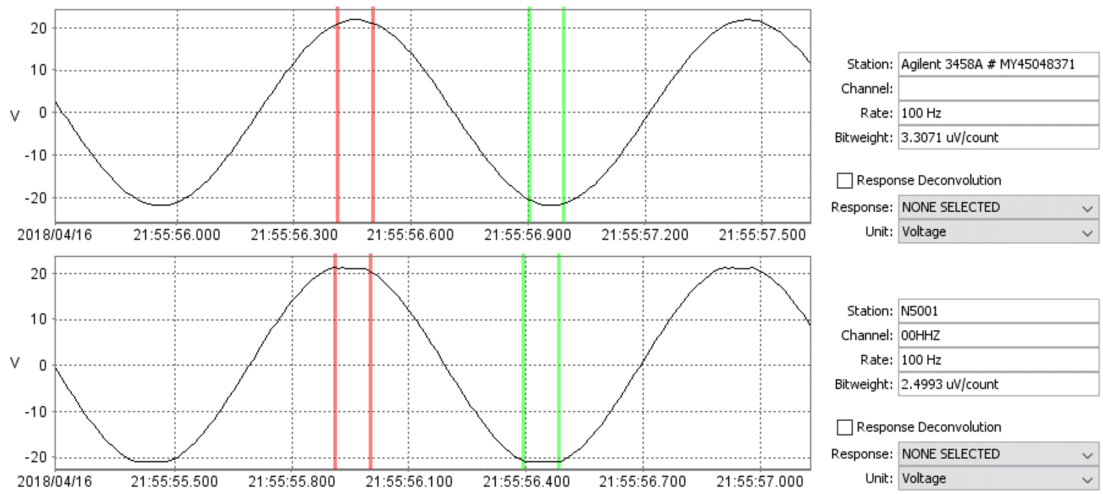

Figure 22 AC Over Scale Time Series

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 19 AC Over Scale: Centaur 5001

		1x	2x	4x	10x	20x	40x
Reference	Max	21.799 V	10.893 V	5.4493 V	2.1819 V	1.0899 V	0.54465 V
	Min	-21.848 V	-10.924 V	-5.4629 V	-2.1879 V	-1.0928 V	-0.54602 V
Z - 40 Hz	Max	21.114 V	10.556 V	5.2751 V	2.1137 V	1.0586 V	0.52820 V
	Min	-21.116 V	-10.564 V	-5.2796 V	-2.1140 V	-1.0587 V	-0.52833 V
N - 40 Hz	Max	21.115 V	10.556 V	5.2742 V	2.1140 V	1.0588 V	0.52826 V
	Min	-21.117 V	-10.564 V	-5.2789 V	-2.1143 V	-1.0588 V	-0.52839 V
E - 40 Hz	Max	21.123 V	10.558 V	5.2762 V	2.1147 V	1.0591 V	0.52886 V
	Min	-21.124 V	-10.565 V	-5.2802 V	-2.1147 V	-1.0590 V	-0.52895 V
Z - 100 Hz	Max	21.092 V	10.547 V	5.2736 V	2.1123 V	1.0572 V	0.52828 V
	Min	-21.091 V	-10.543 V	-5.2732 V	-2.1124 V	-1.0572 V	-0.52818 V
N - 100 Hz	Max	21.094 V	10.546 V	5.2727 V	2.1126 V	1.0575 V	0.52834 V
	Min	-21.093 V	-10.543 V	-5.2725 V	-2.1127 V	-1.0574 V	-0.52823 V
E - 100 Hz	Max	21.103 V	10.549 V	5.2747 V	2.1134 V	1.0578 V	0.52894 V
	Min	-21.100 V	-10.545 V	-5.2739 V	-2.1132 V	-1.0576 V	-0.52882 V

Table 20 AC Over Scale: Centaur 5002

		1x	2x	4x	10x	20x	40x
Reference	Max	21.799 V	10.897 V	5.4493 V	2.1819 V	1.0899 V	0.54466 V
	Min	-21.848 V	-10.924 V	-5.4629 V	-2.1879 V	-1.0928 V	-0.54603 V
Z - 20 Hz	Max	21.198 V	10.584 V	5.2904 V	2.1186 V	1.0603 V	0.53083 V
	Min	-21.196 V	-10.580 V	-5.2886 V	-2.1194 V	-1.0607 V	-0.53084 V
N - 20 Hz	Max	21.194 V	10.581 V	5.2887 V	2.1180 V	1.0601 V	0.53074 V
	Min	-21.196 V	-10.579 V	-5.2878 V	-2.1192 V	-1.0607 V	-0.53086 V
E - 20 Hz	Max	21.190 V	10.579 V	5.2885 V	2.1181 V	1.0603 V	0.53090 V
	Min	-21.187 V	-10.575 V	-5.2867 V	-2.1189 V	-1.0608 V	-0.53091 V
Z - 80 Hz	Max	21.094 V	10.548 V	5.2734 V	2.1128 V	1.0576 V	0.52823 V
	Min	-21.090 V	-10.547 V	-5.2726 V	-2.1127 V	-1.0576 V	-0.52835 V
N - 80 Hz	Max	21.090 V	10.545 V	5.2717 V	2.1122 V	1.0574 V	0.52814 V
	Min	-21.090 V	-10.546 V	-5.2717 V	-2.1125 V	-1.0576 V	-0.52836 V
E - 80 Hz	Max	21.086 V	10.543 V	5.2715 V	2.1123 V	1.0577 V	0.52831 V
	Min	-21.082 V	-10.542 V	-5.2706 V	-2.1122 V	-1.0577 V	-0.52841 V

For all sample rates and gain levels, the digitizer channels were determined to have a full-scale amplitude that exceeded by at least 5% the nominally specified full scale of 20 V at a gain of 1x, 10 V at a gain of 2x, 5 V at a gain of 4x, 2 V at a gain of 10x, 1 V at a gain of 20x, and 0.5 V at a gain of 40x.

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 23 Input Shorted Offset Configuration Diagram

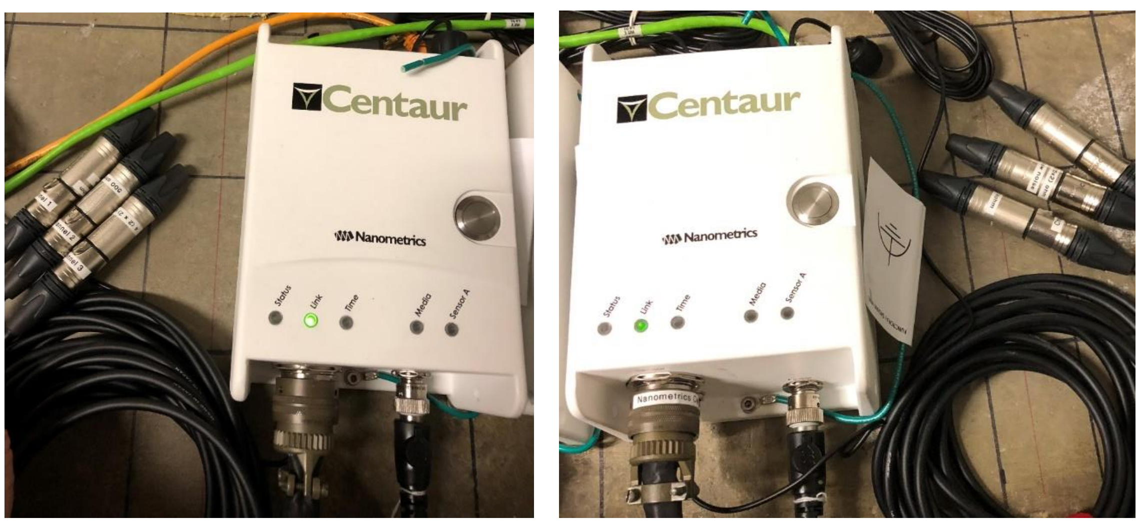

Figure 24 Input Shorted Offset Configuration Picture

Table 21 Input Shorted Offset Testbed Equipment

	Impedance
Resistors	50 (25 x 2) ohm 500 (250 x 2) ohm 4k (2k x 2) ohm 9.4k (4.7k x 2) ohm

A minimum of 12 hours of data is recorded.

3.7.3 Analysis

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

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

The mean value, in volts, is calculated:

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

3.7.4 Result

The figures below show 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. 12 hours of data was selected for use in analyzing the offset, chosen after the DC level of the voltage has stabilized.

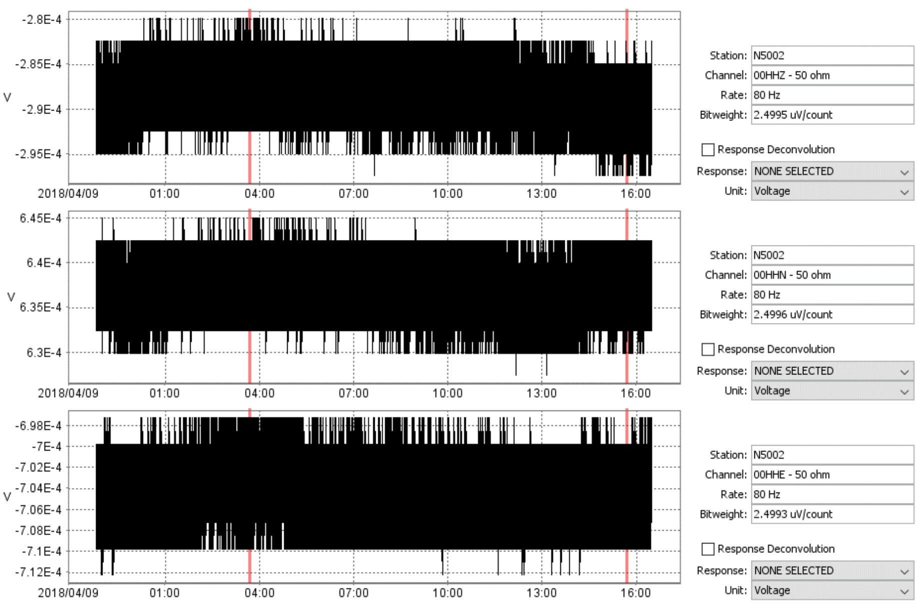

Figure 25 Input Shorted Offset Time Series: Centaur 5001

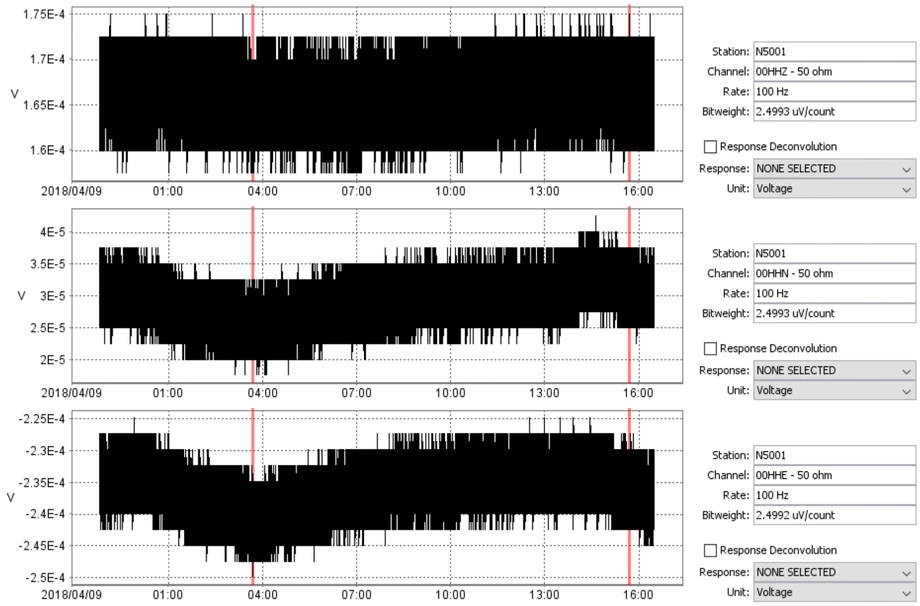

Figure 26 Input Shorted Offset Time Series: Centaur 5002

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

Table 22 Input Shorted Offset: Centaur 5001

	Impedance	Gain 1x	Impedance	Gain 1x	Gain 2x	Gain 4x	Impedance	Gain 10x	Gain 20x	Gain 40x
Z - 40 Hz	50 ohm	0.1660 mV	50 ohm	0.1668 mV	81.03 uV	43.26 uV	9k ohm	23.85 uV	16.52 uV	13.55 uV
N - 40 Hz	50 ohm	29.44 uV	500 ohm	30.79 uV	15.14 uV	8.320 uV	500 ohm	8.552 uV	8.770 uV	7.124 uV
E - 40 Hz	50 ohm	-0.2359 mV	4k ohm	-0.2382 mV	-0.1197 mV	-59.23 uV	4k ohm	-20.41 uV	-8.158 uV	-2.879 uV
Z - 100 Hz	50 ohm	0.1660 mV	50 ohm	0.1668 mV	81.03 uV	43.25 uV	9k ohm	23.85 uV	16.52 uV	13.55 uV
N - 100 Hz	50 ohm	29.43 uV	500 ohm	30.80 uV	15.14 uV	8.320 uV	500 ohm	8.552 uV	8.770 uV	7.124 uV
E - 100 Hz	50 ohm	-0.2359 mV	4k ohm	-0.2382 mV	-0.1197 mV	-59.23 uV	4k ohm	-20.41 uV	-8.158 uV	-2.879 uV

Table 23 Input Shorted Offset: Centaur 5002

	Impedance	Gain 1x	Impedance	Gain 1x	Gain 2x	Gain 4x	Impedance	Gain 10x	Gain 20x	Gain 40x
Z - 20 Hz	50 ohm	-0.2883 mV	50 ohm	-0.2886 mV	-0.1409 mV	-58.71 uV	9k ohm	-58.34 uV	-55.06 uV	-52.43 uV
N - 20 Hz	50 ohm	0.6369 mV	500 ohm	0.6371 mV	0.3293 mV	0.1728 mV	500 ohm	70.16 uV	35.88 uV	17.98 uV
E - 20 Hz	50 ohm	-0.7042 mV	4k ohm	-0.7062 mV	-0.3396 mV	-0.1682 mV	4k ohm	-89.92 uV	-65.80 uV	-53.73 uV
Z - 80 Hz	50 ohm	-0.2883 mV	50 ohm	-0.2886 mV	-0.1409 mV	-58.71 uV	9k ohm	-58.34 uV	-55.06 uV	-52.43 uV
N - 80 Hz	50 ohm	0.6369 mV	500 ohm	0.6371 mV	0.3293 mV	0.1728 mV	500 ohm	70.16 uV	35.88 uV	17.98 uV
E - 80 Hz	50 ohm	-0.7043 mV	4k ohm	-0.7062 mV	-0.3396 mV	-0.1682 mV	4k ohm	-89.92 uV	-65.80 uV	-53.73 uV

The observed offsets ranged between -0.7042 mV to 0.369 mV at a gain of 1x to as low as -53.73 uV to 17.98 uV at a gain of 40x. There does not appear to be any relationship between the offsets observed on each physical channel as each channel has a distinct offset. The selected sample rate does not have any impact on the channel offset. Also, changes in terminating resistor impedances at a gain of 1x did not significantly impact the observed offset. Overall, increasing the gain level resulted in a smaller offset when measured in Volts. For gains of 1x, 2x, and 4x, the offset appears to scale inversely with the gain level. However, for gains of 10x, 20x, and 40x, that was not necessarily the case.

It is important to note that all of these measurements of channel offset were made while the digitizers were operating at an ambient temperature of 23 C.

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 a passband.

3.8.2 Configuration

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

Figure 27 Self Noise Configuration Diagram

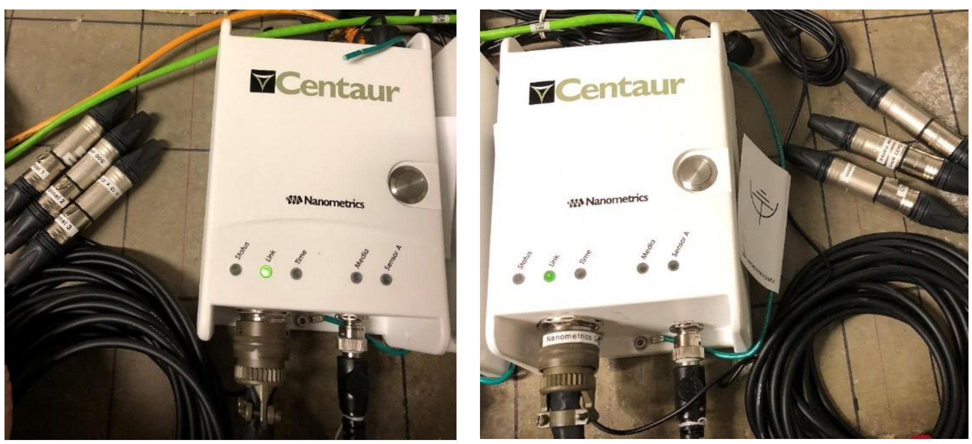

Figure 28 Self Noise Configuration Picture

For the self-noise tests, the digitizer channels were terminated with resistors according to the schedule below:

Table 24 Digitizer Self-Noise Terminator Configuration

	Centaur 5001 (40 Hz and 100 Hz)			Centaur 5002 (20 Hz and 80 Hz)		
	Z	N	E	Z	N	E
Gain 1x	50 ohm	50 ohm	50 ohm	50 ohm	50 ohm	50 ohm
Gain 1x	50 ohm	500 ohm	4k ohm	50 ohm	500 ohm	4k ohm
Gain 2x	50 ohm	500 ohm	4k ohm	50 ohm	500 ohm	4k ohm
Gain 4x	50 ohm	500 ohm	4k ohm	50 ohm	500 ohm	4k ohm
Gain 10x	9.4k ohm	500 ohm	4k ohm	9.4k ohm	500 ohm	4k ohm
Gain 20x	9.4k ohm	500 ohm	4k ohm	9.4k ohm	500 ohm	4k ohm
Gain 40x	9.4k ohm	500 ohm	4k ohm	9.4k ohm	500 ohm	4k ohm

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:

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

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:

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

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 Centaur 5001 channel Z, N, and E at a gain of 1x for a 100 Hz sample rate. The waveforms from the other gain settings, sample rates, and the second digitizer are all very similar in appearance. The window regions bounded by the red lines indicate the segment of data used for analysis. 12 hours of data was selected for use in analyzing the self-noise, chosen after the DC level of the voltage has stabilized.

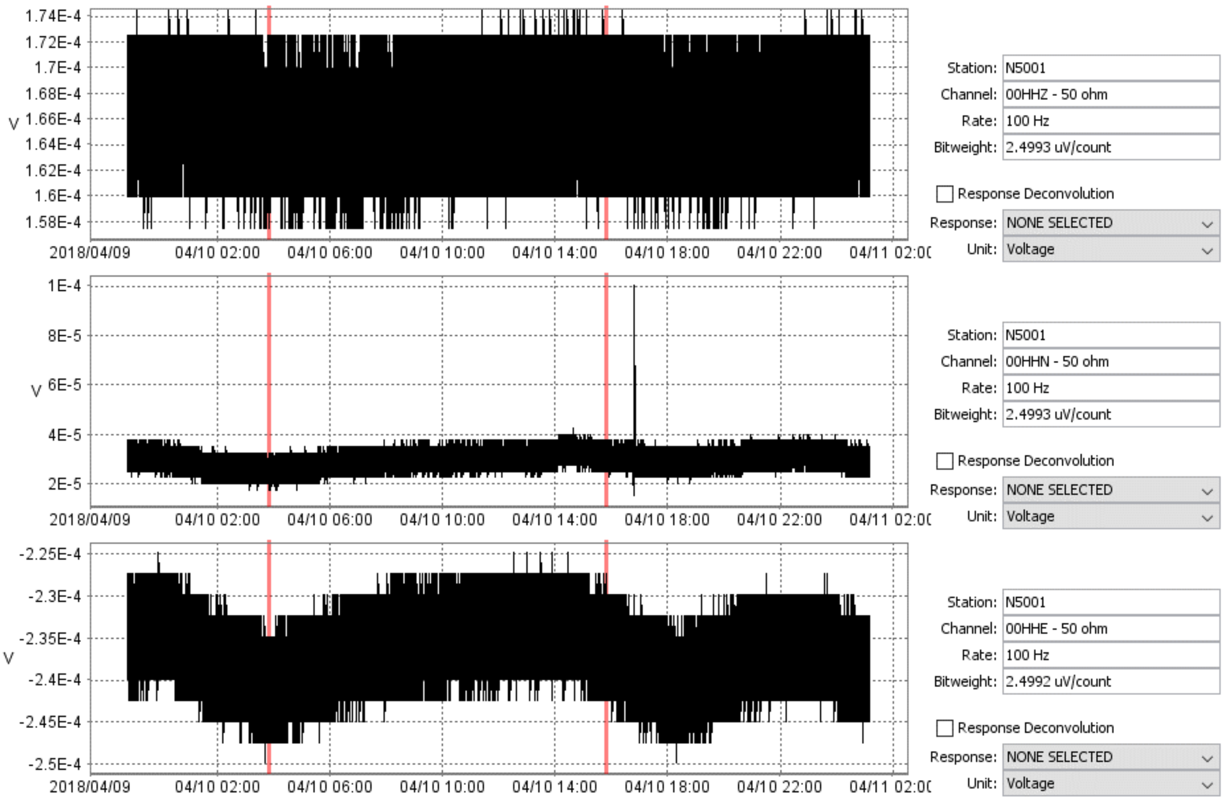

Figure 29 Self Noise Time Series: Centaur 5001, Channel Z (1x gain)

The Centaur 5001 digitizer recorded data at sample rates of 40 Hz and 100 Hz. The Centaur 5002 digitizer recorded at sample rates of 20 Hz and 80 Hz. A comparison of the power spectral density levels at each of the recorded sample rates for 5001 and 5002 while all channels were terminated with a 50 ohm terminator are shown below.

This first test of self-noise was performed to validate the performance of all the digitizer channels relative to one another before changing any of the gain settings or terminator values.

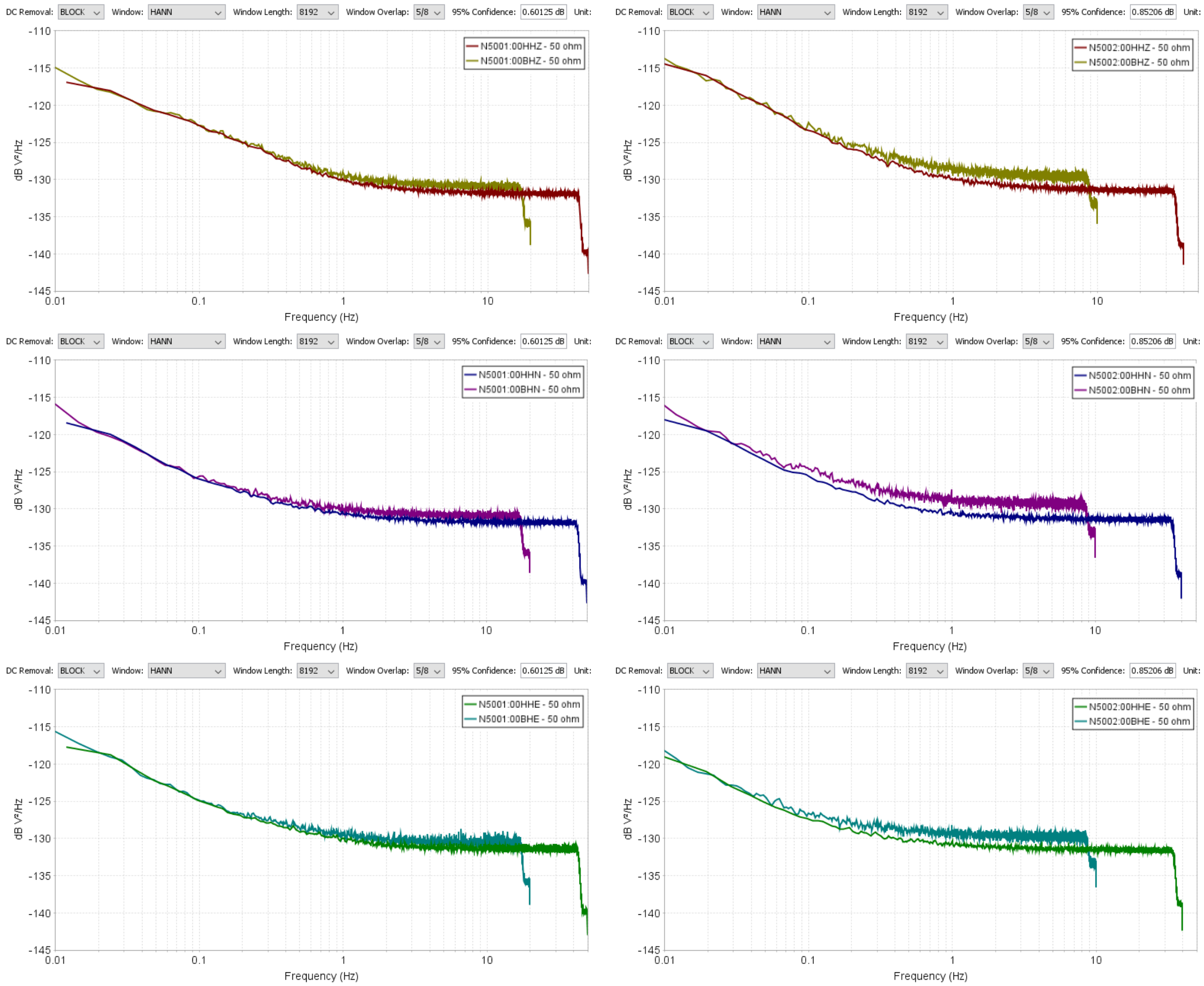

Figure 30 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 1x, 50 ohm

The PSD levels are very similar at frequencies below 1 Hz. However, at frequencies above 1 Hz, the PSD levels are observed to vary with the sampling rate. Higher sampling rates exhibit lower spectral noise levels than lower sampling rates, indicating that the Centaur has very low electronic noise and that the dominant noise source at high frequency is consistent with quantization noise being distributed over a wider frequency pass-band. Transitioning from 40 Hz to 100 Hz, PSD levels above 1 Hz are approximately 1 dB lower. Transitioning from 20 Hz to 80 Hz, PSD levels above 1 Hz are approximately 2 dB lower. Note, however, that total noise in the data channel is still greater at higher sample rates due to the increased passband.

Table 25 Total Channel Self Noise: Centaur 5001 and 5002, gain 1x, 50 ohm

	5001				5002			
	40 Hz (0 - 20 Hz)		100 Hz (0 - 50 Hz)		20 Hz (0 - 10 Hz)		80 Hz (0 - 40 Hz)	
	Volts	Counts	Volts	Counts	Volts	Counts	Volts	Counts
Z	1.321 uV rms	0.5287 cnt rms	1.775 uV rms	0.7102 cnt rms	1.153 uV rms	0.4613 cnt rms	1.685 uV rms	0.6741 cnt rms
N	1.278 uV rms	0.5113 cnt rms	1.754 uV rms	0.7019 cnt rms	1.114 uV rms	0.4455 cnt rms	1.647 uV rms	0.6590 cnt rms
E	1.333 uV rms	0.5333 cnt rms	1.835 uV rms	0.7343 cnt rms	1.037 uV rms	0.4148 cnt rms	1.618 uV rms	0.6474 cnt rms

The PSD plots are arranged for each gain setting with digitizer 5001 on the left and 5002 on the right. Sample rates of 100 Hz and 80 Hz are on the top and 40 Hz and 20 Hz are on the bottom.

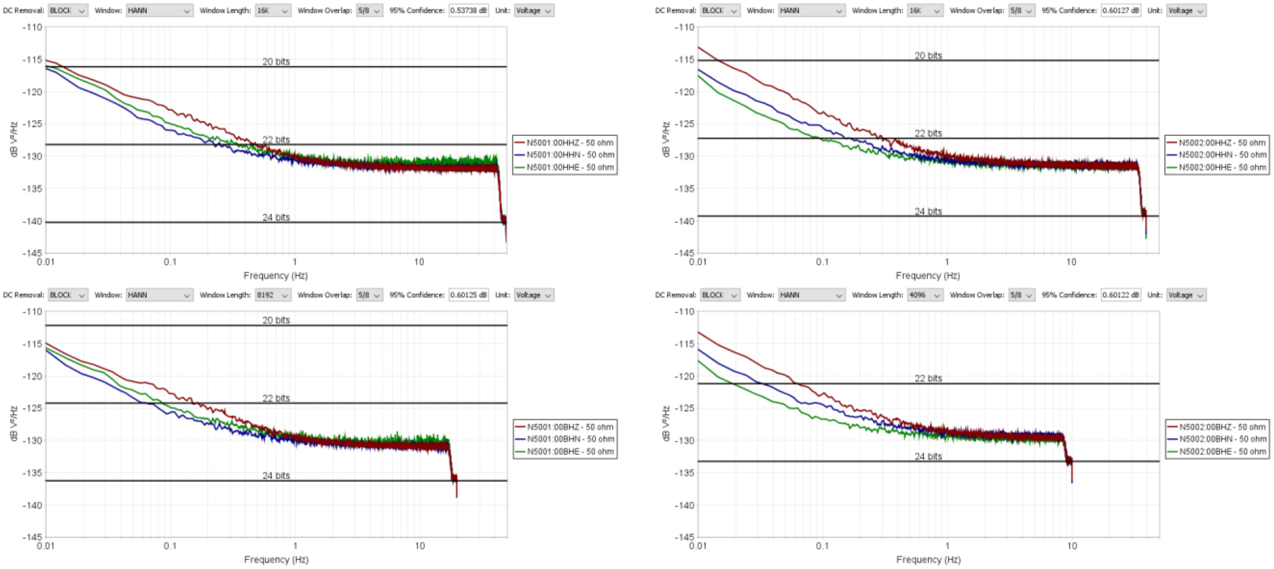

Figure 31 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 1x, 50 ohm

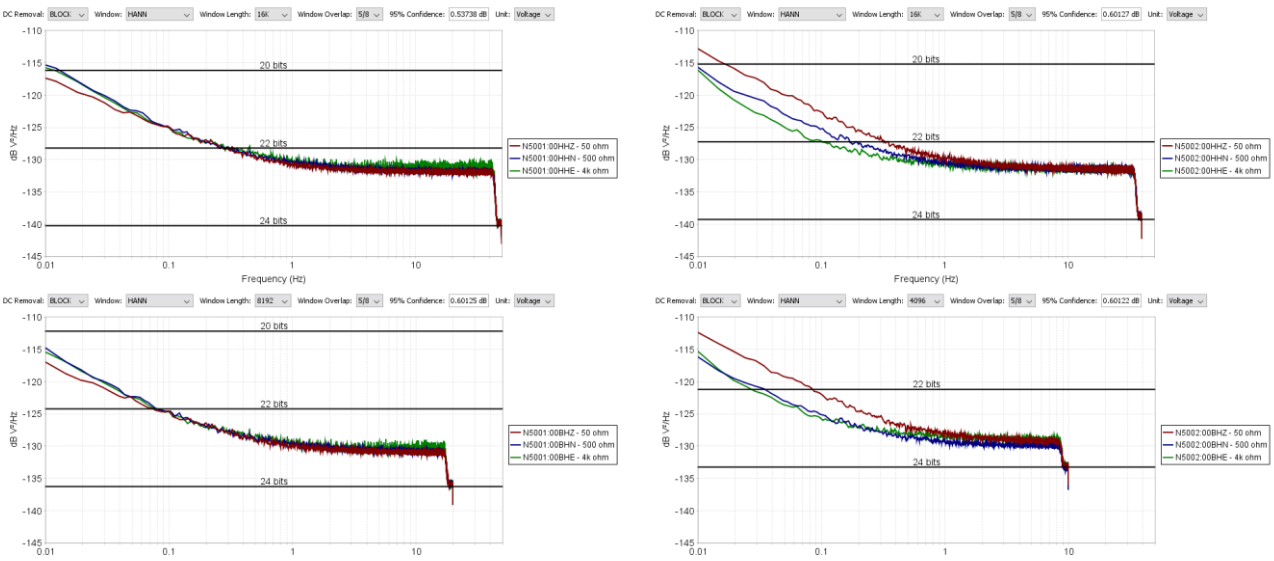

Figure 32 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 1x

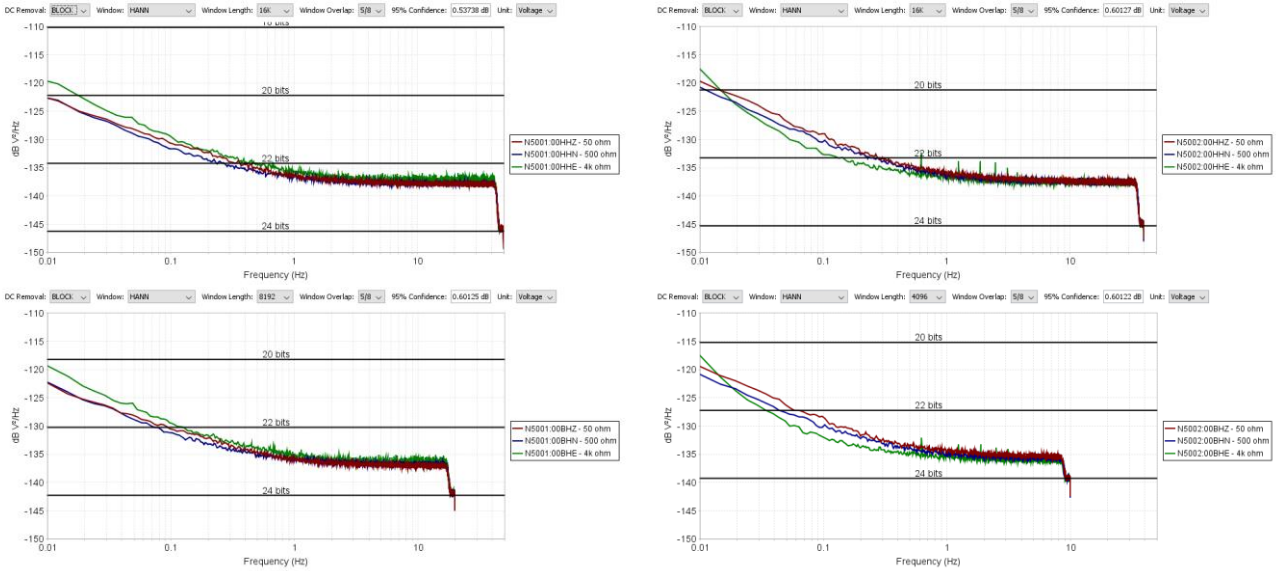

Figure 33 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 2x

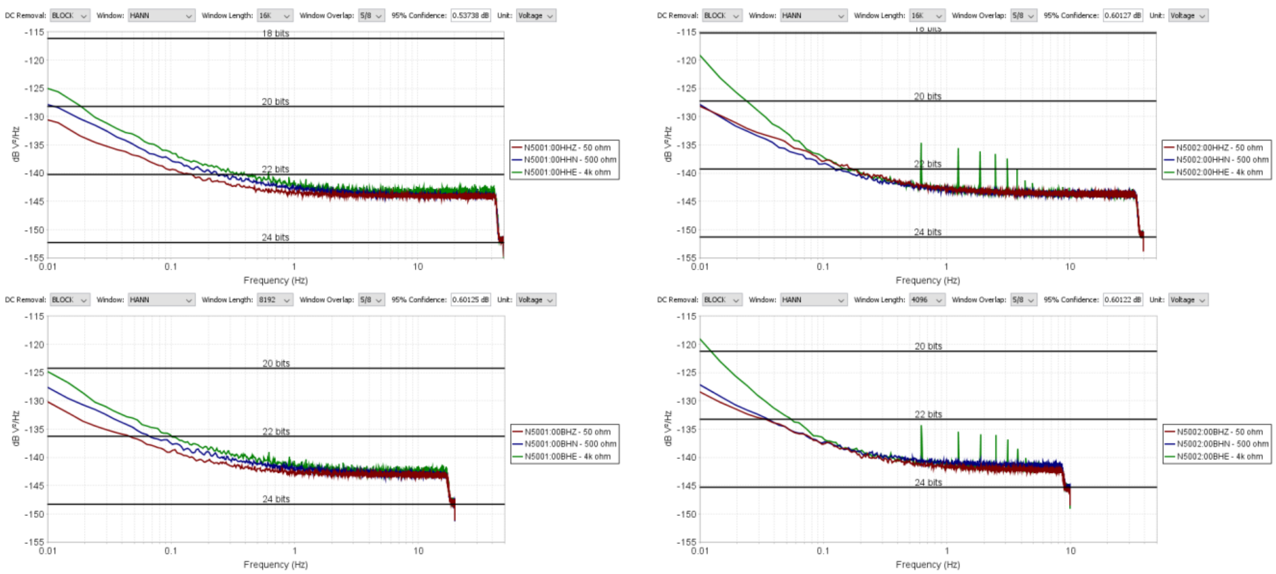

Figure 34 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 4x

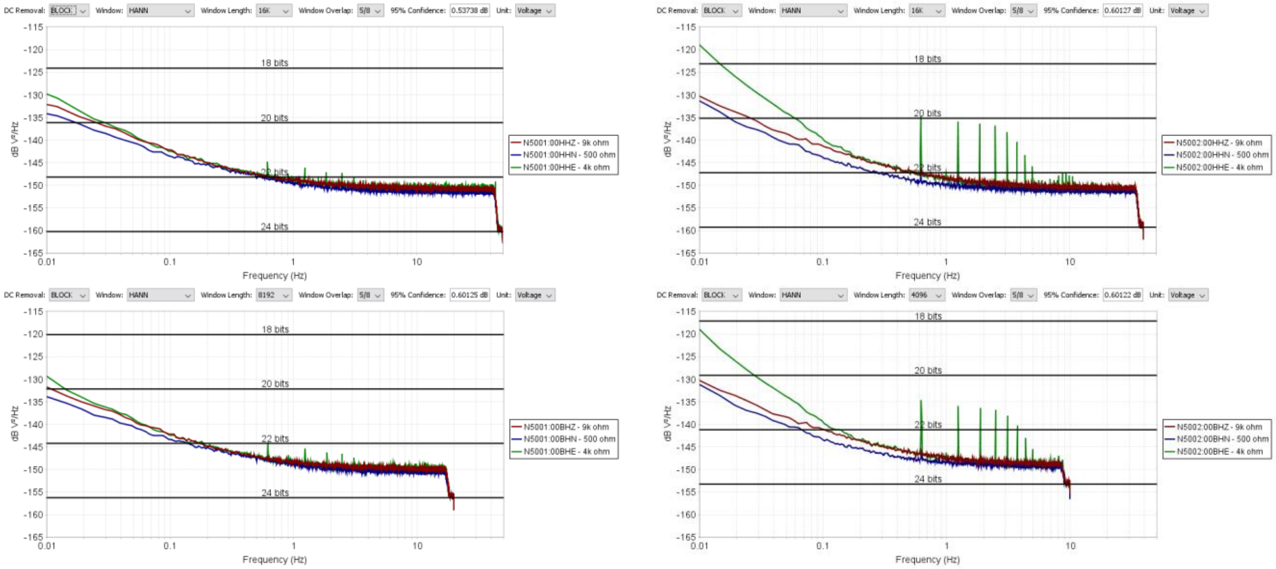

Figure 35 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 10x

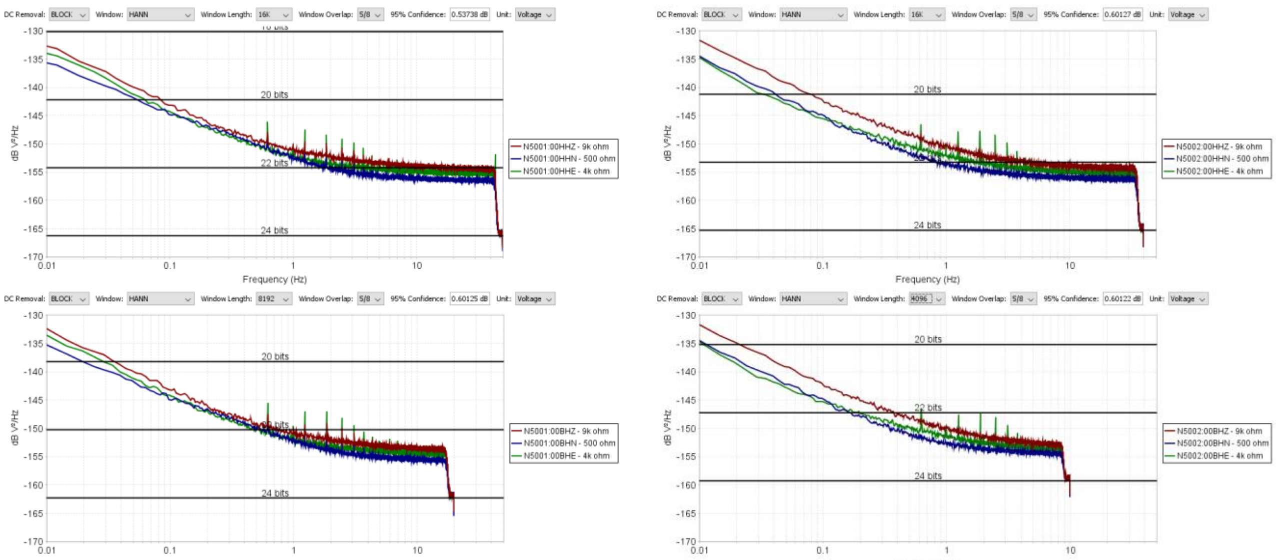

Figure 36 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 20x

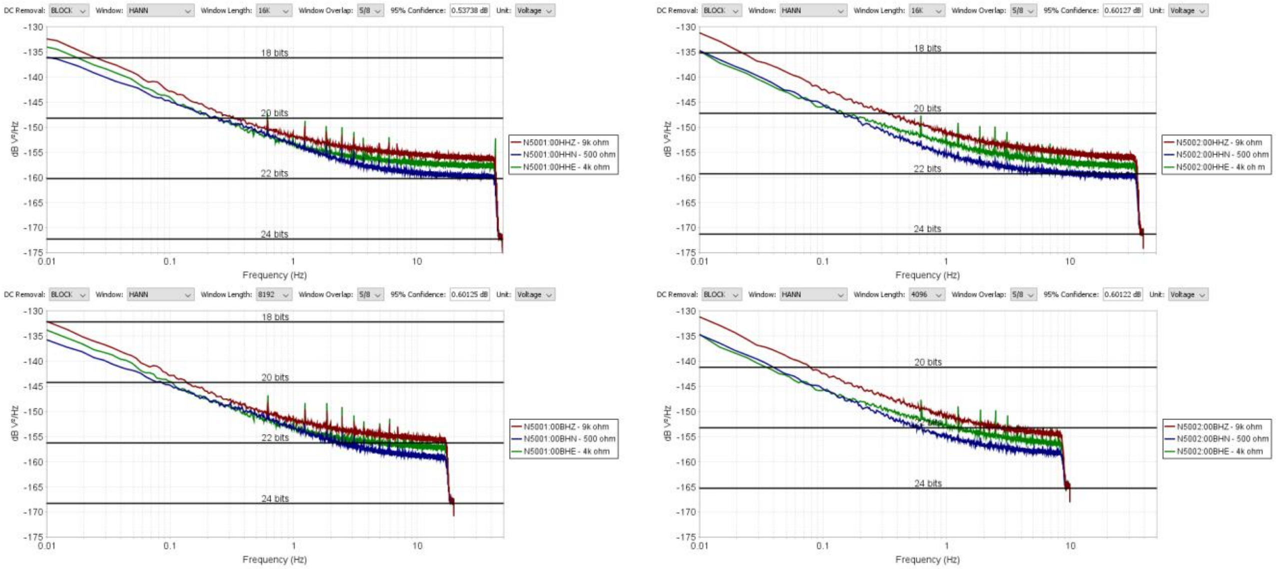

Figure 37 Self Noise Power Spectra: Centaur 5001 (left) and 5002 (right), gain 40x

On Centaur 5001 at gains of 4x and 10x, channel E, which was terminated with a 4k ohm resistor, there appears to be elevated noise at frequencies below 0.1 Hz and periodic spikes in the spectrum. Examining the time series for this data:

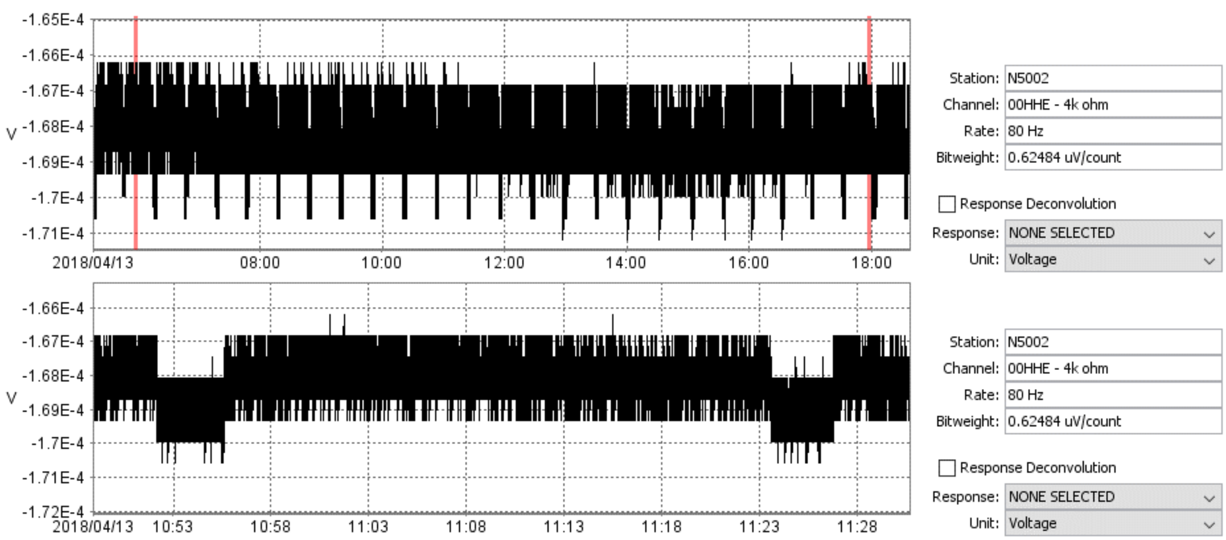

Figure 38 Self Noise Power Spectra: Centaur 5002, gain 4x, Channel E 4k ohm, 12 hour segment (top) and 40 minute segment (bottom).

It is visible that there were changes in the DC offset of the channel by approximately 0.01 mV that occurred regularly at intervals just over every 30 minutes and lasting for approximately 3.5 minutes. This was observed to occur during the 4x and 10x gains of 5002 on this one channel. However, this was not observed to continue performing at other gain levels.

In addition, there were some small spikes in the power spectra with a fundamental frequency of 0.6 Hz plus harmonics that were visible on channel E of 5001 and channels E and NE of 5002 at gains of 10x, 20x, and 40x. However, there was nothing discernable on the time series that would explain this.

There is no explanation for why these issues occurred and may have been related to some temporary ambient condition as they stopped occurring seemingly on their own and have not been observed since.

In general, spectral noise levels decreased at frequencies above 0.1 Hz by 6 dB from a gain of 1x to 2x, 6 dB from a gain of 2x to 4x, 7 dB from a gain of 4x to 10x, 3 – 5 dB from a gain of 10x to 20x, and 2 – 3 dB from a gain of 20x to 40x. This highlights the diminishing returns from increasing gain levels, as is also evidenced by the change in the power spectral levels relative to the theoretical noise free bit plots shown in the plots above. Higher gains levels have fewer noise free bits, as expected.

An additional observation is that there did not appear to be any significant change in self-noise power spectral levels between the 50 ohm, 500 ohm, and 4k ohm impedance terminators at gains of 1x, 2x, and 4x that could not otherwise be explained by intrinsic differences between the digitizer channels. However, when the 9k ohm impedance terminator was used, the corresponding digitizer channel did exhibit slightly elevated noise levels, by as much as 1 – 3 dB relative to the other channels, across the 10x, 20x, and 40x gains.

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 26 Self Noise RMS: Centaur 5001, 100 Hz

Channel	Gain	Impedance	0 Hz - 50 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Z	1x	50 ohm	1.781 mV rms	474.8 uV rms	675.6 uV rms	1.119 mV rms	1.042 mV rms
			0.7126 cnt rms	0.1900 cnt rms	0.2703 cnt rms	0.4476 cnt rms	0.4168 cnt rms
N	1x	50 ohm	1.759 mV rms	376.1 uV rms	602.8 uV rms	1.078 mV rms	1.033 mV rms
			0.7038 cnt rms	0.1505 cnt rms	0.2412 cnt rms	0.4313 cnt rms	0.4135 cnt rms
E	1x	50 ohm	1.840 mV rms	414.5 uV rms	643.2 uV rms	1.132 mV rms	1.080 mV rms
			0.7362 cnt rms	0.1659 cnt rms	0.2574 cnt rms	0.4531 cnt rms	0.4320 cnt rms
Z	1x	50 ohm	1.743 mV rms	386.6 uV rms	605.1 uV rms	1.073 mV rms	1.024 mV rms
			0.6974 cnt rms	0.1547 cnt rms	0.2421 cnt rms	0.4291 cnt rms	0.4096 cnt rms
N	1x	500 ohm	1.773 mV rms	402.4 uV rms	626.6 uV rms	1.095 mV rms	1.043 mV rms
			0.7092 cnt rms	0.1610 cnt rms	0.2507 cnt rms	0.4380 cnt rms	0.4172 cnt rms
E	1x	4k ohm	1.840 mV rms	404.6 uV rms	635.6 uV rms	1.130 mV rms	1.080 mV rms
			0.7363 cnt rms	0.1619 cnt rms	0.2543 cnt rms	0.4520 cnt rms	0.4322 cnt rms
Z	2x	50 ohm	884.7 uV rms	207.6 uV rms	315.5 uV rms	548.4 uV rms	520.2 uV rms
			0.7079 cnt rms	0.1661 cnt rms	0.2525 cnt rms	0.4388 cnt rms	0.4162 cnt rms
N	2x	500 ohm	881.2 uV rms	191.9 uV rms	303.8 uV rms	540.7 uV rms	517.1 uV rms
			0.7051 cnt rms	0.1536 cnt rms	0.2431 cnt rms	0.4327 cnt rms	0.4138 cnt rms
E	2x	4k ohm	940.0 uV rms	230.8 uV rms	343.7 uV rms	584.1 uV rms	550.9 uV rms
			0.7523 cnt rms	0.1847 cnt rms	0.2751 cnt rms	0.4674 cnt rms	0.4409 cnt rms
Z	4x	50 ohm	425.0 uV rms	81.45 uV rms	138.0 uV rms	257.2 uV rms	248.8 uV rms
			0.6802 cnt rms	0.1304 cnt rms	0.2208 cnt rms	0.4117 cnt rms	0.3982 cnt rms
N	4x	500 ohm	434.6 uV rms	95.92 uV rms	151.8 uV rms	267.4 uV rms	255.6 uV rms
			0.6956 cnt rms	0.1535 cnt rms	0.2430 cnt rms	0.4280 cnt rms	0.4091 cnt rms
E	4x	4k ohm	460.7 uV rms	108.8 uV rms	164.3 uV rms	283.7 uV rms	268.8 uV rms
			0.7373 cnt rms	0.1742 cnt rms	0.2630 cnt rms	0.4540 cnt rms	0.4301 cnt rms
Z	10x	9.4k ohm	203.5 uV rms	52.23 uV rms	76.64 uV rms	128.1 uV rms	120.1 uV rms
			0.8141 cnt rms	0.2090 cnt rms	0.3066 cnt rms	0.5126 cnt rms	0.4804 cnt rms
N	10x	500 ohm	185.4 uV rms	47.31 uV rms	69.37 uV rms	116.2 uV rms	109.1 uV rms
			0.7420 cnt rms	0.1893 cnt rms	0.2776 cnt rms	0.4648 cnt rms	0.4366 cnt rms
E	10x	4k ohm	203.8 uV rms	53.23 uV rms	76.59 uV rms	126.6 uV rms	118.1 uV rms
			0.8155 cnt rms	0.2130 cnt rms	0.3065 cnt rms	0.5065 cnt rms	0.4726 cnt rms
Z	20x	9.4k ohm	141.5 uV rms	45.78 uV rms	61.74 uV rms	93.46 uV rms	84.33 uV rms
			1.133 cnt rms	0.3664 cnt rms	0.4940 cnt rms	0.7478 cnt rms	0.6748 cnt rms
N	20x	500 ohm	112.2 uV rms	39.21 uV rms	51.11 uV rms	74.70 uV rms	66.42 uV rms
			0.8981 cnt rms	0.3138 cnt rms	0.4090 cnt rms	0.5977 cnt rms	0.5315 cnt rms
E	20x	4k ohm	127.5 uV rms	40.42 uV rms	54.49 uV rms	83.07 uV rms	75.18 uV rms
			1.020 cnt rms	0.3234 cnt rms	0.4360 cnt rms	0.6648 cnt rms	0.6017 cnt rms
Z	40x	9.4k ohm	122.1 uV rms	46.26 uV rms	58.96 uV rms	83.45 uV rms	72.39 uV rms
			1.953 cnt rms	0.7403 cnt rms	0.9435 cnt rms	1.335 cnt rms	1.159 cnt rms
N	40x	500 ohm	84.27 uV rms	36.96 uV rms	45.84 uV rms	60.23 uV rms	50.73 uV rms
			1.349 cnt rms	0.5915 cnt rms	0.7336 cnt rms	0.9638 cnt rms	0.8118 cnt rms
E	40x	4k ohm	102.0 uV rms	38.83 uV rms	49.34 uV rms	69.38 uV rms	60.08 uV rms
			1.632 cnt rms	0.6214 cnt rms	0.7897 cnt rms	1.110 cnt rms	0.9615 cnt rms

Table 27 Self Noise RMS: Centaur 5001, 40 Hz

Channel	Gain	Impedance	0 Hz - 20 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Z	1x	50 ohm	1.321 mV rms	487.8 uV rms	717.2 uV rms	1.221 mV rms	1.149 mV rms
			0.5287 cnt rms	0.1952 cnt rms	0.2870 cnt rms	0.4887 cnt rms	0.4596 cnt rms
N	1x	50 ohm	1.278 mV rms	392.1 uV rms	647.3 uV rms	1.179 mV rms	1.137 mV rms
			0.5287 cnt rms	0.1952 cnt rms	0.2870 cnt rms	0.4887 cnt rms	0.4596 cnt rms
E	1x	50 ohm	1.333 mV rms	430.0 uV rms	686.9 uV rms	1.233 mV rms	1.182 mV rms
			0.5332 cnt rms	0.1721 cnt rms	0.2748 cnt rms	0.4933 cnt rms	0.4729 cnt rms
Z	1x	50 ohm	1.276 mV rms	406.7 uV rms	655.6 uV rms	1.182 mV rms	1.134 mV rms
			0.5105 cnt rms	0.1627 cnt rms	0.2623 cnt rms	0.4731 cnt rms	0.4539 cnt rms
N	1x	500 ohm	1.306 mV rms	421.1 uV rms	675.1 uV rms	1.205 mV rms	1.154 mV rms
			0.5226 cnt rms	0.1685 cnt rms	0.2701 cnt rms	0.4820 cnt rms	0.4619 cnt rms
E	1x	4k ohm	1.340 mV rms	424.1 uV rms	684.2 uV rms	1.238 mV rms	1.190 mV rms
			0.5361 cnt rms	0.1697 cnt rms	0.2738 cnt rms	0.4954 cnt rms	0.4760 cnt rms
Z	2x	50 ohm	639.0 uV rms	213.5 uV rms	333.8 uV rms	591.9 uV rms	564.9 uV rms
			0.5113 cnt rms	0.1709 cnt rms	0.2671 cnt rms	0.4737 cnt rms	0.4520 cnt rms
N	2x	500 ohm	647.4 uV rms	202.3 uV rms	330.1 uV rms	599.2 uV rms	576.1 uV rms
			0.5180 cnt rms	0.1619 cnt rms	0.2641 cnt rms	0.4795 cnt rms	0.4610 cnt rms
E	2x	4k ohm	688.3 uV rms	237.6 uV rms	364.0 uV rms	632.7 uV rms	601.0 uV rms
			0.5508 cnt rms	0.1901 cnt rms	0.2913 cnt rms	0.5063 cnt rms	0.4810 cnt rms
Z	4x	50 ohm	306.9 uV rms	86.48 uV rms	150.7 uV rms	285.1 uV rms	276.9 uV rms
			0.4912 cnt rms	0.1384 cnt rms	0.2411 cnt rms	0.4563 cnt rms	0.4432 cnt rms
N	4x	500 ohm	317.0 uV rms	99.44 uV rms	162.8 uV rms	293.8 uV rms	282.7 uV rms
			0.5073 cnt rms	0.1592 cnt rms	0.2605 cnt rms	0.4702 cnt rms	0.4524 cnt rms
E	4x	4k ohm	334.2 uV rms	111.8 uV rms	174.4 uV rms	308.0 uV rms	294.0 uV rms
			0.5350 cnt rms	0.1789 cnt rms	0.2791 cnt rms	0.4930 cnt rms	0.4706 cnt rms
Z	10x	9.4k ohm	149.9 uV rms	53.59 uV rms	80.57 uV rms	137.7 uV rms	130.0 uV rms
			0.5997 cnt rms	0.2144 cnt rms	0.3224 cnt rms	0.5510 cnt rms	0.5202 cnt rms
N	10x	500 ohm	137.2 uV rms	48.86 uV rms	73.76 uV rms	126.5 uV rms	119.8 uV rms
			0.5490 cnt rms	0.1955 cnt rms	0.2951 cnt rms	0.5063 cnt rms	0.4794 cnt rms
E	10x	4k ohm	152.4 uV rms	54.45 uV rms	80.41 uV rms	136.0 uV rms	127.9 uV rms
			0.6096 cnt rms	0.2179 cnt rms	0.3217 cnt rms	0.5442 cnt rms	0.5117 cnt rms
Z	20x	9.4k ohm	106.2 uV rms	46.02 uV rms	62.85 uV rms	96.63 uV rms	87.79 uV rms
			0.8497 cnt rms	0.3682 cnt rms	0.5029 cnt rms	0.7732 cnt rms	0.7025 cnt rms
N	20x	500 ohm	85.76 uV rms	39.54 uV rms	52.52 uV rms	78.69 uV rms	70.81 uV rms
			0.6863 cnt rms	0.3164 cnt rms	0.4203 cnt rms	0.6297 cnt rms	0.5666 cnt rms
E	20x	4k ohm	95.29 uV rms	40.68 uV rms	55.77 uV rms	86.69 uV rms	79.14 uV rms
			0.7626 cnt rms	0.3255 cnt rms	0.4463 cnt rms	0.6937 cnt rms	0.6333 cnt rms
Z	40x	9.4k ohm	93.67 uV rms	46.17 uV rms	59.12 uV rms	84.25 uV rms	73.39 uV rms
			1.499 cnt rms	0.7388 cnt rms	0.9461 cnt rms	1.348 cnt rms	1.174 cnt rms
N	40x	500 ohm	67.32 uV rms	36.98 uV rms	46.17 uV rms	61.42 uV rms	52.14 uV rms
			1.077 cnt rms	0.5918 cnt rms	0.7388 cnt rms	0.9829 cnt rms	0.8344 cnt rms
E	40x	4k ohm	78.23 uV rms	38.77 uV rms	49.59 uV rms	70.39 uV rms	61.30 uV rms
			1.252 cnt rms	0.6204 cnt rms	0.7936 cnt rms	1.127 cnt rms	0.9809 cnt rms

Table 28 Self Noise RMS: Centaur 5002, 80 Hz

Channel	Gain	Impedance	0 Hz - 40 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Z	1x	50 ohm	1.695 mV rms	463.4 uV rms	684.5 uV rms	1.160 mV rms	1.090 mV rms
			0.6780 cnt rms	0.1854 cnt rms	0.2738 cnt rms	0.4641 cnt rms	0.4362 cnt rms
N	1x	50 ohm	1.651 mV rms	373.2 uV rms	611.0 uV rms	1.116 mV rms	1.073 mV rms
			0.6607 cnt rms	0.1493 cnt rms	0.2445 cnt rms	0.4463 cnt rms	0.4294 cnt rms
E	1x	50 ohm	1.622 mV rms	337.4 uV rms	584.6 uV rms	1.090 mV rms	1.058 mV rms
			0.6490 cnt rms	0.1350 cnt rms	0.2339 cnt rms	0.4363 cnt rms	0.4233 cnt rms
Z	1x	50 ohm	1.704 mV rms	482.8 uV rms	700.4 uV rms	1.171 mV rms	1.094 mV rms
			0.6817 cnt rms	0.1931 cnt rms	0.2802 cnt rms	0.4684 cnt rms	0.4378 cnt rms
N	1x	500 ohm	1.657 mV rms	387.4 uV rms	621.4 uV rms	1.121 mV rms	1.075 mV rms
			0.6630 cnt rms	0.1550 cnt rms	0.2486 cnt rms	0.4485 cnt rms	0.4300 cnt rms
E	1x	4k ohm	1.630 mV rms	341.8 uV rms	587.5 uV rms	1.093 mV rms	1.059 mV rms
			0.6523 cnt rms	0.1368 cnt rms	0.2351 cnt rms	0.4373 cnt rms	0.4238 cnt rms
Z	2x	50 ohm	846.9 uV rms	229.5 uV rms	341.2 uV rms	580.0 uV rms	546.2 uV rms
			0.6777 cnt rms	0.1836 cnt rms	0.2730 cnt rms	0.4641 cnt rms	0.4371 cnt rms
N	2x	500 ohm	837.4 uV rms	211.3 uV rms	324.4 uV rms	568.4 uV rms	540.0 uV rms
			0.6700 cnt rms	0.1691 cnt rms	0.2595 cnt rms	0.4548 cnt rms	0.4321 cnt rms
E	2x	4k ohm	831.7 uV rms	185.2 uV rms	303.1 uV rms	549.6 uV rms	528.6 uV rms
			0.6656 cnt rms	0.1482 cnt rms	0.2425 cnt rms	0.4398 cnt rms	0.4231 cnt rms
Z	4x	50 ohm	404.9 uV rms	94.87 uV rms	152.1 uV rms	273.7 uV rms	262.3 uV rms
			0.6480 cnt rms	0.1518 cnt rms	0.2434 cnt rms	0.4380 cnt rms	0.4197 cnt rms
N	4x	500 ohm	403.7 uV rms	88.94 uV rms	147.1 uV rms	270.7 uV rms	261.0 uV rms
			0.6460 cnt rms	0.1423 cnt rms	0.2354 cnt rms	0.4332 cnt rms	0.4176 cnt rms
E	4x	4k ohm	439.2 uV rms	104.5 uV rms	159.8 uV rms	277.5 uV rms	262.9 uV rms
			0.7029 cnt rms	0.1672 cnt rms	0.2557 cnt rms	0.4441 cnt rms	0.4208 cnt rms
Z	10x	9.4k ohm	192.6 uV rms	56.59 uV rms	81.19 uV rms	132.8 uV rms	123.6 uV rms
			0.7707 cnt rms	0.2264 cnt rms	0.3248 cnt rms	0.5314 cnt rms	0.4944 cnt rms
N	10x	500 ohm	174.5 uV rms	45.32 uV rms	68.24 uV rms	117.7 uV rms	111.2 uV rms
			0.6981 cnt rms	0.1813 cnt rms	0.2730 cnt rms	0.4710 cnt rms	0.4450 cnt rms
E	10x	4k ohm	259.7 uV rms	77.07 uV rms	98.83 uV rms	141.3 uV rms	122.8 uV rms
			1.039 cnt rms	0.3083 cnt rms	0.3954 cnt rms	0.5654 cnt rms	0.4913 cnt rms
Z	20x	9.4k ohm	133.6 uV rms	49.75 uV rms	65.32 uV rms	95.99 uV rms	85.38 uV rms
			1.069 cnt rms	0.3980 cnt rms	0.5227 cnt rms	0.7681 cnt rms	0.6832 cnt rms
N	20x	500 ohm	103.4 uV rms	34.92 uV rms	46.82 uV rms	72.31 uV rms	65.37 uV rms
			0.8270 cnt rms	0.2794 cnt rms	0.3745 cnt rms	0.5784 cnt rms	0.5230 cnt rms
E	20x	4k ohm	114.6 uV rms	36.66 uV rms	51.93 uV rms	81.02 uV rms	74.84 uV rms
			0.9173 cnt rms	0.2933 cnt rms	0.4155 cnt rms	0.6482 cnt rms	0.5988 cnt rms
Z	40x	9.4k ohm	118.6 uV rms	49.01 uV rms	62.44 uV rms	87.49 uV rms	75.83 uV rms
			1.898 cnt rms	0.7843 cnt rms	0.9991 cnt rms	1.400 cnt rms	1.213 cnt rms
N	40x	500 ohm	76.48 uV rms	32.34 uV rms	40.01 uV rms	55.43 uV rms	47.05 uV rms
			1.224 cnt rms	0.5174 cnt rms	0.6401 cnt rms	0.8867 cnt rms	0.7528 cnt rms
E	40x	4k ohm	93.04 uV rms	34.84 uV rms	46.80 uV rms	67.77 uV rms	60.77 uV rms
			1.489 cnt rms	0.5575 cnt rms	0.7489 cnt rms	1.084 cnt rms	0.9724 cnt rms

Table 29 Self Noise RMS: Centaur 5002, 20 Hz

Channel	Gain	Impedance	0 Hz - 10 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz
Z	1x	50 ohm	1.137 mV rms	501.8 uV rms	782.4 uV rms
			0.4547 cnt rms	0.2008 cnt rms	0.3130 cnt rms
N	1x	50 ohm	1.107 mV rms	438.1 uV rms	746.8 uV rms
			0.4427 cnt rms	0.1753 cnt rms	0.2988 cnt rms
E	1x	50 ohm	1.032 mV rms	383.2 uV rms	688.4 uV rms
			0.4127 cnt rms	0.1533 cnt rms	0.2755 cnt rms
Z	1x	50 ohm	1.203 mV rms	1.203 mV rms	1.203 mV rms
			0.4811 cnt rms	0.4811 cnt rms	0.4811 cnt rms
N	1x	500 ohm	1.040 mV rms	1.040 mV rms	1.040 mV rms
			0.4162 cnt rms	0.4162 cnt rms	0.4162 cnt rms
E	1x	4k ohm	1.143 mV rms	1.143 mV rms	1.143 mV rms
			0.4575 cnt rms	0.4575 cnt rms	0.4575 cnt rms
Z	2x	50 ohm	578.7 uV rms	253.6 uV rms	399.4 uV rms
			0.4631 cnt rms	0.2030 cnt rms	0.3196 cnt rms
N	2x	500 ohm	547.9 uV rms	229.2 uV rms	372.4 uV rms
			0.4384 cnt rms	0.1834 cnt rms	0.2980 cnt rms
E	2x	4k ohm	538.2 uV rms	200.6 uV rms	344.3 uV rms
			0.4307 cnt rms	0.1605 cnt rms	0.2755 cnt rms
Z	4x	50 ohm	252.1 uV rms	100.8 uV rms	170.1 uV rms
			0.4035 cnt rms	0.1612 cnt rms	0.2723 cnt rms
N	4x	500 ohm	275.7 uV rms	106.6 uV rms	183.9 uV rms
			0.4413 cnt rms	0.1706 cnt rms	0.2944 cnt rms
E	4x	4k ohm	315.9 uV rms	115.2 uV rms	186.0 uV rms
			0.5056 cnt rms	0.1843 cnt rms	0.2977 cnt rms
Z	10x	9.4k ohm	130.1 uV rms	59.94 uV rms	90.12 uV rms
			0.5206 cnt rms	0.2398 cnt rms	0.3606 cnt rms
N	10x	500 ohm	118.2 uV rms	49.79 uV rms	79.17 uV rms
			0.4727 cnt rms	0.1992 cnt rms	0.3167 cnt rms
E	10x	4k ohm	222.1 uV rms	79.80 uV rms	106.6 uV rms
			0.8885 cnt rms	0.3193 cnt rms	0.4266 cnt rms
Z	20x	9.4k ohm	92.98 uV rms	50.72 uV rms	68.25 uV rms
			0.7440 cnt rms	0.4058 cnt rms	0.5461 cnt rms
N	20x	500 ohm	71.83 uV rms	36.32 uV rms	50.88 uV rms
			0.5747 cnt rms	0.2906 cnt rms	0.4070 cnt rms
E	20x	4k ohm	77.53 uV rms	38.02 uV rms	55.63 uV rms
			0.6203 cnt rms	0.3042 cnt rms	0.4451 cnt rms
Z	40x	9.4k ohm	84.95 uV rms	49.30 uV rms	63.23 uV rms
			1.359 cnt rms	0.7888 cnt rms	1.012 cnt rms
N	40x	500 ohm	55.87 uV rms	32.71 uV rms	41.21 uV rms
			0.8938 cnt rms	0.5232 cnt rms	0.6593 cnt rms
E	40x	4k ohm	64.51 uV rms	35.18 uV rms	47.84 uV rms
			1.032 cnt rms	0.5629 cnt rms	0.7655 cnt rms

Comparing the total RMS noise across the various frequency passbands, the two digitizers are very similar in their performance, accounting for the differences in sampling rate. As expected, the total noise increases with larger frequency passbands and higher gains. Increasing the gain levels to 20x and 40x results in disproportionally more noise, as shown by the total channel noise represented in counts in the tables above.

Digitizer self-noise values are reported in the tables 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 +/- 0.6 dB based upon the number of time-windows and the resulting spectral averaging that was performed when computing the power spectral densities.

Table 30 Self-Noise PSD, Centaur 5001 and 5002, gain 1x: 50 ohm terminator

	Centaur 5001, Gain 1x						Centaur 5002, Gain 1x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 50 ohm	N 50 ohm	E 50 ohm	Z 50 ohm	N 50 ohm	E 50 ohm	Z 50 ohm	N 50 ohm	E 50 ohm	Z 50 ohm	N 50 ohm	E 50 ohm
0.0100 Hz	-114.89 dB	-115.99 dB	-115.66 dB	-115.17 dB	-116.59 dB	-115.93 dB	-113.50 dB	-116.64 dB	-118.00 dB	-113.65 dB	-115.98 dB	-118.08 dB
0.0125 Hz	-115.92 dB	-117.61 dB	-116.82 dB	-115.90 dB	-117.46 dB	-116.73 dB	-114.65 dB	-117.95 dB	-119.29 dB	-114.68 dB	-117.37 dB	-119.30 dB
0.0160 Hz	-117.00 dB	-118.77 dB	-117.57 dB	-117.33 dB	-119.51 dB	-117.88 dB	-115.94 dB	-119.44 dB	-121.27 dB	-115.83 dB	-119.02 dB	-121.21 dB
0.0200 Hz	-118.13 dB	-120.07 dB	-118.90 dB	-117.97 dB	-119.73 dB	-118.42 dB	-116.63 dB	-120.06 dB	-121.47 dB	-116.56 dB	-119.51 dB	-121.44 dB
0.0250 Hz	-118.21 dB	-120.37 dB	-119.15 dB	-118.20 dB	-120.43 dB	-119.17 dB	-117.02 dB	-120.40 dB	-122.42 dB	-116.82 dB	-119.70 dB	-122.28 dB
0.0315 Hz	-119.04 dB	-121.30 dB	-119.79 dB	-119.07 dB	-121.50 dB	-120.27 dB	-118.66 dB	-121.72 dB	-123.49 dB	-118.38 dB	-121.24 dB	-123.01 dB
0.040 Hz	-120.22 dB	-122.45 dB	-121.77 dB	-119.97 dB	-122.41 dB	-121.68 dB	-119.26 dB	-122.46 dB	-124.32 dB	-119.22 dB	-121.75 dB	-124.01 dB
0.050 Hz	-120.88 dB	-123.27 dB	-122.23 dB	-120.81 dB	-123.32 dB	-122.21 dB	-120.01 dB	-123.37 dB	-124.90 dB	-119.79 dB	-122.63 dB	-124.32 dB
0.063 Hz	-121.09 dB	-123.99 dB	-122.88 dB	-120.89 dB	-124.08 dB	-122.53 dB	-121.23 dB	-124.56 dB	-126.02 dB	-121.22 dB	-124.04 dB	-125.58 dB
0.080 Hz	-122.30 dB	-125.16 dB	-123.76 dB	-122.16 dB	-125.29 dB	-123.61 dB	-122.32 dB	-125.12 dB	-126.83 dB	-122.29 dB	-124.16 dB	-126.15 dB
0.100 Hz	-123.01 dB	-126.14 dB	-125.10 dB	-122.88 dB	-125.88 dB	-125.20 dB	-123.41 dB	-125.44 dB	-127.46 dB	-123.02 dB	-124.53 dB	-126.71 dB
0.125 Hz	-123.55 dB	-126.39 dB	-125.73 dB	-123.50 dB	-125.92 dB	-125.51 dB	-124.09 dB	-126.33 dB	-127.76 dB	-123.75 dB	-125.22 dB	-127.04 dB
0.160 Hz	-124.58 dB	-127.06 dB	-126.48 dB	-124.35 dB	-126.90 dB	-126.41 dB	-125.26 dB	-127.34 dB	-128.62 dB	-124.76 dB	-126.22 dB	-127.59 dB
0.200 Hz	-125.30 dB	-127.79 dB	-127.05 dB	-125.36 dB	-127.20 dB	-126.60 dB	-126.03 dB	-127.70 dB	-129.01 dB	-125.32 dB	-126.42 dB	-127.94 dB
0.250 Hz	-125.85 dB	-127.80 dB	-127.32 dB	-125.41 dB	-127.50 dB	-127.06 dB	-126.48 dB	-128.32 dB	-129.41 dB	-125.65 dB	-126.93 dB	-128.31 dB
0.315 Hz	-126.67 dB	-129.27 dB	-127.63 dB	-126.53 dB	-129.00 dB	-127.51 dB	-127.39 dB	-129.11 dB	-129.65 dB	-126.44 dB	-127.52 dB	-128.40 dB
0.40 Hz	-127.83 dB	-129.57 dB	-128.95 dB	-127.24 dB	-129.08 dB	-127.99 dB	-127.84 dB	-129.47 dB	-130.04 dB	-126.84 dB	-127.94 dB	-128.74 dB
0.50 Hz	-128.34 dB	-129.99 dB	-129.25 dB	-127.93 dB	-129.56 dB	-128.70 dB	-128.55 dB	-129.82 dB	-130.35 dB	-127.50 dB	-128.03 dB	-129.03 dB
0.63 Hz	-128.83 dB	-130.02 dB	-129.69 dB	-128.36 dB	-129.28 dB	-128.89 dB	-129.25 dB	-130.21 dB	-130.33 dB	-128.01 dB	-128.38 dB	-128.97 dB
0.80 Hz	-129.62 dB	-130.37 dB	-129.83 dB	-129.27 dB	-129.77 dB	-129.24 dB	-129.57 dB	-130.42 dB	-130.67 dB	-128.31 dB	-128.59 dB	-129.30 dB
1.00 Hz	-130.01 dB	-130.41 dB	-130.20 dB	-129.35 dB	-129.78 dB	-129.56 dB	-129.99 dB	-130.64 dB	-130.73 dB	-128.64 dB	-128.84 dB	-129.44 dB
1.25 Hz	-130.51 dB	-130.97 dB	-130.59 dB	-129.88 dB	-130.22 dB	-129.97 dB	-130.25 dB	-130.82 dB	-130.95 dB	-128.86 dB	-128.98 dB	-129.43 dB
1.60 Hz	-130.96 dB	-131.29 dB	-130.40 dB	-130.18 dB	-130.23 dB	-129.90 dB	-130.46 dB	-130.99 dB	-131.06 dB	-129.01 dB	-129.06 dB	-129.57 dB
2.00 Hz	-130.98 dB	-131.27 dB	-130.85 dB	-130.39 dB	-130.67 dB	-130.17 dB	-130.63 dB	-131.06 dB	-131.22 dB	-129.16 dB	-129.06 dB	-129.59 dB
2.50 Hz	-131.26 dB	-131.27 dB	-131.22 dB	-130.51 dB	-130.62 dB	-130.50 dB	-130.87 dB	-131.14 dB	-131.21 dB	-129.29 dB	-129.19 dB	-129.65 dB
3.15 Hz	-131.22 dB	-131.54 dB	-131.14 dB	-130.53 dB	-130.66 dB	-130.39 dB	-130.97 dB	-131.22 dB	-131.34 dB	-129.41 dB	-129.22 dB	-129.70 dB
4.0 Hz	-131.58 dB	-131.67 dB	-131.43 dB	-130.57 dB	-130.82 dB	-130.57 dB	-131.07 dB	-131.28 dB	-131.37 dB	-129.46 dB	-129.28 dB	-129.79 dB
5.0 Hz	-131.69 dB	-131.72 dB	-131.28 dB	-130.87 dB	-130.92 dB	-130.60 dB	-131.19 dB	-131.28 dB	-131.45 dB	-129.56 dB	-129.31 dB	-129.79 dB
6.3 Hz	-131.69 dB	-131.82 dB	-131.46 dB	-130.83 dB	-130.92 dB	-130.61 dB	-131.30 dB	-131.30 dB	-131.43 dB	-129.65 dB	-129.31 dB	-129.82 dB
8.0 Hz	-131.84 dB	-131.81 dB	-131.58 dB	-130.93 dB	-130.92 dB	-130.66 dB	-131.34 dB	-131.40 dB	-131.53 dB	-129.69 dB	-129.43 dB	-129.93 dB
10.0 Hz	-131.72 dB	-131.79 dB	-131.53 dB	-130.91 dB	-130.98 dB	-130.66 dB	-131.36 dB	-131.38 dB	-131.51 dB			
12.5 Hz	-131.82 dB	-131.78 dB	-131.42 dB	-130.89 dB	-130.98 dB	-130.65 dB	-131.44 dB	-131.45 dB	-131.55 dB			
16.0 Hz	-131.92 dB	-131.80 dB	-131.56 dB	-131.07 dB	-130.93 dB	-130.70 dB	-131.47 dB	-131.46 dB	-131.59 dB			
20.0 Hz	-131.90 dB	-131.86 dB	-131.61 dB				-131.50 dB	-131.48 dB	-131.58 dB			
25.0 Hz	-131.89 dB	-131.88 dB	-131.56 dB				-131.53 dB	-131.51 dB	-131.60 dB			
31.5 Hz	-131.87 dB	-131.90 dB	-131.60 dB				-131.58 dB	-131.54 dB	-131.64 dB			
40.0 Hz	-131.94 dB	-131.88 dB	-131.58 dB									

Table 31 Self-Noise PSD, Centaur 5001 and 5002, gain 1x: 50, 500, 4k ohm terminators

	Centaur 5001, Gain 1x						Centaur 5002, Gain 1x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm
0.0100 Hz	-116.98 dB	-114.64 dB	-115.44 dB	-117.47 dB	-114.85 dB	-116.07 dB	-112.84 dB	-115.79 dB	-116.79 dB	-112.40 dB	-116.30 dB	-115.86 dB
0.0125 Hz	-118.42 dB	-116.33 dB	-116.71 dB	-118.16 dB	-116.25 dB	-116.75 dB	-113.95 dB	-117.03 dB	-117.85 dB	-113.49 dB	-117.33 dB	-116.98 dB
0.0160 Hz	-119.29 dB	-117.48 dB	-117.10 dB	-119.38 dB	-117.51 dB	-117.57 dB	-115.40 dB	-118.97 dB	-120.31 dB	-114.78 dB	-119.27 dB	-119.41 dB
0.0200 Hz	-120.23 dB	-118.82 dB	-119.01 dB	-119.86 dB	-118.09 dB	-118.64 dB	-115.64 dB	-119.54 dB	-120.89 dB	-115.15 dB	-119.64 dB	-119.87 dB
0.0250 Hz	-120.25 dB	-119.54 dB	-119.50 dB	-120.22 dB	-119.64 dB	-119.41 dB	-117.21 dB	-120.04 dB	-121.92 dB	-116.61 dB	-120.21 dB	-120.78 dB
0.0315 Hz	-121.37 dB	-120.12 dB	-120.46 dB	-121.57 dB	-120.09 dB	-120.49 dB	-117.42 dB	-120.62 dB	-122.96 dB	-116.83 dB	-120.95 dB	-121.85 dB
0.040 Hz	-122.76 dB	-121.33 dB	-121.59 dB	-122.37 dB	-120.94 dB	-121.25 dB	-119.13 dB	-121.70 dB	-123.97 dB	-118.41 dB	-121.92 dB	-122.71 dB
0.050 Hz	-122.40 dB	-122.43 dB	-122.80 dB	-122.02 dB	-122.47 dB	-122.62 dB	-120.04 dB	-122.83 dB	-124.97 dB	-119.34 dB	-122.94 dB	-123.60 dB
0.063 Hz	-123.94 dB	-123.32 dB	-123.61 dB	-123.62 dB	-123.20 dB	-123.29 dB	-120.73 dB	-123.87 dB	-125.72 dB	-119.87 dB	-123.83 dB	-124.09 dB
0.080 Hz	-124.57 dB	-124.61 dB	-124.42 dB	-124.56 dB	-124.55 dB	-124.15 dB	-121.79 dB	-124.64 dB	-126.89 dB	-121.08 dB	-124.61 dB	-125.42 dB
0.100 Hz	-124.65 dB	-125.05 dB	-124.84 dB	-124.45 dB	-124.59 dB	-124.41 dB	-122.76 dB	-125.35 dB	-127.33 dB	-121.99 dB	-125.21 dB	-125.63 dB
0.125 Hz	-126.31 dB	-125.19 dB	-125.84 dB	-125.89 dB	-124.89 dB	-125.52 dB	-123.80 dB	-126.45 dB	-127.95 dB	-122.76 dB	-126.22 dB	-126.04 dB
0.160 Hz	-126.98 dB	-126.67 dB	-127.00 dB	-126.48 dB	-126.26 dB	-126.66 dB	-124.79 dB	-126.84 dB	-128.43 dB	-123.78 dB	-126.17 dB	-126.58 dB
0.200 Hz	-127.01 dB	-127.57 dB	-127.47 dB	-126.54 dB	-127.36 dB	-126.87 dB	-125.50 dB	-127.55 dB	-128.66 dB	-124.70 dB	-126.97 dB	-127.02 dB
0.250 Hz	-127.74 dB	-128.29 dB	-128.02 dB	-127.45 dB	-128.05 dB	-127.50 dB	-126.32 dB	-127.96 dB	-129.26 dB	-125.10 dB	-127.59 dB	-127.32 dB
0.315 Hz	-128.73 dB	-128.21 dB	-128.51 dB	-128.50 dB	-127.90 dB	-127.72 dB	-127.14 dB	-128.73 dB	-129.76 dB	-125.78 dB	-127.93 dB	-127.70 dB
0.40 Hz	-129.66 dB	-128.94 dB	-129.03 dB	-128.92 dB	-128.32 dB	-128.19 dB	-127.88 dB	-129.22 dB	-129.89 dB	-126.55 dB	-128.41 dB	-127.87 dB
0.50 Hz	-129.61 dB	-129.41 dB	-128.96 dB	-129.00 dB	-128.89 dB	-128.43 dB	-128.45 dB	-129.45 dB	-130.30 dB	-127.07 dB	-128.67 dB	-128.10 dB
0.63 Hz	-130.13 dB	-129.83 dB	-129.83 dB	-129.68 dB	-129.18 dB	-129.02 dB	-129.01 dB	-129.88 dB	-130.33 dB	-127.37 dB	-128.90 dB	-128.15 dB
0.80 Hz	-130.61 dB	-130.13 dB	-129.89 dB	-130.09 dB	-129.37 dB	-129.29 dB	-129.44 dB	-130.30 dB	-130.60 dB	-127.71 dB	-129.12 dB	-128.35 dB
1.00 Hz	-130.72 dB	-130.29 dB	-130.09 dB	-129.93 dB	-129.81 dB	-129.37 dB	-129.81 dB	-130.60 dB	-130.78 dB	-128.09 dB	-129.38 dB	-128.51 dB
1.25 Hz	-131.14 dB	-130.42 dB	-130.37 dB	-130.17 dB	-129.72 dB	-129.63 dB	-130.13 dB	-130.76 dB	-130.87 dB	-128.36 dB	-129.55 dB	-128.45 dB
1.60 Hz	-131.17 dB	-130.57 dB	-130.68 dB	-130.18 dB	-129.84 dB	-130.02 dB	-130.41 dB	-130.83 dB	-131.07 dB	-128.56 dB	-129.53 dB	-128.74 dB
2.00 Hz	-131.52 dB	-131.14 dB	-130.92 dB	-130.58 dB	-130.24 dB	-130.25 dB	-130.60 dB	-130.96 dB	-131.15 dB	-128.66 dB	-129.71 dB	-128.79 dB
2.50 Hz	-131.47 dB	-131.16 dB	-131.12 dB	-130.46 dB	-130.24 dB	-130.34 dB	-130.84 dB	-131.17 dB	-131.26 dB	-128.86 dB	-129.76 dB	-128.83 dB
3.15 Hz	-131.57 dB	-131.48 dB	-131.31 dB	-130.75 dB	-130.57 dB	-130.55 dB	-130.92 dB	-131.22 dB	-131.37 dB	-128.96 dB	-129.83 dB	-128.90 dB
4.0 Hz	-131.72 dB	-131.47 dB	-131.25 dB	-130.81 dB	-130.51 dB	-130.52 dB	-131.04 dB	-131.27 dB	-131.36 dB	-129.06 dB	-129.88 dB	-128.94 dB
5.0 Hz	-131.76 dB	-131.63 dB	-131.30 dB	-130.82 dB	-130.77 dB	-130.38 dB	-131.16 dB	-131.31 dB	-131.40 dB	-129.17 dB	-129.88 dB	-128.95 dB
6.3 Hz	-131.89 dB	-131.67 dB	-131.40 dB	-130.86 dB	-130.71 dB	-130.44 dB	-131.23 dB	-131.37 dB	-131.48 dB	-129.23 dB	-129.98 dB	-129.06 dB
8.0 Hz	-131.82 dB	-131.71 dB	-131.45 dB	-130.88 dB	-130.78 dB	-130.58 dB	-131.33 dB	-131.40 dB	-131.51 dB	-129.33 dB	-130.03 dB	-129.12 dB
10.0 Hz	-131.83 dB	-131.87 dB	-131.49 dB	-130.97 dB	-130.89 dB	-130.60 dB	-131.39 dB	-131.40 dB	-131.50 dB			
12.5 Hz	-131.93 dB	-131.85 dB	-131.51 dB	-130.95 dB	-130.91 dB	-130.63 dB	-131.46 dB	-131.45 dB	-131.54 dB			
16.0 Hz	-131.88 dB	-131.83 dB	-131.55 dB	-131.05 dB	-130.94 dB	-130.65 dB	-131.49 dB	-131.47 dB	-131.57 dB			
20.0 Hz	-131.98 dB	-131.84 dB	-131.63 dB				-131.51 dB	-131.49 dB	-131.58 dB			
25.0 Hz	-131.93 dB	-131.87 dB	-131.56 dB				-131.51 dB	-131.50 dB	-131.59 dB			
31.5 Hz	-131.97 dB	-131.91 dB	-131.61 dB				-131.57 dB	-131.56 dB	-131.65 dB			
40.0 Hz	-131.92 dB	-131.86 dB	-131.59 dB									

Table 32 Self-Noise PSD, Centaur 5001 and 5002, gain 2x: 50, 500, 4k ohm terminators

	Centaur 5001, Gain 1x						Centaur 5002, Gain 1x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm
0.0100 Hz	-122.20 dB	-121.97 dB	-119.35 dB	-122.66 dB	-122.14 dB	-119.69 dB	-119.88 dB	-121.73 dB	-118.39 dB	-119.64 dB	-121.82 dB	-118.45 dB
0.0125 Hz	-123.58 dB	-123.65 dB	-120.50 dB	-123.67 dB	-123.59 dB	-120.59 dB	-121.06 dB	-122.36 dB	-119.84 dB	-120.92 dB	-122.49 dB	-119.99 dB
0.0160 Hz	-124.71 dB	-124.45 dB	-121.33 dB	-125.13 dB	-124.62 dB	-122.43 dB	-122.13 dB	-122.80 dB	-122.98 dB	-121.86 dB	-122.85 dB	-123.00 dB
0.0200 Hz	-125.41 dB	-126.20 dB	-123.41 dB	-125.27 dB	-125.44 dB	-123.08 dB	-122.25 dB	-123.38 dB	-123.99 dB	-121.98 dB	-123.50 dB	-124.07 dB
0.0250 Hz	-125.72 dB	-126.25 dB	-124.05 dB	-125.78 dB	-126.26 dB	-123.96 dB	-123.21 dB	-124.93 dB	-125.52 dB	-123.13 dB	-124.90 dB	-125.65 dB
0.0315 Hz	-126.47 dB	-126.76 dB	-125.06 dB	-126.59 dB	-126.67 dB	-125.34 dB	-124.10 dB	-125.68 dB	-127.04 dB	-123.74 dB	-125.64 dB	-126.97 dB
0.040 Hz	-127.66 dB	-128.10 dB	-125.76 dB	-127.64 dB	-127.70 dB	-125.88 dB	-125.42 dB	-126.54 dB	-128.06 dB	-125.01 dB	-126.50 dB	-127.80 dB
0.050 Hz	-128.28 dB	-129.00 dB	-126.48 dB	-128.14 dB	-128.74 dB	-126.34 dB	-126.58 dB	-127.71 dB	-128.98 dB	-126.43 dB	-127.61 dB	-129.00 dB
0.063 Hz	-129.14 dB	-129.80 dB	-127.61 dB	-129.00 dB	-129.61 dB	-127.59 dB	-127.83 dB	-128.49 dB	-130.48 dB	-127.37 dB	-128.41 dB	-130.09 dB
0.080 Hz	-129.88 dB	-130.86 dB	-128.72 dB	-129.78 dB	-130.44 dB	-128.67 dB	-128.73 dB	-129.39 dB	-131.52 dB	-128.01 dB	-129.28 dB	-131.23 dB
0.100 Hz	-130.67 dB	-131.51 dB	-129.55 dB	-130.57 dB	-131.28 dB	-129.46 dB	-129.23 dB	-130.29 dB	-132.70 dB	-128.56 dB	-130.36 dB	-131.99 dB
0.125 Hz	-131.21 dB	-132.23 dB	-130.67 dB	-131.06 dB	-131.99 dB	-130.42 dB	-130.84 dB	-131.40 dB	-133.07 dB	-130.17 dB	-130.74 dB	-132.68 dB
0.160 Hz	-131.67 dB	-132.90 dB	-131.48 dB	-131.60 dB	-132.49 dB	-131.22 dB	-131.30 dB	-131.80 dB	-133.89 dB	-130.42 dB	-131.49 dB	-133.28 dB
0.200 Hz	-132.38 dB	-133.54 dB	-131.92 dB	-132.25 dB	-133.23 dB	-131.68 dB	-132.10 dB	-132.52 dB	-134.39 dB	-131.25 dB	-132.05 dB	-133.63 dB
0.250 Hz	-133.19 dB	-134.19 dB	-132.59 dB	-132.88 dB	-133.76 dB	-132.37 dB	-132.82 dB	-133.39 dB	-134.94 dB	-131.95 dB	-132.70 dB	-134.31 dB
0.315 Hz	-133.94 dB	-134.79 dB	-133.13 dB	-133.65 dB	-134.34 dB	-132.89 dB	-133.60 dB	-133.98 dB	-135.21 dB	-132.68 dB	-133.11 dB	-134.35 dB
0.40 Hz	-134.47 dB	-135.25 dB	-133.93 dB	-134.22 dB	-134.64 dB	-133.52 dB	-134.32 dB	-134.61 dB	-135.51 dB	-133.16 dB	-133.74 dB	-134.79 dB
0.50 Hz	-135.12 dB	-135.68 dB	-134.37 dB	-134.72 dB	-135.04 dB	-134.01 dB	-134.72 dB	-135.13 dB	-135.97 dB	-133.42 dB	-134.04 dB	-134.86 dB
0.63 Hz	-135.68 dB	-136.06 dB	-134.78 dB	-135.22 dB	-135.42 dB	-134.24 dB	-135.15 dB	-135.63 dB	-136.28 dB	-133.86 dB	-134.49 dB	-135.12 dB
0.80 Hz	-136.13 dB	-136.38 dB	-135.28 dB	-135.63 dB	-135.65 dB	-134.84 dB	-135.58 dB	-135.89 dB	-136.52 dB	-134.14 dB	-134.68 dB	-135.44 dB
1.00 Hz	-136.49 dB	-136.63 dB	-135.74 dB	-135.96 dB	-135.97 dB	-135.24 dB	-135.92 dB	-136.35 dB	-136.74 dB	-134.32 dB	-134.96 dB	-135.45 dB
1.25 Hz	-136.81 dB	-136.90 dB	-136.02 dB	-136.31 dB	-136.07 dB	-135.44 dB	-136.23 dB	-136.59 dB	-136.95 dB	-134.59 dB	-135.16 dB	-135.68 dB
1.60 Hz	-136.99 dB	-137.13 dB	-136.34 dB	-136.41 dB	-136.25 dB	-135.76 dB	-136.43 dB	-136.70 dB	-137.02 dB	-134.75 dB	-135.24 dB	-135.74 dB
2.00 Hz	-137.22 dB	-137.29 dB	-136.71 dB	-136.51 dB	-136.40 dB	-136.03 dB	-136.72 dB	-136.88 dB	-137.13 dB	-135.02 dB	-135.39 dB	-135.79 dB
2.50 Hz	-137.37 dB	-137.46 dB	-136.79 dB	-136.66 dB	-136.52 dB	-136.05 dB	-136.90 dB	-137.06 dB	-137.30 dB	-135.08 dB	-135.48 dB	-135.91 dB
3.15 Hz	-137.43 dB	-137.53 dB	-137.03 dB	-136.77 dB	-136.63 dB	-136.27 dB	-136.93 dB	-137.15 dB	-137.37 dB	-135.16 dB	-135.58 dB	-136.00 dB
4.0 Hz	-137.55 dB	-137.59 dB	-137.15 dB	-136.82 dB	-136.64 dB	-136.35 dB	-137.11 dB	-137.25 dB	-137.43 dB	-135.30 dB	-135.62 dB	-136.04 dB
5.0 Hz	-137.66 dB	-137.67 dB	-137.26 dB	-136.89 dB	-136.77 dB	-136.50 dB	-137.21 dB	-137.31 dB	-137.48 dB	-135.31 dB	-135.67 dB	-136.09 dB
6.3 Hz	-137.75 dB	-137.70 dB	-137.32 dB	-136.96 dB	-136.78 dB	-136.49 dB	-137.32 dB	-137.31 dB	-137.52 dB	-135.37 dB	-135.68 dB	-136.11 dB
8.0 Hz	-137.75 dB	-137.76 dB	-137.40 dB	-137.01 dB	-136.84 dB	-136.54 dB	-137.32 dB	-137.44 dB	-137.55 dB	-135.54 dB	-135.80 dB	-136.20 dB
10.0 Hz	-137.79 dB	-137.82 dB	-137.39 dB	-137.01 dB	-136.84 dB	-136.58 dB	-137.41 dB	-137.42 dB	-137.60 dB			
12.5 Hz	-137.82 dB	-137.81 dB	-137.45 dB	-137.09 dB	-136.84 dB	-136.59 dB	-137.44 dB	-137.44 dB	-137.63 dB			
16.0 Hz	-137.87 dB	-137.84 dB	-137.50 dB	-137.17 dB	-136.95 dB	-136.72 dB	-137.49 dB	-137.53 dB	-137.62 dB			
20.0 Hz	-137.86 dB	-137.83 dB	-137.51 dB				-137.49 dB	-137.51 dB	-137.65 dB			
25.0 Hz	-137.90 dB	-137.91 dB	-137.48 dB				-137.52 dB	-137.52 dB	-137.66 dB			
31.5 Hz	-137.96 dB	-137.89 dB	-137.48 dB				-137.58 dB	-137.57 dB	-137.69 dB			
40.0 Hz	-137.89 dB	-137.93 dB	-137.48 dB									

Table 33 Self-Noise PSD, Centaur 5001 and 5002, gain 4x: 50, 500, 4k ohm terminators

	Centaur 5001, Gain 4x						Centaur 5002, Gain 4x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm	Z 50 ohm	N 500 ohm	E 4k ohm
0.0100 Hz	-130.16 dB	-127.46 dB	-125.06 dB	-130.25 dB	-127.99 dB	-125.62 dB	-128.61 dB	-128.50 dB	-120.56 dB	-128.76 dB	-127.78 dB	-120.50 dB
0.0125 Hz	-131.42 dB	-129.07 dB	-125.96 dB	-131.28 dB	-129.13 dB	-125.90 dB	-129.51 dB	-129.01 dB	-121.77 dB	-129.83 dB	-128.34 dB	-121.67 dB
0.0160 Hz	-132.67 dB	-129.77 dB	-126.92 dB	-132.98 dB	-130.41 dB	-127.79 dB	-130.48 dB	-131.37 dB	-124.46 dB	-130.98 dB	-130.39 dB	-124.36 dB
0.0200 Hz	-134.42 dB	-131.10 dB	-129.43 dB	-133.98 dB	-130.92 dB	-128.92 dB	-131.26 dB	-131.75 dB	-126.06 dB	-131.58 dB	-130.78 dB	-126.02 dB
0.0250 Hz	-134.57 dB	-131.45 dB	-130.41 dB	-134.40 dB	-131.44 dB	-130.47 dB	-132.17 dB	-132.71 dB	-127.54 dB	-132.42 dB	-131.77 dB	-127.53 dB
0.0315 Hz	-135.30 dB	-132.67 dB	-131.26 dB	-135.29 dB	-132.93 dB	-131.65 dB	-133.04 dB	-133.75 dB	-129.70 dB	-133.11 dB	-132.68 dB	-129.79 dB
0.040 Hz	-136.15 dB	-133.97 dB	-132.67 dB	-135.86 dB	-133.90 dB	-132.60 dB	-133.79 dB	-134.45 dB	-131.54 dB	-133.93 dB	-133.63 dB	-131.38 dB
0.050 Hz	-136.97 dB	-134.84 dB	-133.05 dB	-136.70 dB	-134.75 dB	-133.03 dB	-134.17 dB	-135.88 dB	-132.66 dB	-134.46 dB	-134.63 dB	-132.67 dB
0.063 Hz	-137.89 dB	-136.24 dB	-134.69 dB	-137.71 dB	-136.16 dB	-134.48 dB	-135.79 dB	-136.61 dB	-134.41 dB	-135.83 dB	-135.67 dB	-134.01 dB
0.080 Hz	-138.63 dB	-137.05 dB	-135.45 dB	-138.33 dB	-136.99 dB	-135.54 dB	-136.70 dB	-137.62 dB	-136.19 dB	-136.97 dB	-136.67 dB	-135.88 dB
0.100 Hz	-139.45 dB	-137.93 dB	-136.34 dB	-139.06 dB	-137.55 dB	-136.16 dB	-137.91 dB	-138.46 dB	-137.05 dB	-137.50 dB	-137.41 dB	-136.63 dB
0.125 Hz	-140.02 dB	-138.49 dB	-137.46 dB	-139.52 dB	-138.18 dB	-137.14 dB	-138.42 dB	-139.34 dB	-138.18 dB	-138.04 dB	-137.85 dB	-137.60 dB
0.160 Hz	-140.79 dB	-139.29 dB	-138.02 dB	-140.40 dB	-139.10 dB	-137.96 dB	-138.92 dB	-140.03 dB	-139.53 dB	-138.74 dB	-138.74 dB	-138.67 dB
0.200 Hz	-141.30 dB	-139.70 dB	-138.57 dB	-140.81 dB	-139.52 dB	-138.43 dB	-140.06 dB	-140.60 dB	-140.02 dB	-139.54 dB	-139.18 dB	-138.90 dB
0.250 Hz	-141.58 dB	-140.32 dB	-139.13 dB	-141.03 dB	-139.96 dB	-138.96 dB	-140.50 dB	-141.06 dB	-140.70 dB	-140.02 dB	-139.40 dB	-139.68 dB
0.315 Hz	-142.10 dB	-140.80 dB	-139.82 dB	-141.56 dB	-140.53 dB	-139.47 dB	-140.85 dB	-141.78 dB	-141.17 dB	-140.32 dB	-139.90 dB	-139.85 dB
0.40 Hz	-142.47 dB	-141.29 dB	-140.27 dB	-141.89 dB	-140.80 dB	-139.98 dB	-141.49 dB	-141.92 dB	-141.69 dB	-140.71 dB	-139.99 dB	-140.32 dB
0.50 Hz	-142.81 dB	-141.65 dB	-140.77 dB	-142.17 dB	-141.14 dB	-140.34 dB	-141.99 dB	-142.26 dB	-141.94 dB	-141.03 dB	-140.38 dB	-140.57 dB
0.63 Hz	-143.15 dB	-142.09 dB	-141.23 dB	-142.30 dB	-141.50 dB	-140.66 dB	-142.26 dB	-142.57 dB	-142.40 dB	-141.35 dB	-140.70 dB	-140.80 dB
0.80 Hz	-143.33 dB	-142.38 dB	-141.68 dB	-142.56 dB	-141.72 dB	-141.12 dB	-142.55 dB	-142.82 dB	-142.57 dB	-141.47 dB	-140.77 dB	-141.02 dB
1.00 Hz	-143.49 dB	-142.61 dB	-142.07 dB	-142.79 dB	-142.03 dB	-141.48 dB	-142.79 dB	-142.94 dB	-142.84 dB	-141.76 dB	-140.94 dB	-141.19 dB
1.25 Hz	-143.60 dB	-142.85 dB	-142.43 dB	-142.83 dB	-142.20 dB	-141.80 dB	-142.97 dB	-143.16 dB	-142.95 dB	-141.79 dB	-141.03 dB	-141.37 dB
1.60 Hz	-143.68 dB	-143.10 dB	-142.73 dB	-142.86 dB	-142.32 dB	-142.10 dB	-143.18 dB	-143.27 dB	-143.20 dB	-141.97 dB	-141.15 dB	-141.54 dB
2.00 Hz	-143.80 dB	-143.31 dB	-142.93 dB	-142.89 dB	-142.58 dB	-142.22 dB	-143.18 dB	-143.37 dB	-143.29 dB	-142.00 dB	-141.28 dB	-141.60 dB
2.50 Hz	-143.87 dB	-143.41 dB	-143.17 dB	-143.00 dB	-142.59 dB	-142.38 dB	-143.31 dB	-143.44 dB	-143.35 dB	-142.09 dB	-141.25 dB	-141.62 dB
3.15 Hz	-143.93 dB	-143.61 dB	-143.27 dB	-143.03 dB	-142.75 dB	-142.49 dB	-143.45 dB	-143.53 dB	-143.49 dB	-142.16 dB	-141.38 dB	-141.75 dB
4.0 Hz	-144.01 dB	-143.68 dB	-143.41 dB	-143.07 dB	-142.84 dB	-142.58 dB	-143.50 dB	-143.58 dB	-143.54 dB	-142.18 dB	-141.36 dB	-141.78 dB
5.0 Hz	-143.99 dB	-143.83 dB	-143.41 dB	-143.05 dB	-142.95 dB	-142.65 dB	-143.55 dB	-143.62 dB	-143.60 dB	-142.23 dB	-141.41 dB	-141.81 dB
6.3 Hz	-144.04 dB	-143.91 dB	-143.49 dB	-143.10 dB	-142.97 dB	-142.65 dB	-143.59 dB	-143.58 dB	-143.65 dB	-142.28 dB	-141.42 dB	-141.85 dB
8.0 Hz	-143.99 dB	-143.91 dB	-143.57 dB	-143.10 dB	-142.98 dB	-142.75 dB	-143.65 dB	-143.64 dB	-143.67 dB	-142.39 dB	-141.54 dB	-141.96 dB
10.0 Hz	-144.12 dB	-143.97 dB	-143.55 dB	-143.13 dB	-143.08 dB	-142.76 dB	-143.67 dB	-143.68 dB	-143.68 dB			
12.5 Hz	-144.13 dB	-144.02 dB	-143.63 dB	-143.16 dB	-143.09 dB	-142.77 dB	-143.69 dB	-143.71 dB	-143.76 dB			
16.0 Hz	-144.12 dB	-144.02 dB	-143.60 dB	-143.26 dB	-143.17 dB	-142.89 dB	-143.70 dB	-143.70 dB	-143.73 dB			
20.0 Hz	-144.11 dB	-144.03 dB	-143.65 dB				-143.71 dB	-143.74 dB	-143.73 dB			
25.0 Hz	-144.16 dB	-144.02 dB	-143.65 dB				-143.75 dB	-143.76 dB	-143.76 dB			
31.5 Hz	-144.10 dB	-144.09 dB	-143.75 dB				-143.80 dB	-143.77 dB	-143.80 dB			
40.0 Hz	-144.07 dB	-144.09 dB	-143.76 dB									

Table 34 Self-Noise PSD, Centaur 5001 and 5002, gain 10x: 9.4k, 500, 4k ohm terminators

	Centaur 5001, Gain 4x						Centaur 5002, Gain 4x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm
0.0100 Hz	-131.64 dB	-134.03 dB	-129.45 dB	-131.97 dB	-134.41 dB	-130.36 dB	-130.68 dB	-131.97 dB	-120.15 dB	-130.69 dB	-131.82 dB	-120.14 dB
0.0125 Hz	-132.90 dB	-134.97 dB	-131.43 dB	-132.89 dB	-134.90 dB	-131.34 dB	-132.05 dB	-133.10 dB	-122.00 dB	-132.02 dB	-132.94 dB	-122.00 dB
0.0160 Hz	-134.08 dB	-135.71 dB	-133.04 dB	-135.04 dB	-136.06 dB	-133.52 dB	-133.29 dB	-134.98 dB	-124.93 dB	-133.22 dB	-134.80 dB	-124.94 dB
0.0200 Hz	-135.50 dB	-137.31 dB	-134.58 dB	-135.41 dB	-136.88 dB	-134.33 dB	-133.72 dB	-136.50 dB	-126.05 dB	-133.65 dB	-136.21 dB	-126.05 dB
0.0250 Hz	-136.07 dB	-138.16 dB	-135.51 dB	-135.99 dB	-138.18 dB	-135.65 dB	-135.05 dB	-137.27 dB	-128.06 dB	-135.00 dB	-137.02 dB	-128.06 dB
0.0315 Hz	-136.98 dB	-138.65 dB	-136.29 dB	-137.00 dB	-138.60 dB	-136.39 dB	-136.46 dB	-138.31 dB	-130.48 dB	-136.47 dB	-138.14 dB	-130.43 dB
0.040 Hz	-138.01 dB	-140.13 dB	-137.76 dB	-137.78 dB	-139.98 dB	-137.70 dB	-137.76 dB	-139.54 dB	-131.96 dB	-137.72 dB	-139.35 dB	-131.95 dB
0.050 Hz	-139.09 dB	-140.47 dB	-138.81 dB	-139.06 dB	-140.37 dB	-138.69 dB	-138.38 dB	-140.32 dB	-133.67 dB	-138.31 dB	-139.81 dB	-133.58 dB
0.063 Hz	-140.46 dB	-141.69 dB	-140.44 dB	-140.36 dB	-141.62 dB	-140.31 dB	-139.68 dB	-141.24 dB	-135.79 dB	-139.78 dB	-140.82 dB	-135.65 dB
0.080 Hz	-141.09 dB	-142.78 dB	-141.59 dB	-141.07 dB	-142.60 dB	-141.57 dB	-140.81 dB	-142.78 dB	-138.00 dB	-140.75 dB	-142.29 dB	-138.00 dB
0.100 Hz	-142.30 dB	-143.57 dB	-142.42 dB	-142.18 dB	-143.39 dB	-142.38 dB	-141.39 dB	-143.78 dB	-139.96 dB	-141.21 dB	-143.38 dB	-139.73 dB
0.125 Hz	-143.35 dB	-144.05 dB	-143.37 dB	-143.20 dB	-143.87 dB	-143.16 dB	-142.43 dB	-144.67 dB	-141.39 dB	-142.20 dB	-144.17 dB	-141.07 dB
0.160 Hz	-144.14 dB	-145.19 dB	-144.19 dB	-144.04 dB	-144.91 dB	-144.05 dB	-143.43 dB	-145.57 dB	-142.58 dB	-143.02 dB	-145.09 dB	-142.27 dB
0.200 Hz	-145.08 dB	-145.56 dB	-144.98 dB	-144.94 dB	-145.26 dB	-144.80 dB	-144.14 dB	-146.23 dB	-143.89 dB	-143.63 dB	-145.50 dB	-143.55 dB
0.250 Hz	-145.80 dB	-146.20 dB	-145.60 dB	-145.54 dB	-145.91 dB	-145.36 dB	-145.07 dB	-146.95 dB	-144.76 dB	-144.52 dB	-146.06 dB	-144.34 dB
0.315 Hz	-146.41 dB	-146.85 dB	-146.40 dB	-146.08 dB	-146.61 dB	-146.05 dB	-145.56 dB	-147.60 dB	-145.38 dB	-145.08 dB	-146.59 dB	-144.87 dB
0.40 Hz	-147.10 dB	-147.36 dB	-146.80 dB	-146.77 dB	-147.09 dB	-146.49 dB	-146.36 dB	-148.32 dB	-146.26 dB	-145.69 dB	-147.31 dB	-145.50 dB
0.50 Hz	-147.62 dB	-147.93 dB	-147.51 dB	-147.17 dB	-147.48 dB	-147.22 dB	-146.98 dB	-148.73 dB	-147.04 dB	-146.14 dB	-147.73 dB	-146.20 dB
0.63 Hz	-148.14 dB	-148.64 dB	-148.07 dB	-147.74 dB	-148.14 dB	-147.74 dB	-147.51 dB	-149.26 dB	-147.63 dB	-146.68 dB	-147.95 dB	-146.71 dB
0.80 Hz	-148.53 dB	-149.07 dB	-148.51 dB	-148.15 dB	-148.66 dB	-148.23 dB	-148.03 dB	-149.71 dB	-148.20 dB	-147.02 dB	-148.32 dB	-147.23 dB
1.00 Hz	-148.88 dB	-149.60 dB	-148.96 dB	-148.35 dB	-148.98 dB	-148.49 dB	-148.50 dB	-149.95 dB	-148.63 dB	-147.46 dB	-148.42 dB	-147.52 dB
1.25 Hz	-149.22 dB	-149.97 dB	-149.32 dB	-148.67 dB	-149.34 dB	-148.77 dB	-148.78 dB	-150.25 dB	-149.11 dB	-147.63 dB	-148.70 dB	-147.88 dB
1.60 Hz	-149.53 dB	-150.28 dB	-149.71 dB	-148.94 dB	-149.61 dB	-149.20 dB	-149.15 dB	-150.41 dB	-149.56 dB	-147.99 dB	-148.82 dB	-148.26 dB
2.00 Hz	-149.75 dB	-150.62 dB	-149.99 dB	-149.12 dB	-149.93 dB	-149.39 dB	-149.40 dB	-150.65 dB	-149.81 dB	-148.13 dB	-149.00 dB	-148.40 dB
2.50 Hz	-149.89 dB	-150.81 dB	-150.16 dB	-149.27 dB	-150.04 dB	-149.51 dB	-149.62 dB	-150.74 dB	-149.97 dB	-148.28 dB	-149.10 dB	-148.62 dB
3.15 Hz	-150.10 dB	-150.97 dB	-150.36 dB	-149.44 dB	-150.17 dB	-149.69 dB	-149.81 dB	-150.84 dB	-150.17 dB	-148.44 dB	-149.14 dB	-148.69 dB
4.0 Hz	-150.20 dB	-151.12 dB	-150.50 dB	-149.51 dB	-150.32 dB	-149.77 dB	-149.96 dB	-150.95 dB	-150.38 dB	-148.59 dB	-149.28 dB	-148.85 dB
5.0 Hz	-150.30 dB	-151.30 dB	-150.56 dB	-149.60 dB	-150.44 dB	-149.87 dB	-150.11 dB	-151.04 dB	-150.56 dB	-148.70 dB	-149.26 dB	-148.99 dB
6.3 Hz	-150.44 dB	-151.25 dB	-150.73 dB	-149.73 dB	-150.47 dB	-149.98 dB	-150.21 dB	-151.09 dB	-150.62 dB	-148.77 dB	-149.36 dB	-149.02 dB
8.0 Hz	-150.52 dB	-151.35 dB	-150.77 dB	-149.80 dB	-150.56 dB	-150.01 dB	-150.37 dB	-151.13 dB	-150.75 dB	-148.93 dB	-149.46 dB	-149.18 dB
10.0 Hz	-150.65 dB	-151.42 dB	-150.82 dB	-149.86 dB	-150.57 dB	-150.07 dB	-150.37 dB	-151.18 dB	-150.78 dB			
12.5 Hz	-150.67 dB	-151.46 dB	-150.89 dB	-149.94 dB	-150.61 dB	-150.10 dB	-150.48 dB	-151.20 dB	-150.88 dB			
16.0 Hz	-150.72 dB	-151.50 dB	-150.95 dB	-150.05 dB	-150.73 dB	-150.22 dB	-150.51 dB	-151.26 dB	-150.91 dB			
20.0 Hz	-150.75 dB	-151.62 dB	-150.92 dB				-150.55 dB	-151.25 dB	-150.93 dB			
25.0 Hz	-150.85 dB	-151.57 dB	-150.94 dB				-150.57 dB	-151.27 dB	-150.97 dB			
31.5 Hz	-150.83 dB	-151.59 dB	-151.00 dB				-150.65 dB	-151.34 dB	-151.02 dB			
40.0 Hz	-150.86 dB	-151.63 dB	-151.04 dB									

Table 35 Self-Noise PSD, Centaur 5001 and 5002, gain 10x: 9.4k, 500, 4k ohm terminators

	Centaur 5001, Gain 4x						Centaur 5002, Gain 4x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm
0.0100 Hz	-132.32 dB	-135.26 dB	-133.28 dB	-132.79 dB	-135.46 dB	-133.69 dB	-131.91 dB	-134.92 dB	-135.02 dB	-131.91 dB	-134.92 dB	-134.98 dB
0.0125 Hz	-133.56 dB	-136.46 dB	-135.03 dB	-133.58 dB	-136.58 dB	-135.10 dB	-132.91 dB	-135.97 dB	-136.13 dB	-132.92 dB	-135.98 dB	-136.08 dB
0.0160 Hz	-134.81 dB	-137.12 dB	-135.78 dB	-135.35 dB	-137.79 dB	-135.98 dB	-134.55 dB	-137.21 dB	-137.96 dB	-134.57 dB	-137.18 dB	-137.87 dB
0.0200 Hz	-136.17 dB	-138.62 dB	-136.61 dB	-135.51 dB	-138.33 dB	-136.15 dB	-134.84 dB	-137.52 dB	-138.48 dB	-134.85 dB	-137.43 dB	-138.40 dB
0.0250 Hz	-136.46 dB	-139.22 dB	-137.40 dB	-136.47 dB	-139.28 dB	-137.42 dB	-135.92 dB	-139.27 dB	-139.98 dB	-135.90 dB	-139.20 dB	-140.05 dB
0.0315 Hz	-137.35 dB	-139.95 dB	-138.59 dB	-137.81 dB	-140.03 dB	-138.67 dB	-136.87 dB	-139.90 dB	-141.07 dB	-136.82 dB	-139.83 dB	-140.99 dB
0.040 Hz	-138.91 dB	-140.82 dB	-140.28 dB	-138.82 dB	-140.65 dB	-140.25 dB	-138.25 dB	-140.89 dB	-141.95 dB	-138.26 dB	-140.81 dB	-141.91 dB
0.050 Hz	-139.85 dB	-141.58 dB	-141.11 dB	-139.86 dB	-141.55 dB	-141.10 dB	-139.19 dB	-142.25 dB	-143.01 dB	-139.15 dB	-142.16 dB	-142.72 dB
0.063 Hz	-140.85 dB	-142.98 dB	-142.50 dB	-140.64 dB	-142.92 dB	-142.44 dB	-140.39 dB	-142.90 dB	-144.04 dB	-140.33 dB	-142.82 dB	-143.92 dB
0.080 Hz	-141.81 dB	-143.66 dB	-143.21 dB	-141.76 dB	-143.93 dB	-143.28 dB	-141.24 dB	-144.27 dB	-144.93 dB	-141.22 dB	-144.15 dB	-144.66 dB
0.100 Hz	-143.25 dB	-144.76 dB	-144.34 dB	-143.23 dB	-144.94 dB	-144.31 dB	-142.33 dB	-144.98 dB	-145.64 dB	-142.25 dB	-144.90 dB	-145.45 dB
0.125 Hz	-144.07 dB	-145.41 dB	-145.36 dB	-144.01 dB	-145.29 dB	-145.39 dB	-143.44 dB	-146.74 dB	-146.08 dB	-143.34 dB	-146.48 dB	-145.90 dB
0.160 Hz	-145.12 dB	-146.12 dB	-146.26 dB	-145.23 dB	-146.14 dB	-146.30 dB	-144.45 dB	-147.39 dB	-147.23 dB	-144.23 dB	-147.27 dB	-146.87 dB
0.200 Hz	-146.30 dB	-146.92 dB	-147.26 dB	-146.00 dB	-146.79 dB	-147.15 dB	-145.27 dB	-148.28 dB	-147.59 dB	-145.13 dB	-147.95 dB	-147.32 dB
0.250 Hz	-147.09 dB	-147.62 dB	-148.13 dB	-147.06 dB	-147.53 dB	-148.04 dB	-145.92 dB	-149.21 dB	-148.31 dB	-145.72 dB	-148.87 dB	-147.92 dB
0.315 Hz	-147.65 dB	-148.46 dB	-148.84 dB	-147.61 dB	-148.36 dB	-148.70 dB	-146.93 dB	-149.91 dB	-148.97 dB	-146.67 dB	-149.44 dB	-148.69 dB
0.40 Hz	-148.50 dB	-149.17 dB	-149.56 dB	-148.34 dB	-149.15 dB	-149.37 dB	-147.76 dB	-150.91 dB	-149.97 dB	-147.53 dB	-150.38 dB	-149.41 dB
0.50 Hz	-149.32 dB	-150.12 dB	-150.22 dB	-149.35 dB	-149.93 dB	-150.09 dB	-148.39 dB	-151.62 dB	-150.35 dB	-148.09 dB	-150.99 dB	-149.95 dB
0.63 Hz	-149.94 dB	-150.89 dB	-151.03 dB	-149.79 dB	-150.76 dB	-150.88 dB	-149.02 dB	-152.43 dB	-151.10 dB	-148.78 dB	-151.75 dB	-150.52 dB
0.80 Hz	-150.58 dB	-151.73 dB	-151.69 dB	-150.49 dB	-151.52 dB	-151.56 dB	-149.96 dB	-153.11 dB	-151.63 dB	-149.51 dB	-152.32 dB	-150.91 dB
1.00 Hz	-151.08 dB	-152.49 dB	-152.16 dB	-150.88 dB	-152.23 dB	-151.99 dB	-150.47 dB	-153.62 dB	-152.12 dB	-150.06 dB	-152.71 dB	-151.48 dB
1.25 Hz	-151.52 dB	-153.17 dB	-152.72 dB	-151.34 dB	-152.87 dB	-152.40 dB	-151.03 dB	-154.03 dB	-152.61 dB	-150.54 dB	-153.12 dB	-151.90 dB
1.60 Hz	-151.92 dB	-153.83 dB	-153.16 dB	-151.71 dB	-153.49 dB	-152.83 dB	-151.65 dB	-154.50 dB	-153.16 dB	-151.07 dB	-153.46 dB	-152.37 dB
2.00 Hz	-152.31 dB	-154.33 dB	-153.58 dB	-152.05 dB	-153.91 dB	-153.16 dB	-152.14 dB	-154.84 dB	-153.45 dB	-151.50 dB	-153.69 dB	-152.60 dB
2.50 Hz	-152.68 dB	-154.79 dB	-153.89 dB	-152.38 dB	-154.33 dB	-153.47 dB	-152.54 dB	-155.15 dB	-153.78 dB	-151.85 dB	-153.92 dB	-152.86 dB
3.15 Hz	-152.97 dB	-155.23 dB	-154.12 dB	-152.67 dB	-154.62 dB	-153.70 dB	-152.79 dB	-155.31 dB	-154.06 dB	-152.05 dB	-154.09 dB	-153.07 dB
4.0 Hz	-153.21 dB	-155.48 dB	-154.39 dB	-152.86 dB	-154.90 dB	-153.87 dB	-153.13 dB	-155.51 dB	-154.36 dB	-152.32 dB	-154.16 dB	-153.36 dB
5.0 Hz	-153.47 dB	-155.72 dB	-154.54 dB	-153.06 dB	-155.13 dB	-154.02 dB	-153.39 dB	-155.66 dB	-154.55 dB	-152.56 dB	-154.33 dB	-153.46 dB
6.3 Hz	-153.68 dB	-155.86 dB	-154.66 dB	-153.29 dB	-155.27 dB	-154.18 dB	-153.60 dB	-155.84 dB	-154.75 dB	-152.71 dB	-154.44 dB	-153.66 dB
8.0 Hz	-153.79 dB	-156.01 dB	-154.84 dB	-153.43 dB	-155.41 dB	-154.33 dB	-153.79 dB	-155.94 dB	-154.84 dB	-152.96 dB	-154.61 dB	-153.83 dB
10.0 Hz	-153.98 dB	-156.14 dB	-154.94 dB	-153.53 dB	-155.47 dB	-154.43 dB	-153.93 dB	-156.03 dB	-155.00 dB			
12.5 Hz	-154.10 dB	-156.23 dB	-155.10 dB	-153.67 dB	-155.58 dB	-154.52 dB	-154.05 dB	-156.11 dB	-155.10 dB			
16.0 Hz	-154.24 dB	-156.29 dB	-155.14 dB	-153.88 dB	-155.73 dB	-154.71 dB	-154.17 dB	-156.16 dB	-155.21 dB			
20.0 Hz	-154.25 dB	-156.42 dB	-155.16 dB				-154.26 dB	-156.21 dB	-155.25 dB			
25.0 Hz	-154.35 dB	-156.41 dB	-155.24 dB				-154.32 dB	-156.25 dB	-155.28 dB			
31.5 Hz	-154.50 dB	-156.46 dB	-155.27 dB				-154.41 dB	-156.32 dB	-155.36 dB			
40.0 Hz	-154.51 dB	-156.49 dB	-155.27 dB									

Table 36 Self-Noise PSD, Centaur 5001 and 5002, gain 10x: 9.4k, 500, 4k ohm terminators

	Centaur 5001, Gain 4x						Centaur 5002, Gain 4x					
	100 Hz			40 Hz			80 Hz			20 Hz		
Frequency	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm	Z 9.4k ohm	N 500 ohm	E 4k ohm
0.0100 Hz	-132.21 dB	-135.84 dB	-133.68 dB	-132.74 dB	-136.12 dB	-134.08 dB	-131.35 dB	-134.89 dB	-135.44 dB	-131.35 dB	-134.91 dB	-135.42 dB
0.0125 Hz	-133.03 dB	-136.84 dB	-134.89 dB	-133.00 dB	-136.94 dB	-134.93 dB	-132.12 dB	-135.70 dB	-136.63 dB	-132.11 dB	-135.70 dB	-136.63 dB
0.0160 Hz	-133.87 dB	-137.36 dB	-135.87 dB	-134.69 dB	-137.69 dB	-136.04 dB	-133.98 dB	-137.39 dB	-138.36 dB	-133.98 dB	-137.34 dB	-138.38 dB
0.0200 Hz	-135.66 dB	-138.72 dB	-136.98 dB	-135.44 dB	-138.13 dB	-136.43 dB	-134.36 dB	-138.04 dB	-138.41 dB	-134.36 dB	-138.00 dB	-138.41 dB
0.0250 Hz	-136.13 dB	-139.39 dB	-138.05 dB	-136.15 dB	-139.34 dB	-138.07 dB	-135.65 dB	-138.83 dB	-139.58 dB	-135.66 dB	-138.81 dB	-139.61 dB
0.0315 Hz	-137.04 dB	-140.00 dB	-138.28 dB	-137.30 dB	-140.01 dB	-138.24 dB	-137.20 dB	-140.22 dB	-140.94 dB	-137.19 dB	-140.12 dB	-140.99 dB
0.040 Hz	-138.22 dB	-141.19 dB	-139.81 dB	-138.03 dB	-141.04 dB	-139.75 dB	-137.78 dB	-141.34 dB	-141.84 dB	-137.73 dB	-141.32 dB	-141.83 dB
0.050 Hz	-139.08 dB	-141.98 dB	-140.45 dB	-139.05 dB	-141.93 dB	-140.56 dB	-138.97 dB	-142.51 dB	-142.83 dB	-138.95 dB	-142.52 dB	-142.78 dB
0.063 Hz	-140.75 dB	-143.24 dB	-142.26 dB	-140.68 dB	-143.04 dB	-142.23 dB	-140.19 dB	-143.46 dB	-144.24 dB	-140.20 dB	-143.46 dB	-144.19 dB
0.080 Hz	-141.27 dB	-144.14 dB	-143.55 dB	-141.11 dB	-144.15 dB	-143.61 dB	-141.44 dB	-144.82 dB	-144.74 dB	-141.42 dB	-144.80 dB	-144.74 dB
0.100 Hz	-142.75 dB	-144.81 dB	-144.15 dB	-142.93 dB	-144.79 dB	-144.12 dB	-142.53 dB	-145.50 dB	-145.84 dB	-142.49 dB	-145.50 dB	-145.77 dB
0.125 Hz	-143.61 dB	-145.77 dB	-145.61 dB	-143.61 dB	-145.74 dB	-145.56 dB	-143.34 dB	-146.58 dB	-146.74 dB	-143.27 dB	-146.52 dB	-146.65 dB
0.160 Hz	-145.03 dB	-146.84 dB	-146.69 dB	-145.19 dB	-146.82 dB	-146.72 dB	-144.40 dB	-147.93 dB	-147.47 dB	-144.40 dB	-147.90 dB	-147.42 dB
0.200 Hz	-146.12 dB	-147.68 dB	-147.64 dB	-146.04 dB	-147.59 dB	-147.60 dB	-145.25 dB	-149.21 dB	-148.06 dB	-145.16 dB	-149.14 dB	-148.05 dB
0.250 Hz	-147.11 dB	-148.34 dB	-148.39 dB	-147.11 dB	-148.28 dB	-148.36 dB	-146.20 dB	-149.91 dB	-148.90 dB	-146.17 dB	-149.73 dB	-148.77 dB
0.315 Hz	-147.98 dB	-149.15 dB	-149.24 dB	-147.97 dB	-149.09 dB	-149.26 dB	-147.02 dB	-150.83 dB	-149.70 dB	-147.00 dB	-150.66 dB	-149.56 dB
0.40 Hz	-148.70 dB	-149.82 dB	-150.39 dB	-148.91 dB	-149.91 dB	-150.44 dB	-147.98 dB	-152.02 dB	-150.55 dB	-147.94 dB	-151.82 dB	-150.39 dB
0.50 Hz	-149.75 dB	-150.67 dB	-151.19 dB	-149.66 dB	-150.64 dB	-151.01 dB	-148.86 dB	-152.86 dB	-151.10 dB	-148.76 dB	-152.65 dB	-151.03 dB
0.63 Hz	-150.37 dB	-151.63 dB	-151.98 dB	-150.35 dB	-151.60 dB	-151.90 dB	-149.57 dB	-153.83 dB	-151.70 dB	-149.48 dB	-153.57 dB	-151.53 dB
0.80 Hz	-151.21 dB	-152.58 dB	-152.75 dB	-151.22 dB	-152.49 dB	-152.71 dB	-150.46 dB	-154.70 dB	-152.53 dB	-150.33 dB	-154.39 dB	-152.38 dB
1.00 Hz	-151.85 dB	-153.40 dB	-153.43 dB	-151.84 dB	-153.36 dB	-153.35 dB	-151.06 dB	-155.41 dB	-153.10 dB	-150.91 dB	-155.05 dB	-152.90 dB
1.25 Hz	-152.31 dB	-154.36 dB	-154.05 dB	-152.26 dB	-154.22 dB	-153.96 dB	-151.69 dB	-156.07 dB	-153.54 dB	-151.59 dB	-155.72 dB	-153.35 dB
1.60 Hz	-152.92 dB	-155.14 dB	-154.60 dB	-152.93 dB	-154.98 dB	-154.50 dB	-152.31 dB	-156.74 dB	-154.33 dB	-152.12 dB	-156.23 dB	-154.05 dB
2.00 Hz	-153.39 dB	-155.95 dB	-155.10 dB	-153.34 dB	-155.81 dB	-154.98 dB	-152.91 dB	-157.23 dB	-154.92 dB	-152.68 dB	-156.74 dB	-154.56 dB
2.50 Hz	-153.78 dB	-156.63 dB	-155.61 dB	-153.71 dB	-156.44 dB	-155.47 dB	-153.29 dB	-157.66 dB	-155.23 dB	-153.06 dB	-157.04 dB	-154.87 dB
3.15 Hz	-154.18 dB	-157.24 dB	-155.94 dB	-154.06 dB	-157.04 dB	-155.78 dB	-153.69 dB	-158.00 dB	-155.67 dB	-153.49 dB	-157.34 dB	-155.33 dB
4.0 Hz	-154.52 dB	-157.85 dB	-156.21 dB	-154.40 dB	-157.56 dB	-156.07 dB	-154.08 dB	-158.34 dB	-156.06 dB	-153.81 dB	-157.68 dB	-155.63 dB
5.0 Hz	-154.82 dB	-158.27 dB	-156.51 dB	-154.71 dB	-158.01 dB	-156.32 dB	-154.40 dB	-158.59 dB	-156.44 dB	-154.10 dB	-157.90 dB	-155.99 dB
6.3 Hz	-155.05 dB	-158.61 dB	-156.76 dB	-154.94 dB	-158.28 dB	-156.57 dB	-154.66 dB	-158.84 dB	-156.68 dB	-154.35 dB	-158.11 dB	-156.23 dB
8.0 Hz	-155.29 dB	-158.82 dB	-156.98 dB	-155.12 dB	-158.57 dB	-156.82 dB	-154.92 dB	-159.04 dB	-156.92 dB	-154.67 dB	-158.33 dB	-156.52 dB
10.0 Hz	-155.50 dB	-159.14 dB	-157.14 dB	-155.34 dB	-158.81 dB	-156.96 dB	-155.15 dB	-159.23 dB	-157.12 dB			
12.5 Hz	-155.64 dB	-159.31 dB	-157.29 dB	-155.49 dB	-158.96 dB	-157.06 dB	-155.38 dB	-159.38 dB	-157.27 dB			
16.0 Hz	-155.83 dB	-159.43 dB	-157.46 dB	-155.75 dB	-159.20 dB	-157.31 dB	-155.63 dB	-159.49 dB	-157.43 dB			
20.0 Hz	-155.92 dB	-159.56 dB	-157.57 dB				-155.79 dB	-159.59 dB	-157.55 dB			
25.0 Hz	-156.10 dB	-159.73 dB	-157.60 dB				-155.92 dB	-159.67 dB	-157.66 dB			
31.5 Hz	-156.19 dB	-159.79 dB	-157.70 dB				-156.11 dB	-159.77 dB	-157.76 dB			
40.0 Hz	-156.28 dB	-159.88 dB	-157.76 dB									

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

$$signal\ power = \left(peak\ fullscale/\sqrt{2}\right)^2$$
$$noise\ power = (RMS\ Noise)^2$$

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 37 Dynamic Range: Centaur 5001, 100 Hz

Channel	Gain	Impedance	0 Hz - 50 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Z	1x	50 ohm	138.00 dB	149.48 dB	146.42 dB	142.04 dB	142.66 dB
N	1x	50 ohm	138.10 dB	151.50 dB	147.41 dB	142.36 dB	142.72 dB
E	1x	50 ohm	137.71 dB	150.66 dB	146.84 dB	141.93 dB	142.34 dB
Z	1x	50 ohm	138.18 dB	151.27 dB	147.37 dB	142.40 dB	142.81 dB
N	1x	500 ohm	138.04 dB	150.92 dB	147.07 dB	142.22 dB	142.65 dB
E	1x	4k ohm	137.71 dB	150.87 dB	146.95 dB	141.95 dB	142.34 dB
Z	2x	50 ohm	138.05 dB	150.65 dB	147.01 dB	142.21 dB	142.67 dB
N	2x	500 ohm	138.09 dB	151.33 dB	147.34 dB	142.33 dB	142.72 dB
E	2x	4k ohm	137.53 dB	149.73 dB	146.27 dB	141.66 dB	142.17 dB
Z	4x	50 ohm	138.40 dB	152.75 dB	148.17 dB	142.76 dB	143.05 dB
N	4x	500 ohm	138.21 dB	151.33 dB	147.34 dB	142.42 dB	142.82 dB
E	4x	4k ohm	137.70 dB	150.23 dB	146.65 dB	141.91 dB	142.38 dB
Z	10x	9.4k ohm	136.84 dB	148.65 dB	145.32 dB	140.86 dB	141.42 dB
N	10x	500 ohm	137.65 dB	149.51 dB	146.19 dB	141.71 dB	142.25 dB
E	10x	4k ohm	136.83 dB	148.49 dB	145.33 dB	140.96 dB	141.57 dB
Z	20x	9.4k ohm	133.97 dB	143.78 dB	141.18 dB	137.58 dB	138.47 dB
N	20x	500 ohm	135.99 dB	145.12 dB	142.82 dB	139.52 dB	140.54 dB
E	20x	4k ohm	134.88 dB	144.86 dB	142.26 dB	138.60 dB	139.47 dB
Z	40x	9.4k ohm	129.24 dB	137.66 dB	135.56 dB	132.54 dB	133.77 dB
N	40x	500 ohm	132.46 dB	139.61 dB	137.74 dB	135.37 dB	136.86 dB
E	40x	4k ohm	130.80 dB	139.19 dB	137.10 dB	134.14 dB	135.39 dB

Table 38 Dynamic Range: Centaur 5001, 40 Hz

Channel	Gain	Impedance	0 Hz - 20 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Z	1x	50 ohm	140.59 dB	149.24 dB	145.90 dB	141.27 dB	141.81 dB
N	1x	50 ohm	140.88 dB	151.14 dB	146.79 dB	141.58 dB	141.90 dB
E	1x	50 ohm	140.52 dB	150.34 dB	146.27 dB	141.19 dB	141.56 dB
Z	1x	50 ohm	140.89 dB	150.82 dB	146.68 dB	141.56 dB	141.91 dB
N	1x	500 ohm	140.69 dB	150.52 dB	146.42 dB	141.39 dB	141.76 dB
E	1x	4k ohm	140.47 dB	150.46 dB	146.31 dB	141.16 dB	141.50 dB
Z	2x	50 ohm	140.88 dB	150.40 dB	146.52 dB	141.54 dB	141.95 dB
N	2x	500 ohm	140.77 dB	150.87 dB	146.62 dB	141.44 dB	141.78 dB
E	2x	4k ohm	140.23 dB	149.47 dB	145.77 dB	140.97 dB	141.41 dB
Z	4x	50 ohm	141.20 dB	152.21 dB	147.40 dB	141.87 dB	142.12 dB
N	4x	500 ohm	140.90 dB	150.97 dB	146.72 dB	141.60 dB	141.94 dB
E	4x	4k ohm	140.38 dB	149.95 dB	146.11 dB	141.19 dB	141.60 dB
Z	10x	9.4k ohm	139.49 dB	148.43 dB	144.89 dB	140.23 dB	140.73 dB
N	10x	500 ohm	140.26 dB	149.23 dB	145.65 dB	140.97 dB	141.44 dB
E	10x	4k ohm	139.35 dB	148.29 dB	144.90 dB	140.34 dB	140.87 dB
Z	20x	9.4k ohm	136.47 dB	143.73 dB	141.02 dB	137.29 dB	138.12 dB
N	20x	500 ohm	138.32 dB	145.05 dB	142.58 dB	139.07 dB	139.99 dB
E	20x	4k ohm	137.41 dB	144.80 dB	142.06 dB	138.23 dB	139.02 dB
Z	40x	9.4k ohm	131.54 dB	137.68 dB	135.53 dB	132.46 dB	133.66 dB
N	40x	500 ohm	134.41 dB	139.61 dB	137.68 dB	135.20 dB	136.62 dB
E	40x	4k ohm	133.10 dB	139.20 dB	137.06 dB	134.02 dB	135.22 dB

Table 39 Dynamic Range: Centaur 5002, 80 Hz

Channel	Gain	Impedance	0 Hz - 40 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Z	1x	50 ohm	138.43 dB	149.69 dB	146.30 dB	141.72 dB	142.26 dB
N	1x	50 ohm	138.65 dB	151.57 dB	147.29 dB	142.06 dB	142.40 dB
E	1x	50 ohm	138.81 dB	152.45 dB	147.67 dB	142.26 dB	142.52 dB
Z	1x	50 ohm	138.38 dB	149.34 dB	146.10 dB	141.64 dB	142.23 dB
N	1x	500 ohm	138.62 dB	151.25 dB	147.14 dB	142.02 dB	142.38 dB
E	1x	4k ohm	138.77 dB	152.33 dB	147.63 dB	142.24 dB	142.51 dB
Z	2x	50 ohm	138.43 dB	149.78 dB	146.33 dB	141.72 dB	142.24 dB
N	2x	500 ohm	138.53 dB	150.49 dB	146.77 dB	141.90 dB	142.34 dB
E	2x	4k ohm	138.59 dB	151.63 dB	147.36 dB	142.19 dB	142.53 dB
Z	4x	50 ohm	138.82 dB	151.43 dB	147.33 dB	142.22 dB	142.59 dB
N	4x	500 ohm	138.85 dB	151.99 dB	147.62 dB	142.32 dB	142.64 dB
E	4x	4k ohm	138.12 dB	150.59 dB	146.90 dB	142.10 dB	142.57 dB
Z	10x	9.4k ohm	137.32 dB	147.96 dB	144.82 dB	140.54 dB	141.17 dB
N	10x	500 ohm	138.17 dB	149.89 dB	146.33 dB	141.59 dB	142.09 dB
E	10x	4k ohm	134.72 dB	145.27 dB	143.11 dB	140.01 dB	141.23 dB
Z	20x	9.4k ohm	134.48 dB	143.05 dB	140.69 dB	137.34 dB	138.36 dB
N	20x	500 ohm	136.70 dB	146.13 dB	143.58 dB	139.81 dB	140.68 dB
E	20x	4k ohm	135.80 dB	145.71 dB	142.68 dB	138.82 dB	139.51 dB
Z	40x	9.4k ohm	129.48 dB	137.16 dB	135.06 dB	132.13 dB	133.37 dB
N	40x	500 ohm	133.30 dB	140.77 dB	138.92 dB	136.09 dB	137.52 dB
E	40x	4k ohm	131.60 dB	140.13 dB	137.56 dB	134.35 dB	135.30 dB

Table 40 Dynamic Range: Centaur 5002, 20 Hz

Channel	Gain	Impedance	0 Hz - 10 Hz	20 mHz - 1 Hz	20 mHz - 4 Hz
Z	1x	50 ohm	141.90 dB	149.00 dB	145.14 dB
N	1x	50 ohm	142.13 dB	150.18 dB	145.55 dB
E	1x	50 ohm	142.74 dB	151.34 dB	146.25 dB
Z	1x	50 ohm	141.74 dB	148.91 dB	144.96 dB
N	1x	500 ohm	142.22 dB	149.78 dB	145.57 dB
E	1x	4k ohm	142.37 dB	150.94 dB	146.25 dB
Z	2x	50 ohm	141.74 dB	148.91 dB	144.96 dB
N	2x	500 ohm	142.22 dB	149.78 dB	145.57 dB
E	2x	4k ohm	142.37 dB	150.94 dB	146.25 dB
Z	4x	50 ohm	142.94 dB	150.90 dB	146.35 dB
N	4x	500 ohm	142.16 dB	150.42 dB	145.68 dB
E	4x	4k ohm	140.98 dB	149.74 dB	145.58 dB
Z	10x	9.4k ohm	140.72 dB	147.46 dB	143.91 dB
N	10x	500 ohm	141.56 dB	149.07 dB	145.04 dB
E	10x	4k ohm	136.08 dB	144.97 dB	142.45 dB
Z	20x	9.4k ohm	137.62 dB	137.62 dB	137.62 dB
N	20x	500 ohm	139.86 dB	139.86 dB	139.86 dB
E	20x	4k ohm	139.20 dB	139.20 dB	139.20 dB
Z	40x	9.4k ohm	132.39 dB	137.11 dB	134.95 dB
N	40x	500 ohm	136.03 dB	140.68 dB	138.67 dB
E	40x	4k ohm	134.78 dB	140.04 dB	137.37 dB

Dynamic range can vary considerably depending upon the spectral level of the self-noise, passband over which the noise is integrated, sample rate, gain settings, and terminating resistor. The above tables contain the estimates for dynamic range over a number of these parameters.

At 100 Hz sampling rate dynamic ranges varied from as low as 130 dB at a gain of 40x up to 138.4 dB at a gain of 1x-4x. At 40 Hz, dynamic ranges varied from as low as 131 dB at a gain of 40 x up to 141 dB at a gain of 1x-4x. At 80 Hz, dynamic ranges varied from as low as 131 dB at a gain of 40x up to 139 dB at a gain of 1x-4x. At 20 Hz, dynamic ranges varied from as low as 135 dB at a gain of 40x up to 143 dB at gains of 1x-4x.

These values are consistent with the observed self-noise levels at each gain and the associated passbands. In general, these dynamic ranges represent noise free bits of between 21.6 and 23.8 bits.

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. The appropriate terminated noise data was used to match the chosen sensor output impedance and the desired sample rate for the application passband. Where available, reference sensor and background noise models are provided for comparison.

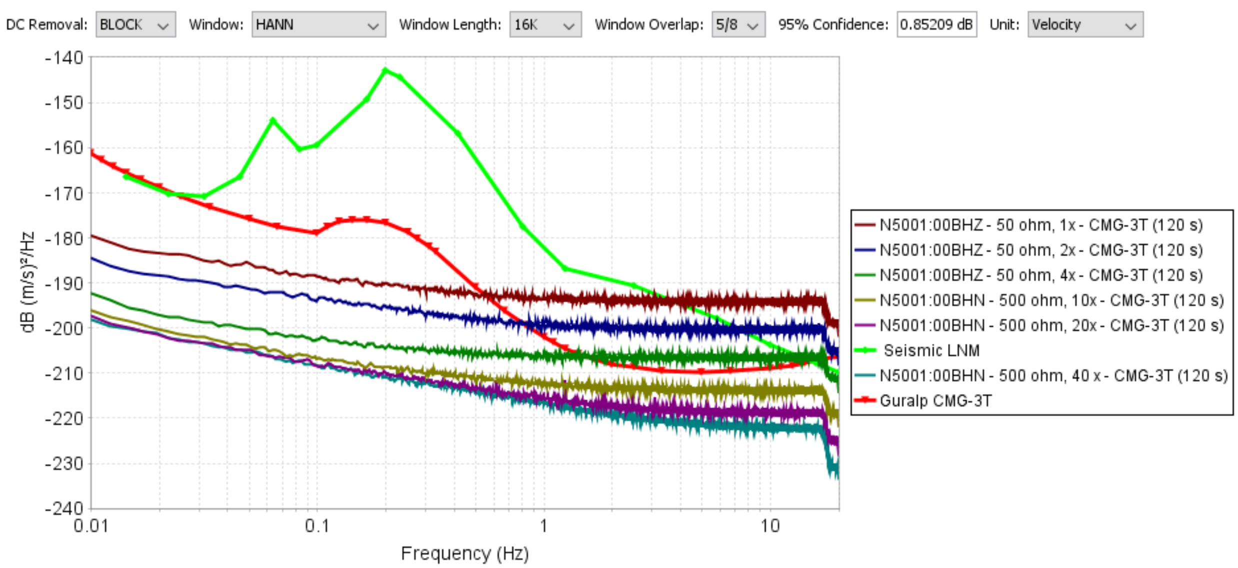

Figure 39 Seismic System Noise for Guralp CMG-3T (1500 V/(m/s) and 120 sec corner) at gains of 1, 2, 4, 10, 20, and 40

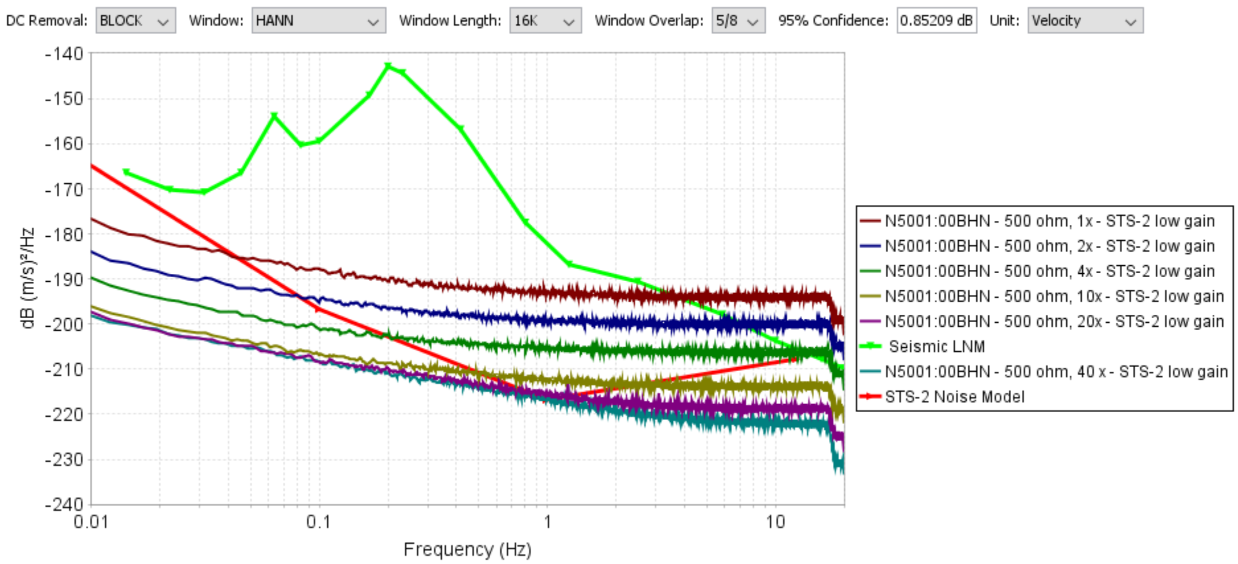

Figure 40 Seismic System Noise for STS-2 low gain at gains of 1, 2, 4, 10, 20, and 40

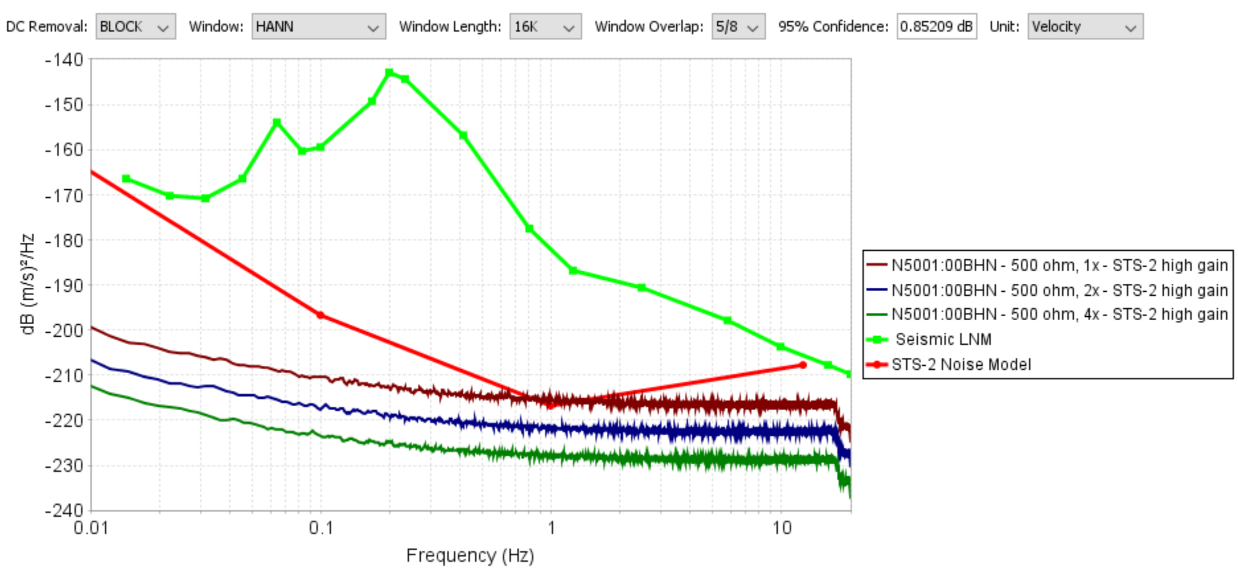

Figure 41 Seismic System Noise for STS-2 high gain at gains of 1, 2, and 4

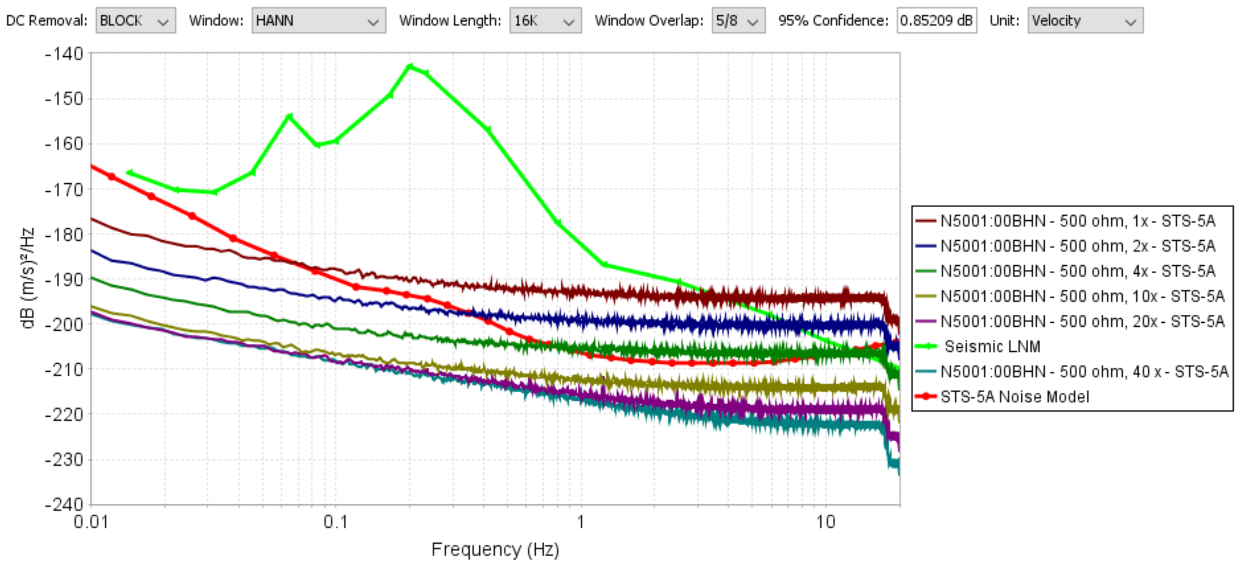

Figure 42 Seismic System Noise for Kinemetrics STS-5A at gains of 1, 2, 4, 10, 20, and 40

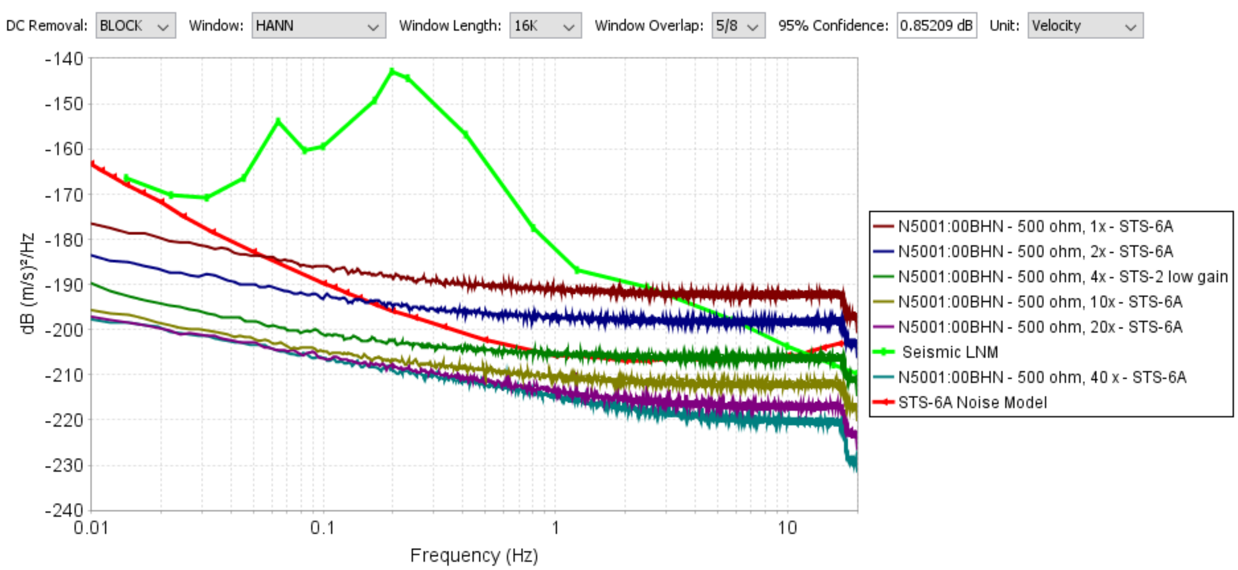

Figure 43 Seismic System Noise for Kinemetrics STS-6A at gains of 1, 2, 4, 10, 20, and 40

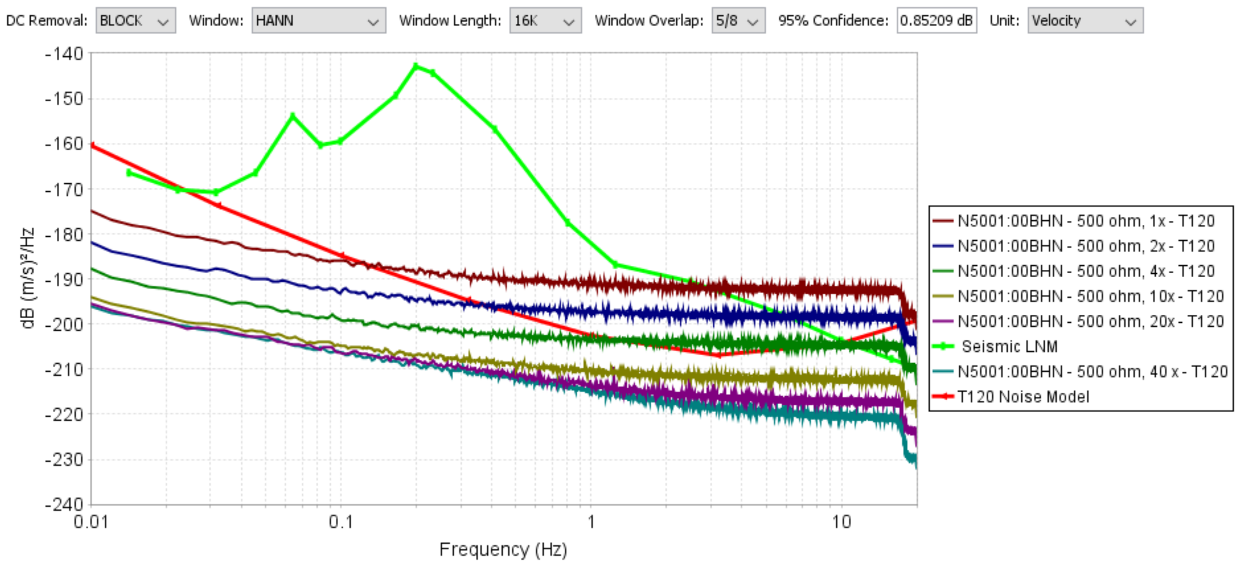

Figure 44 Seismic System Noise for Trillium 120 at gains of 1, 2, 4, 10, 20, and 40

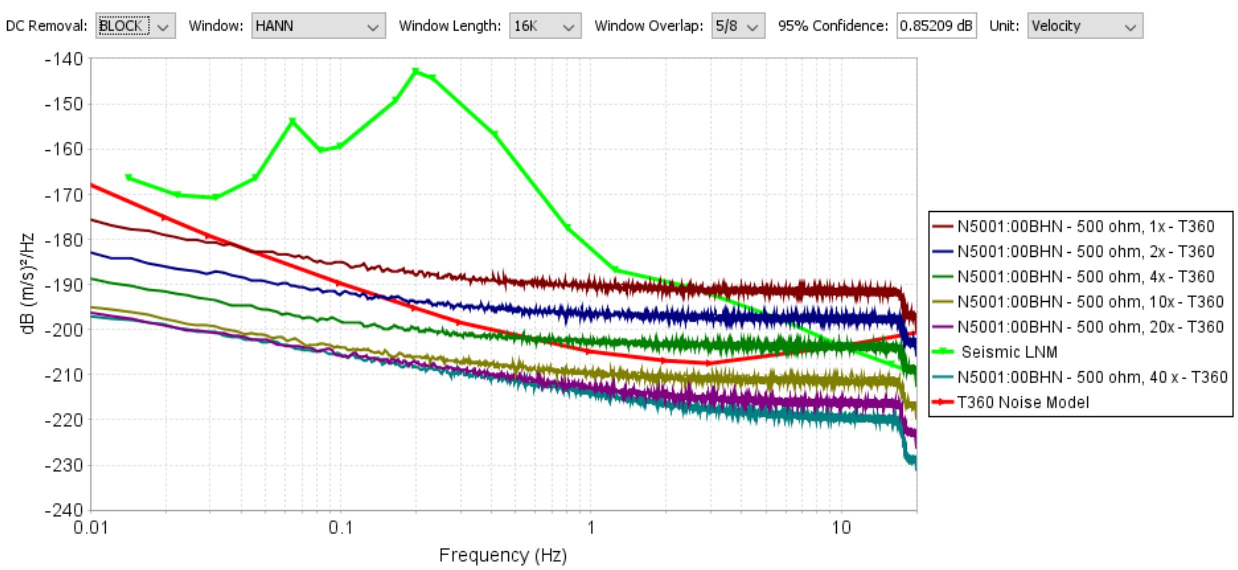

Figure 45 Seismic System Noise for Trillium 360 at gains of 1, 2, 4, 10, 20, and 40

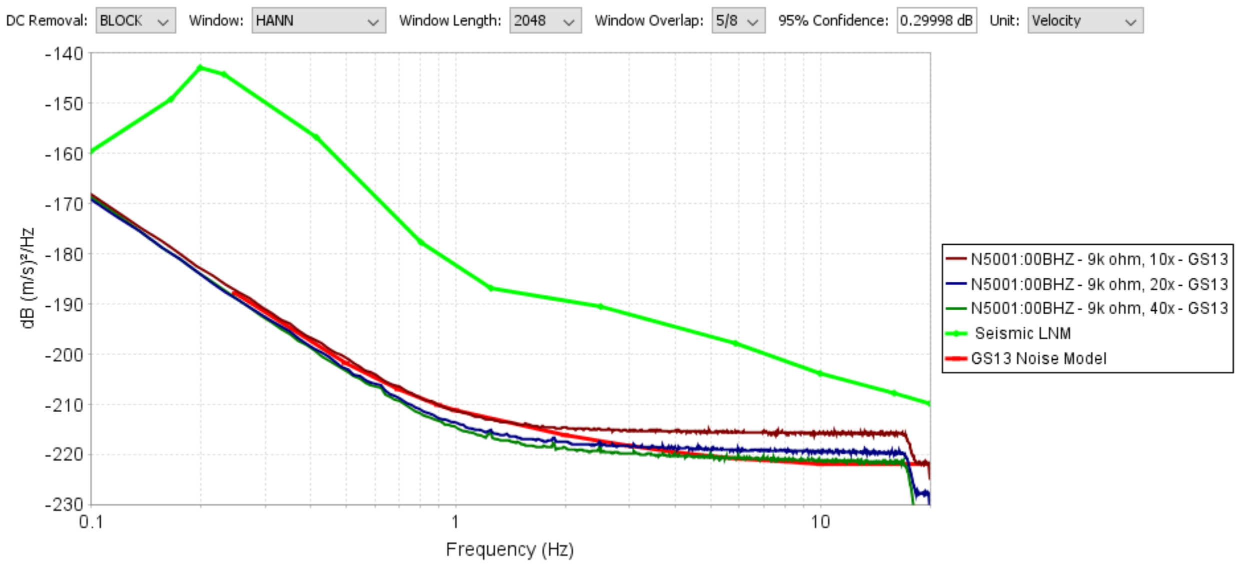

Figure 46 Seismic System Noise for Geotech GS13 at gains of 1, 2, 4, 10, 20, and 40

Note that the Centaur CTR4-3A that was tested was the low impedance model and not suitable for operation of a high impedance passive sensor such as the Geotech GS13 as shown in the figure above. This figure is intended to represent only that the noise floor is sufficiently low.

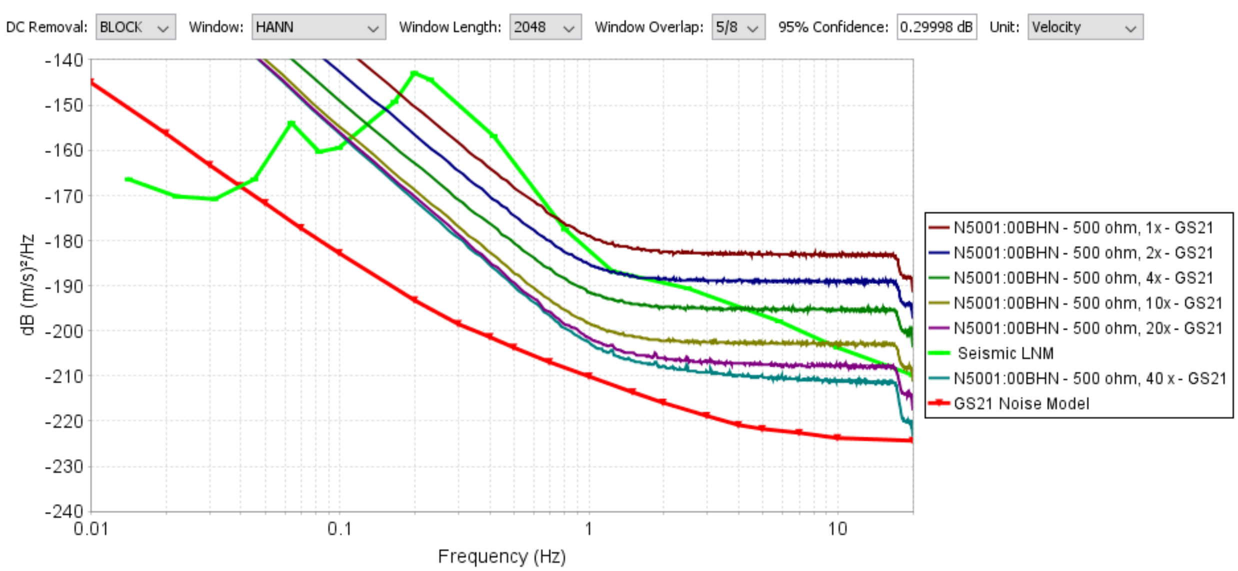

Figure 47 Seismic System Noise for Geotech GS21 at gains of 1, 2, 4, 10, 20, and 40

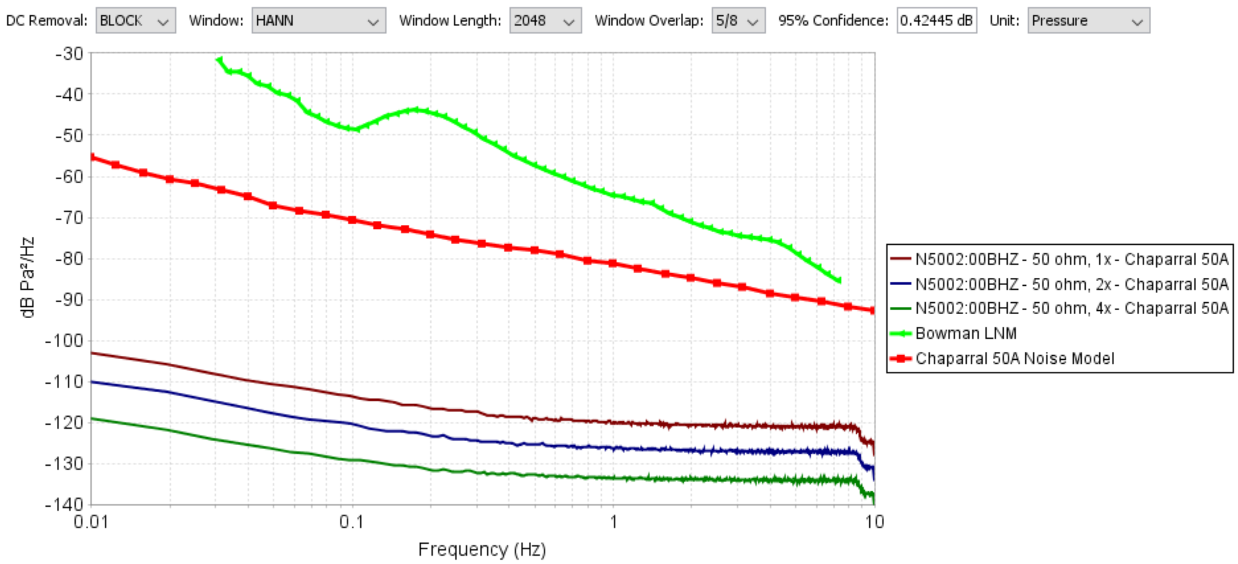

Figure 48 Infrasound System Noise for Chaparral 50A at gains of 1, 2, and 4

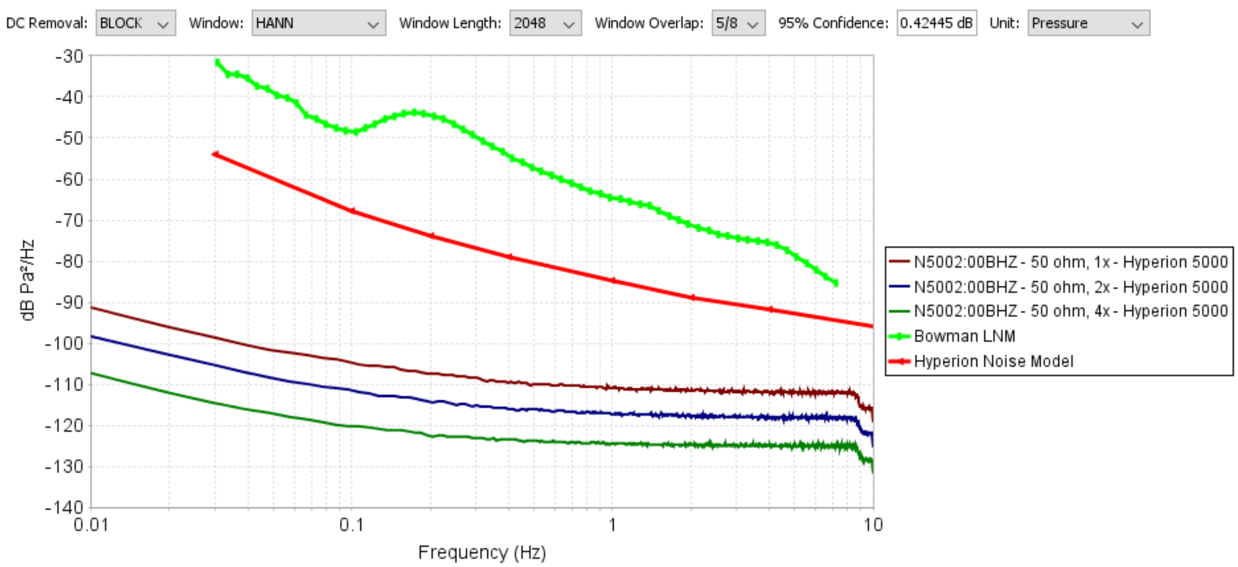

Figure 49 Infrasound System Noise for Hyperion 5000 at gains of 1, 2, and 4

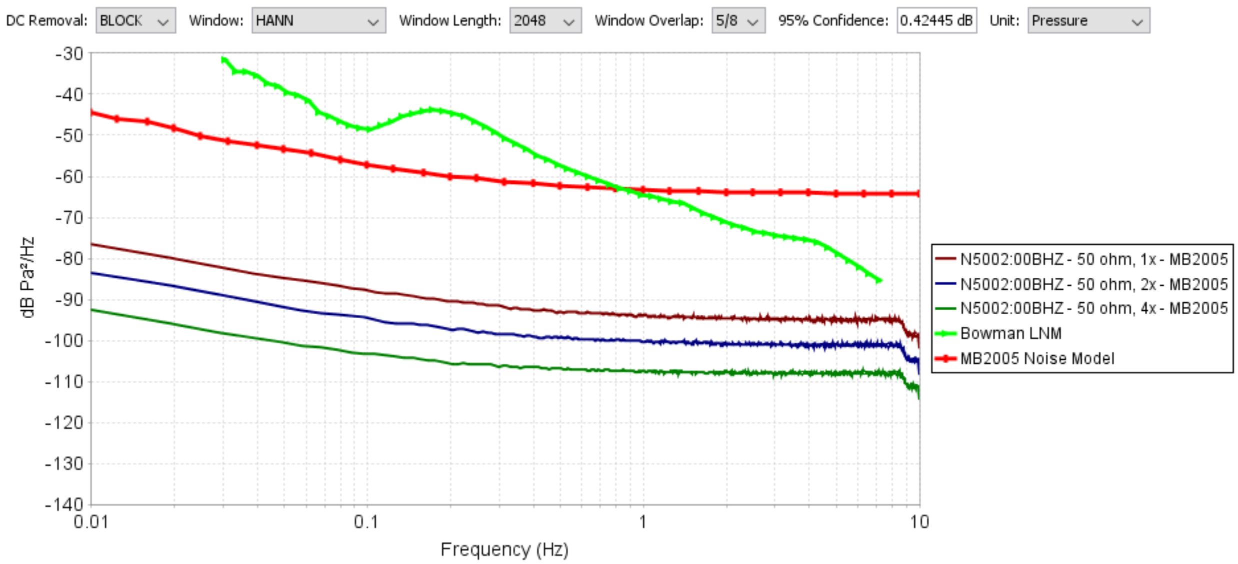

Figure 50 Infrasound System Noise for MB2005 at gains of 1, 2, and 4

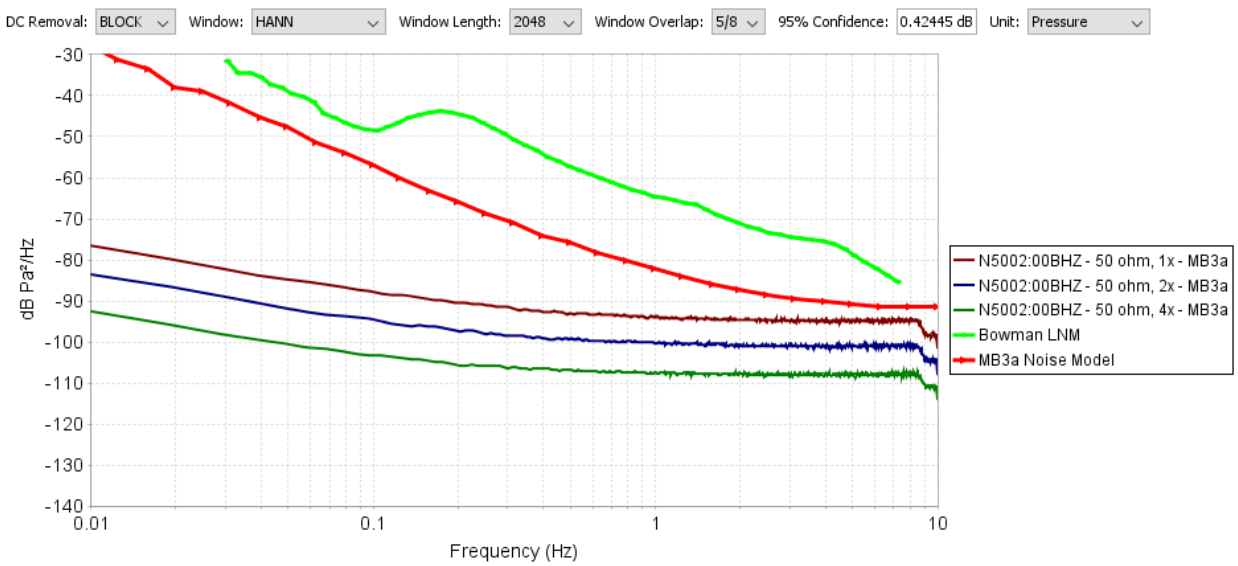

Figure 51 Infrasound System Noise for MB3a at gains of 1, 2, and 4

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 52 Temperature Self Noise Configuration Diagram

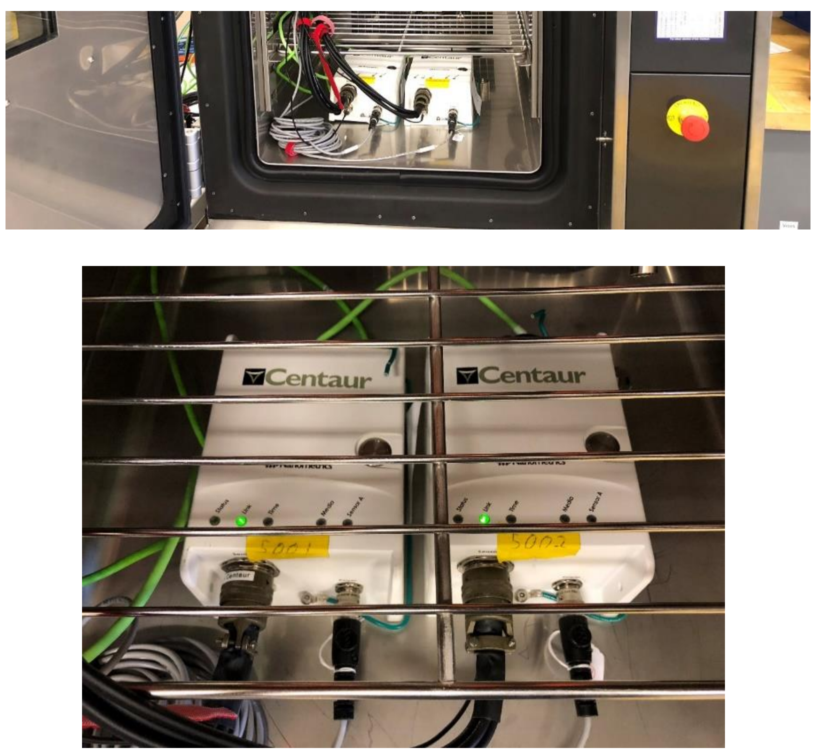

Figure 53 Temperature Self Noise Configuration Picture

The digitizers were placed inside of a temperature chamber so that they could be exposed to a range of ambient temperatures. The analog input cables to the digitizers were routed through a cable port in the sidewall of the temperature chamber so that the terminating resistors could be connected to the inputs of the digitizers without exposing the terminating resistors to the thermal conditions within the chamber. The room ambient temperature was kept at 20 C +/- 2 C.

Figure 54 Temperature Self Noise Configuration Picture

For the self-noise tests, the digitizer channels were terminated with resistors according to the schedule below:

Table 41 Digitizer Temperature Self-Noise Terminator Configuration

	Z	N	E
5001 Gain 10x	9.4 kohm	500 ohm	4k ohm
5002 Gain 1x	50 ohm	500 ohm	4k ohm

The temperature chamber was programmed to cycle the digitizer for 24 hours at -10 C, 12 hours at 0 C, 12 hours at 10 C, 12 hours at 20 C, 12 hours at 30 C, and 24 hours at 40 C.

Table 42 Self Noise Testbed Equipment

	Manufacturer / Model
Temperature Chamber	ESPEC EPL-2H

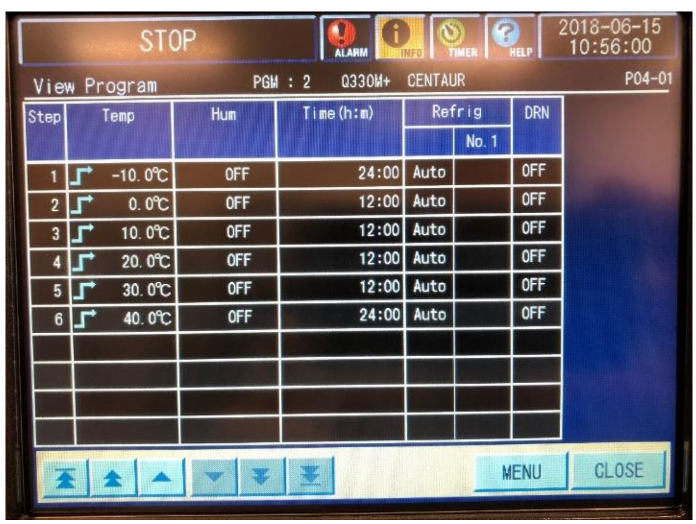

Figure 55 Temperature Chamber Program

3.11.3 Analysis

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

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

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 plots from 5001 and 5002 are shown below. Only the data from 100 Hz and 80 Hz is shown.

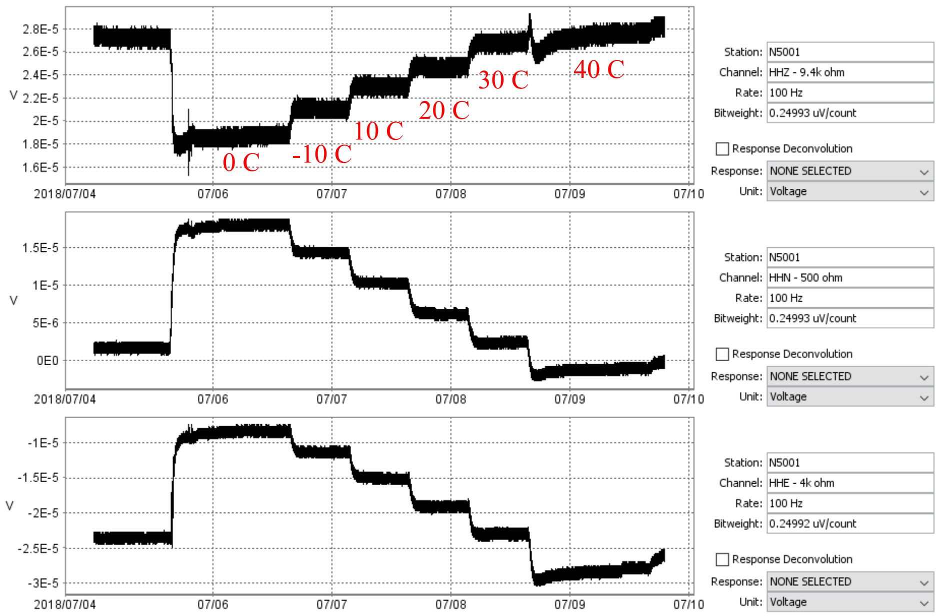

Figure 56 Temperature Self Noise Time Series, 5001

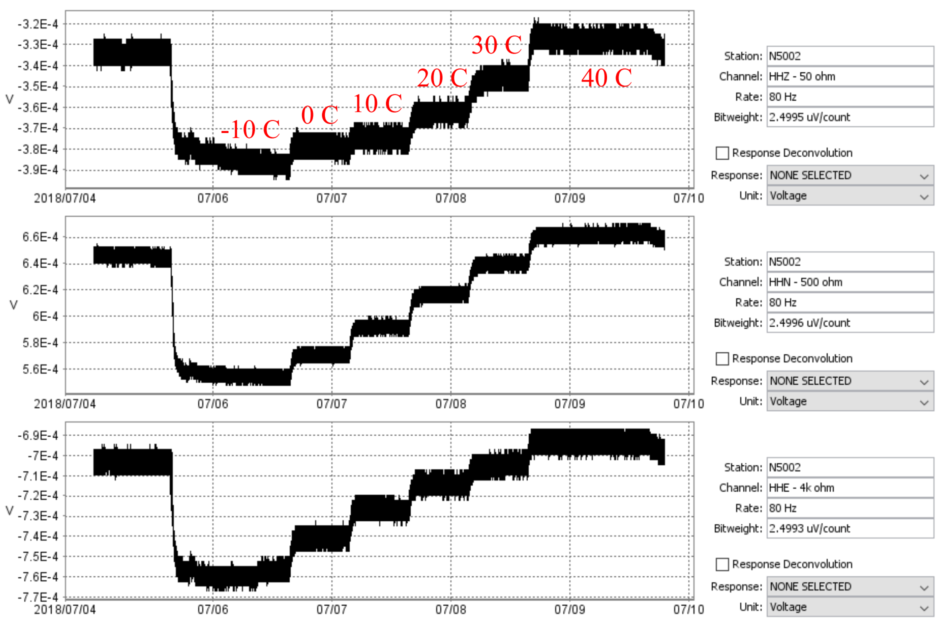

Figure 57 Temperature Self Noise Time Series, 5002

There were no issues with the Centaurs performance or operation during the range of temperatures that were tested. The power spectra for the data collected at each temperature are shown in the plots below.

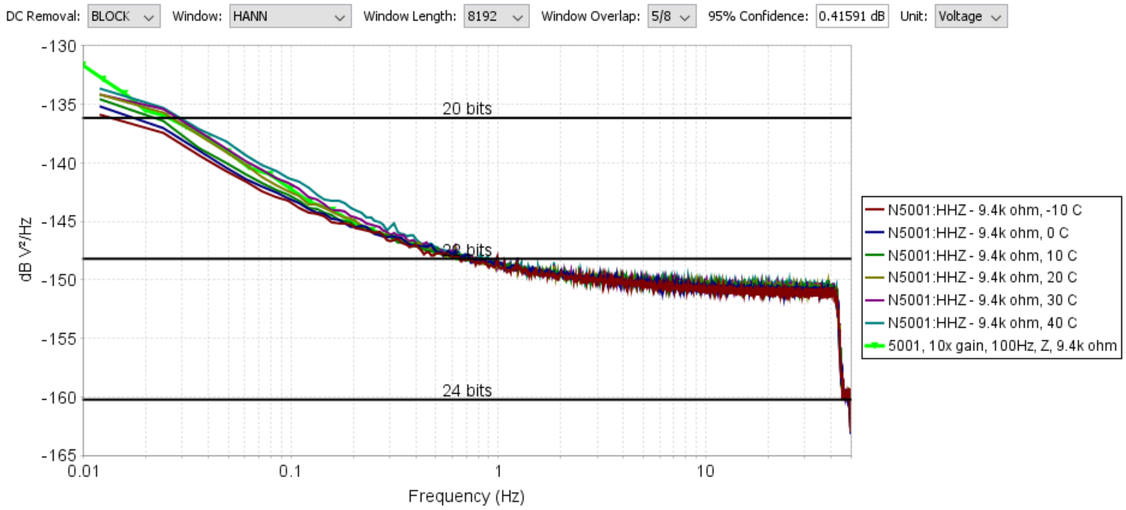

Figure 58 Temperature Self Noise Power Spectra, 5001, Gain 10x, Z, 9.4k ohm

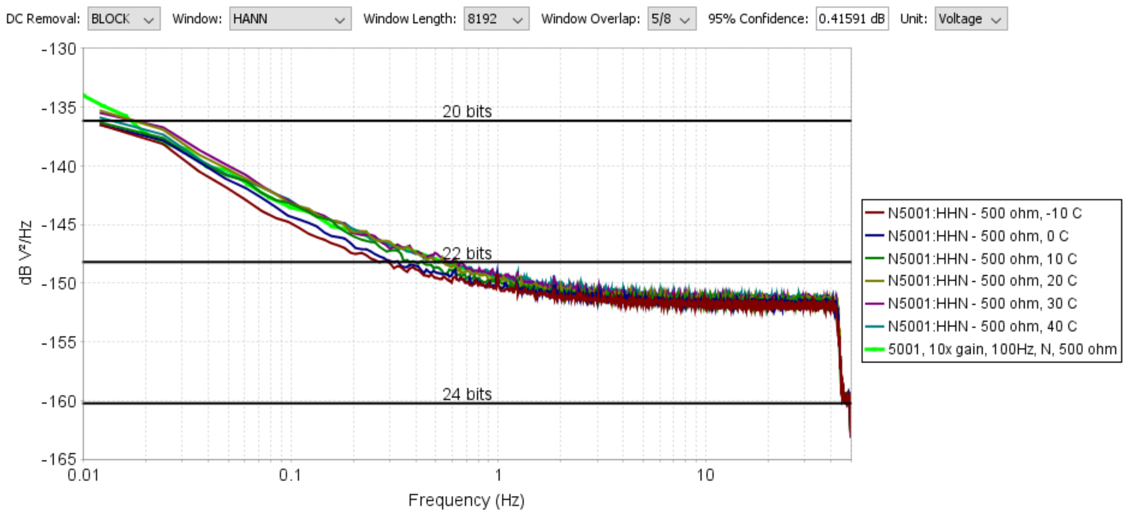

Figure 59 Temperature Self Noise Power Spectra, 5001, Gain 10x, N, 500 ohm

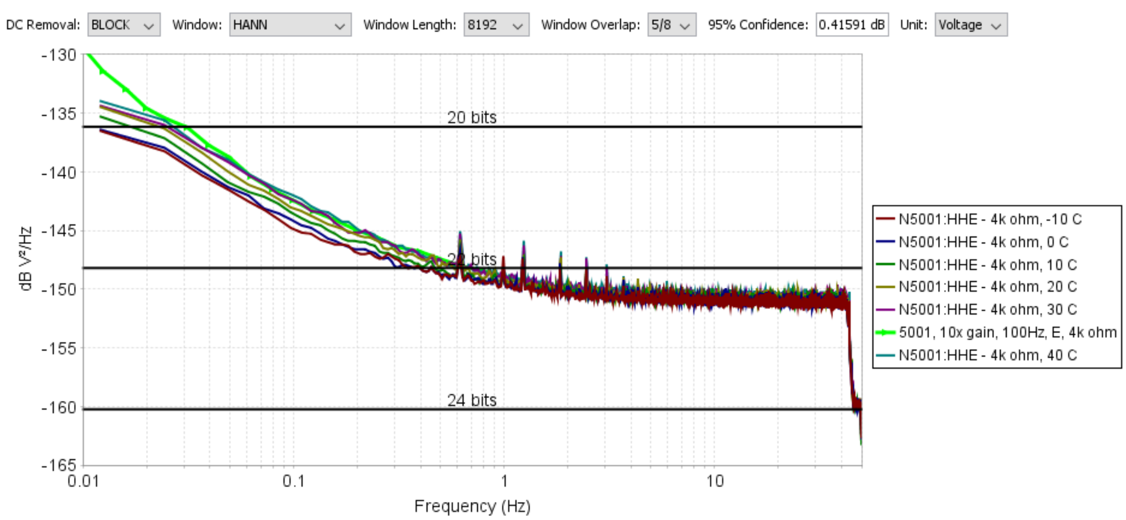

Figure 60 Temperature Self Noise Power Spectra, 5001, Gain 10x, E, 4k ohm

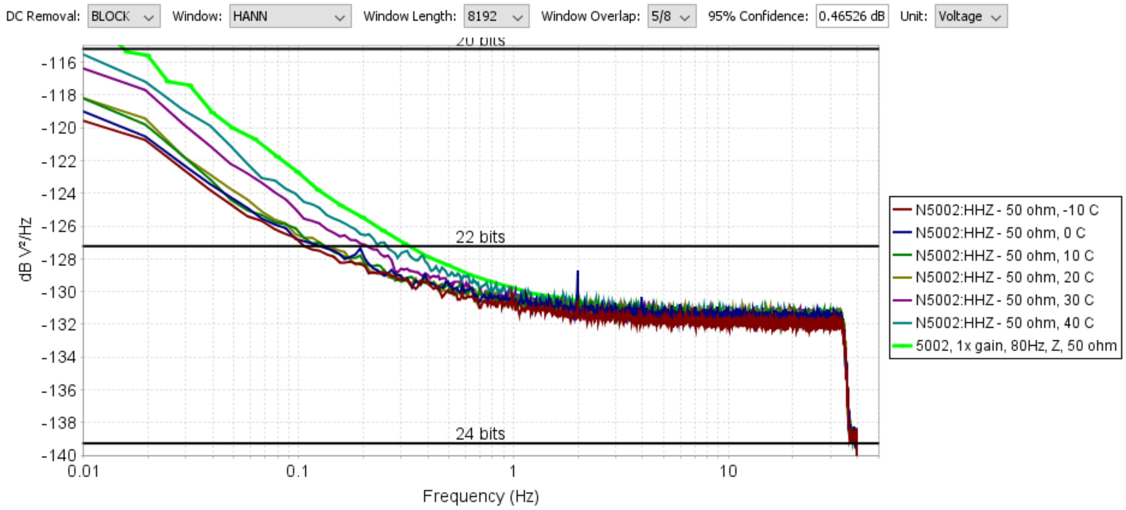

Figure 61 Temperature Self Noise Power Spectra, 5002, Gain 1x, Z, 50 ohm

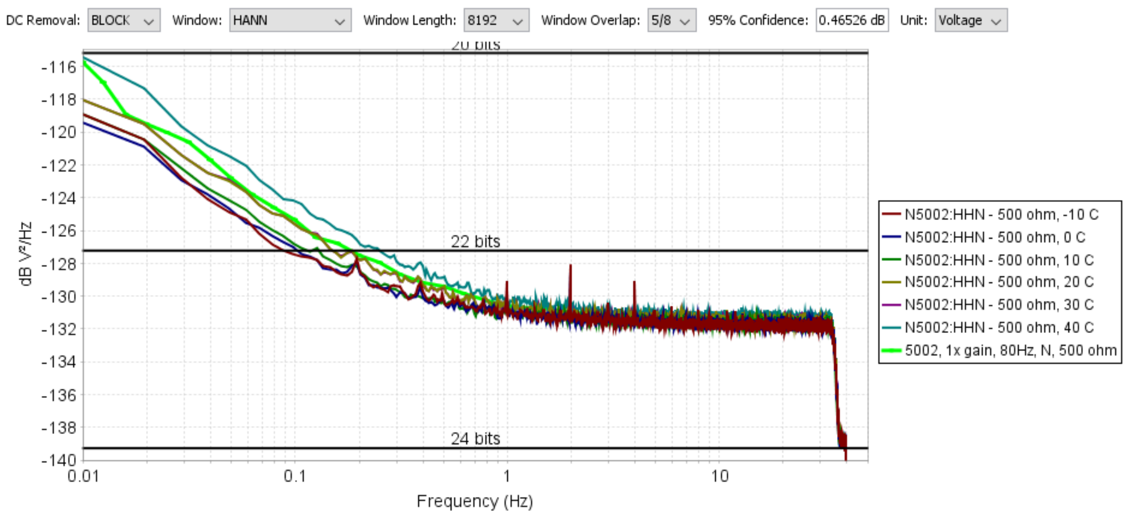

Figure 62 Temperature Self Noise Power Spectra, 5002, Gain 1x, N, 500 ohm

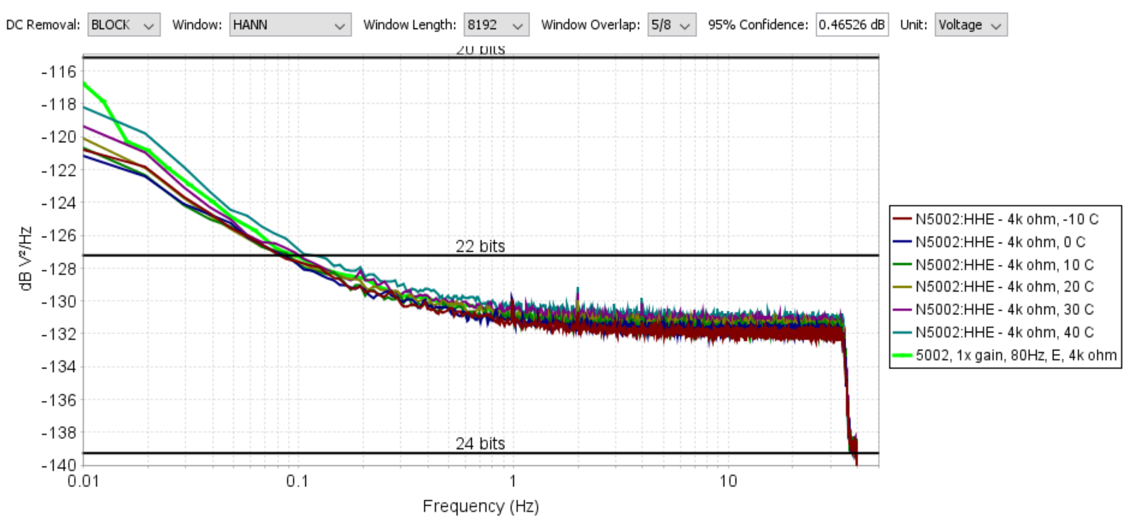

Figure 63 Temperature Self Noise Power Spectra, 5002, Gain 1x, E, 2k ohm

As may be seen, the power spectra collected was very similar to the comparison self-noise levels obtained at 23 C, shown in green. The only variation observed was a slight change in the DC offset related to temperature.

Table 43 Temperature Self Noise DC Offset, Centaur 5001

	-10 C	0 C	10 C	20 C	30 C	40 C
Z	18.66 uV	21.07 uV	23.00 uV	24.64 uV	26.74 uV	27.50 uV
	Change Z:	0.24 uV/C	0.19 uV/C	0.16 uV/C	0.21 uV/C	0.08 uV/C
N	18.00 uV	14.34 uV	10.30 uV	6.159 uV	2.333 uV	-1.151 uV
	Change N:	-0.37 uV/C	-0.40 uV/C	-0.41 uV/C	-0.38 uV/C	-0.35 uV/C
E	-8.418 uV	-11.39 uV	-15.11 uV	-19.14 uV	-23.04 uV	-28.26 uV
	Change E:	-0.30 uV/C	-0.37 uV/C	-0.40 uV/C	-0.39 uV/C	-0.52 uV/C

Table 44 Temperature Self Noise DC Offset, Centaur 5002

	-10 C	0 C	10 C	20 C	30 C	40 C
Z	-0.3842 mV	-0.3791 mV	-0.3748 mV	-0.3627 mV	-0.3463 mV	-0.3279 mV
	Change Z:	0.51 uV/C	0.43 uV/C	1.21 uV/C	1.64 uV/C	1.84 uV/C
N	0.5551 mV	0.5707 mV	0.5921 mV	0.6164 mV	0.6397 mV	0.6616 mV
	Change N:	1.56 uV/C	2.14 uV/C	2.44 uV/C	2.33 uV/C	2.19 uV/C
E	-0.7602 mV	-0.7407 mV	-0.7266 mV	-0.7145 mV	-0.7050 mV	-0.6939 mV
	Change E:	1.95 uV/C	1.41 uV/C	1.21 uV/C	0.96 uV/C	1.11 uV/C

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.

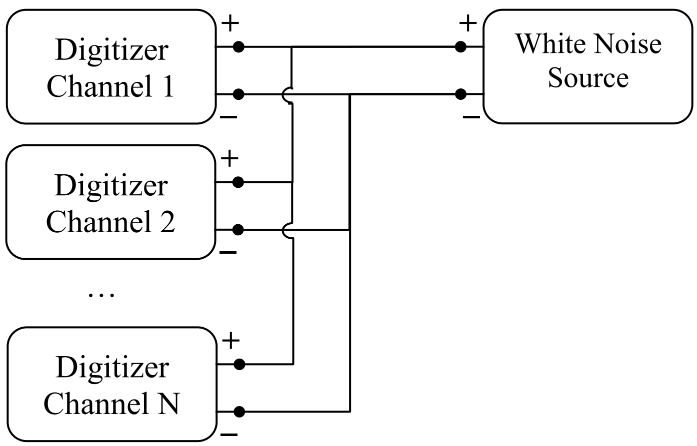

Figure 64 Response Verification Configuration Diagram

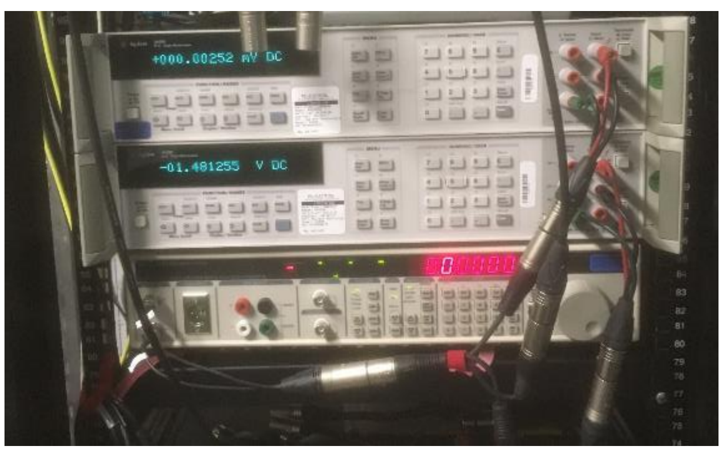

Figure 65 Response Verification Configuration Picture

Table 45 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:

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

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

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

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 40 Hz and 100 Hz on 5001 and 20 Hz and 80 Hz on 5002. The results were identical at the various sample rates, therefore only the 100 Hz and 80 Hz data is shown below. The power spectra, coherence, relative amplitude, and relative phase are shown in the plots below.

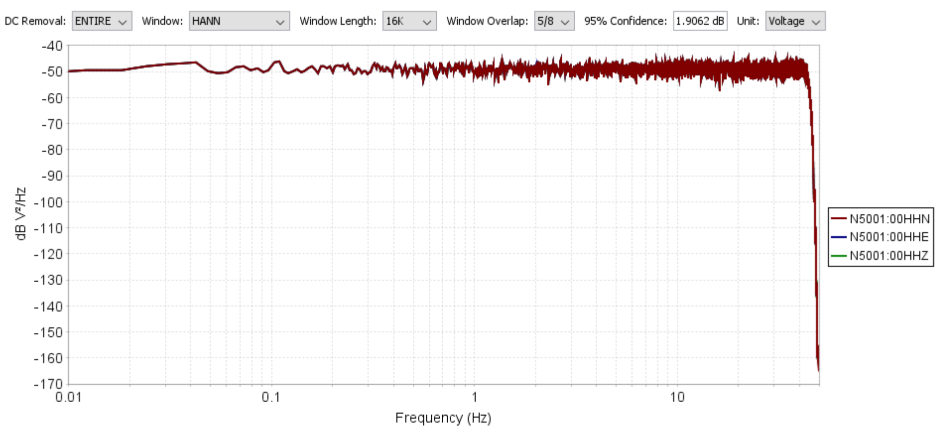

Figure 66 White Noise Power Spectra, Centaur 5001, gain 10x, 100 Hz

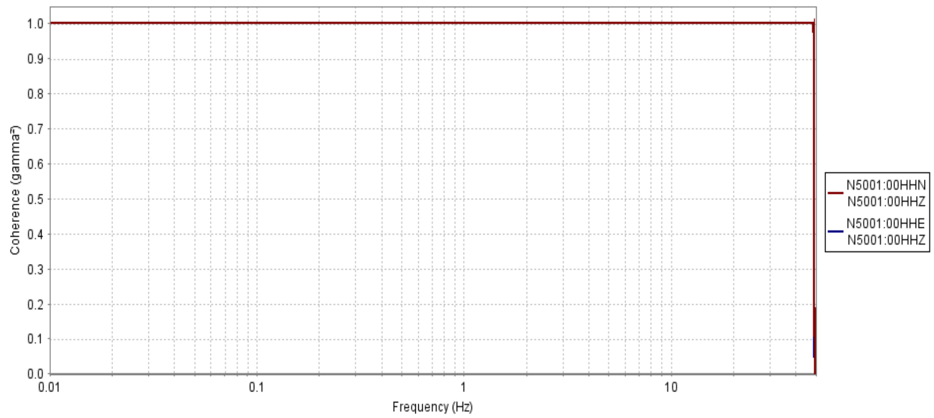

Figure 67 White Noise Coherence, Centaur 5001, gain 10x, 100 Hz

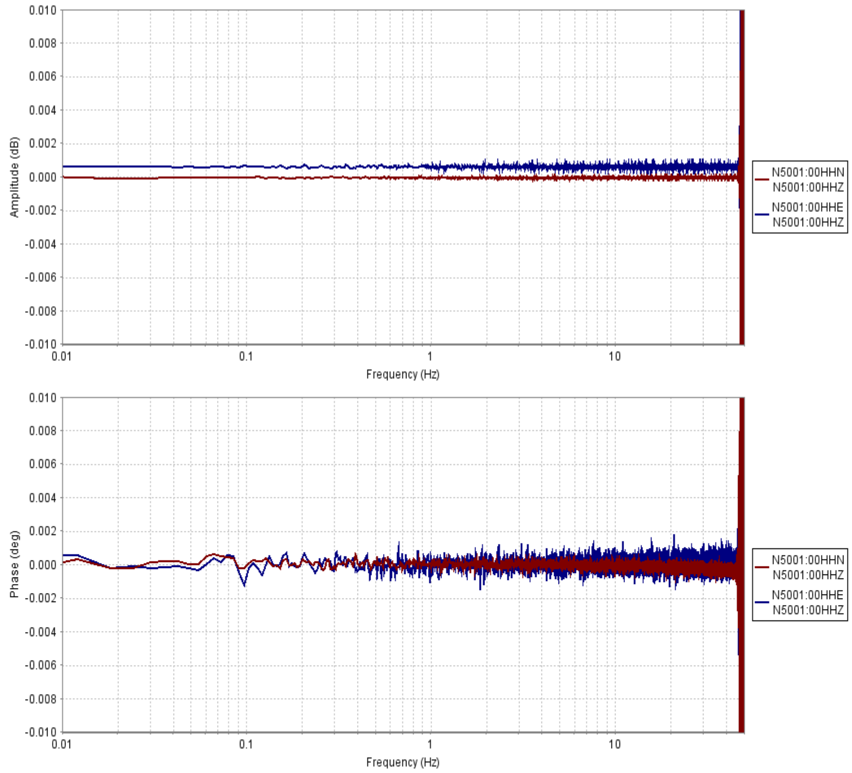

Figure 68 Relative Amplitude and Phase: Centaur 5001, gain 10x, 100 Hz

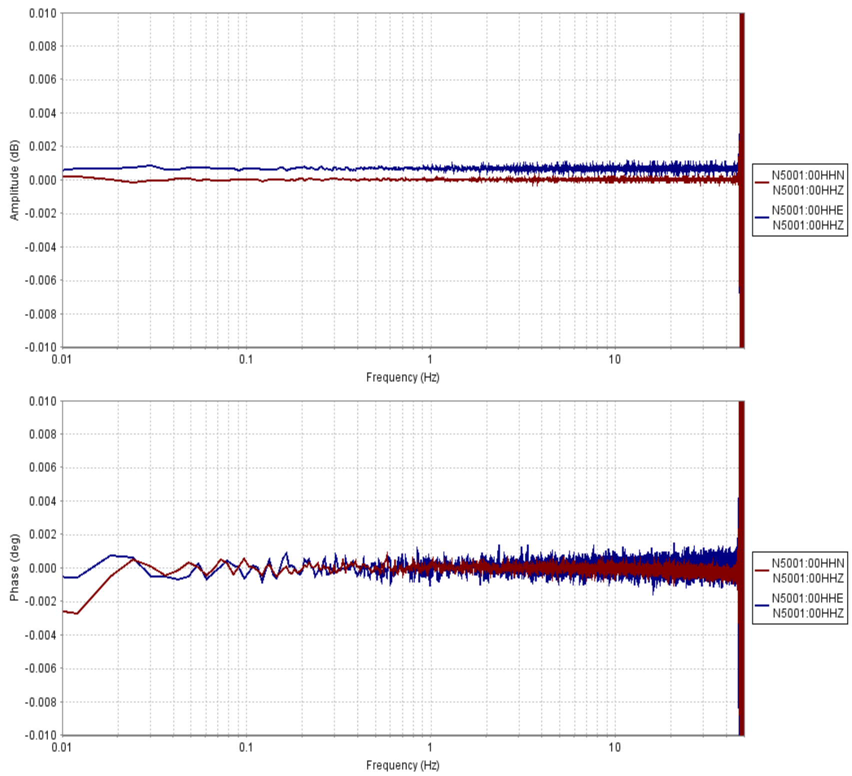

Figure 69 Relative Amplitude and Phase: Centaur 5001, gain 20x, 100 Hz

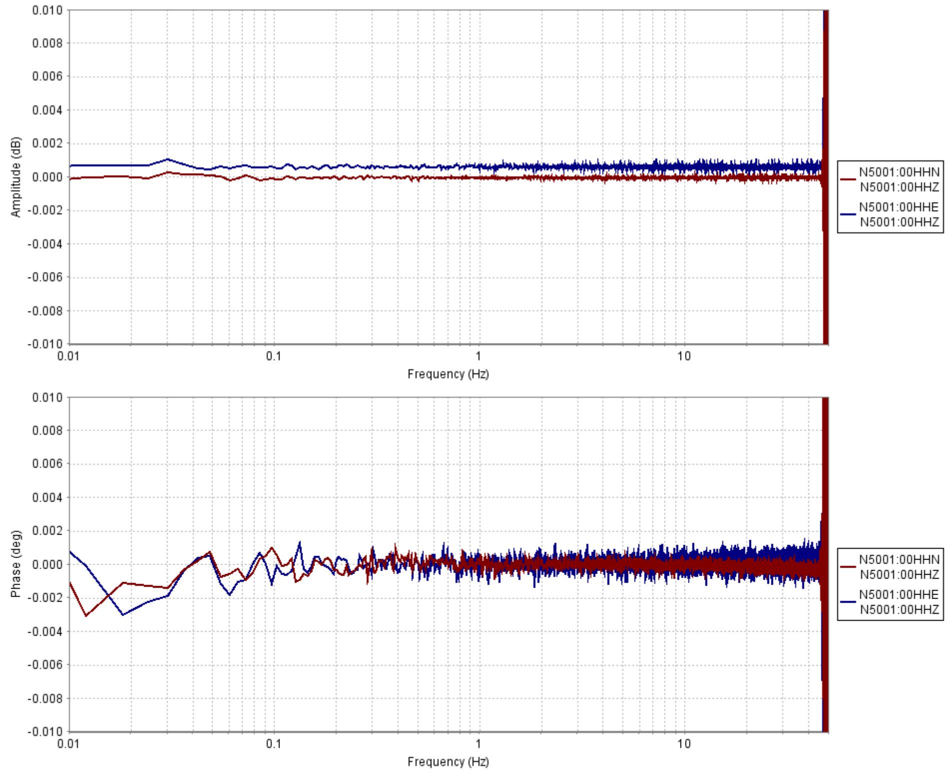

Figure 70 Relative Amplitude and Phase: Centaur 5001, gain 40x, 100 Hz

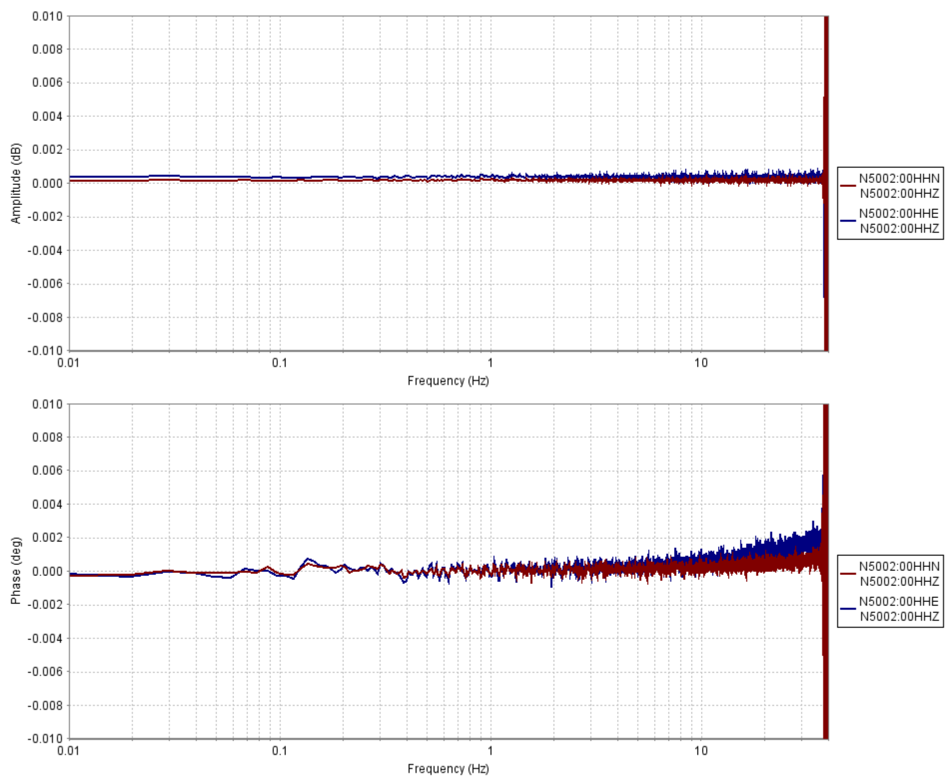

Figure 71 Relative Amplitude and Phase: Centaur 5002, gain 1x, 80 Hz

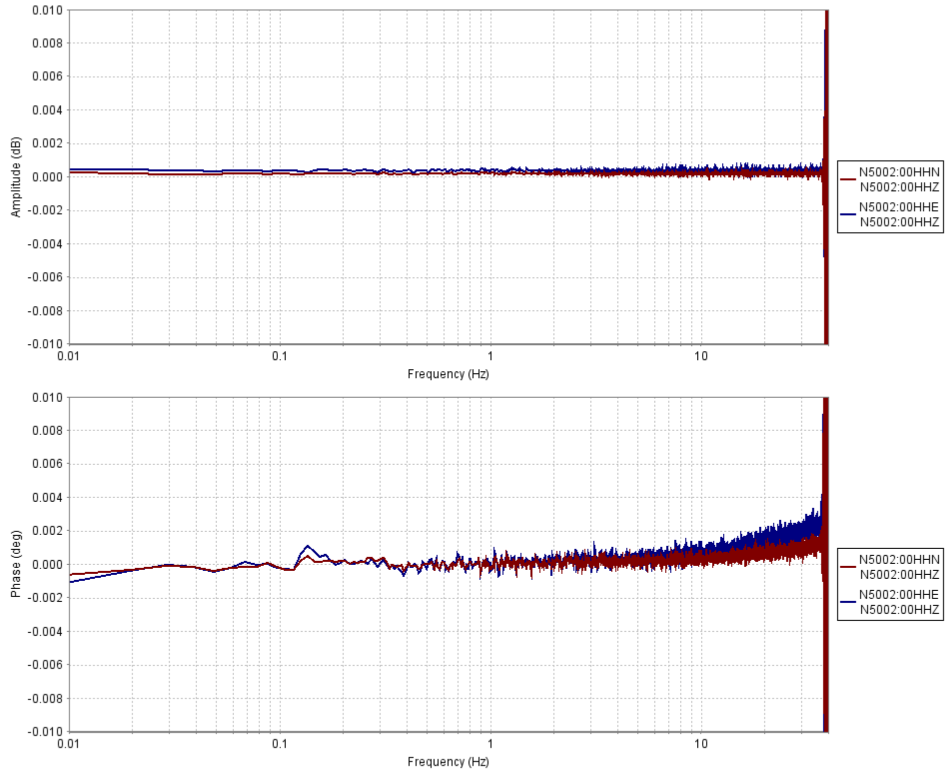

Figure 72 Relative Amplitude and Phase: Centaur 5002, gain 2x, 80 Hz

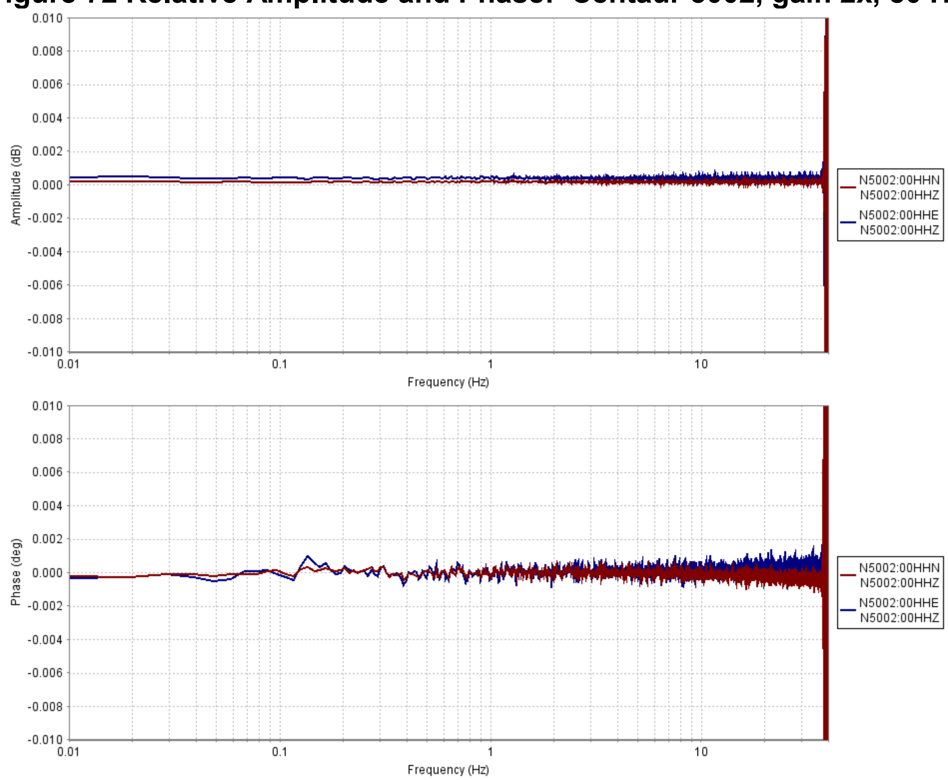

Figure 73 Relative Amplitude and Phase: Centaur 5002, gain 4x, 80 Hz

In all cases, the relative amplitudes were flat across the passband and any differences in amplitude were very small, less than +/- 0.001 dB or +/- 0.01 %. 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.

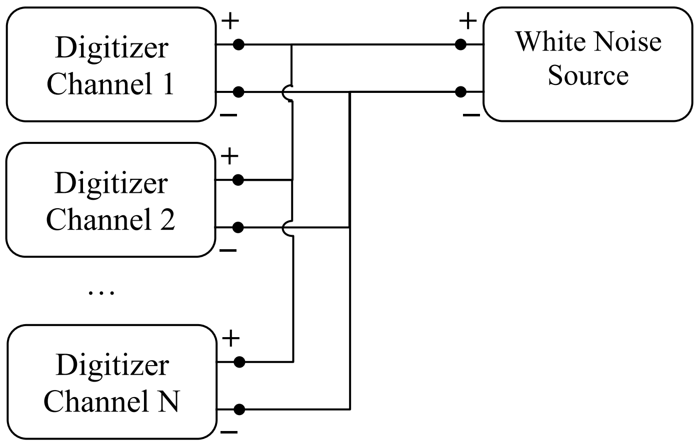

Figure 74 Relative Transfer Function Configuration Diagram

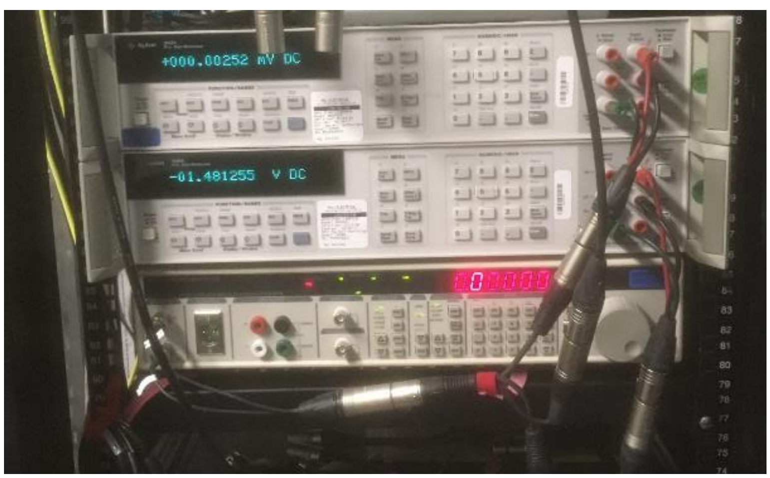

Figure 75 Relative Transfer Function Configuration Picture

Table 46 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:

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

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

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

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

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

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.

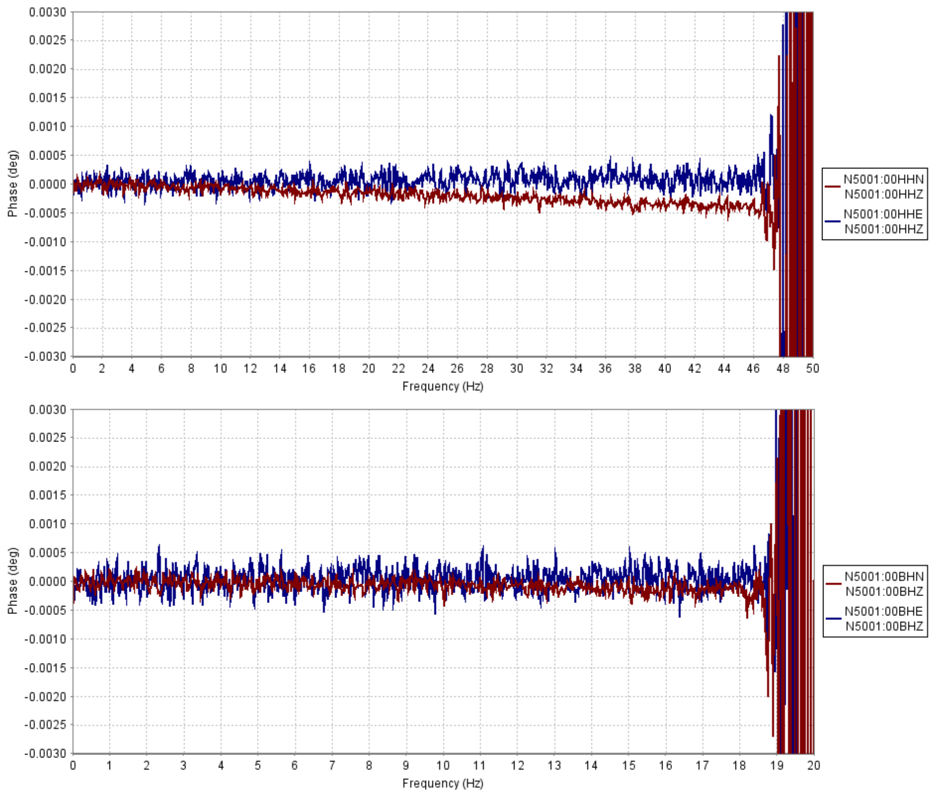

Figure 76 Relative Transfer Function: Centaur 5001, Gain 10

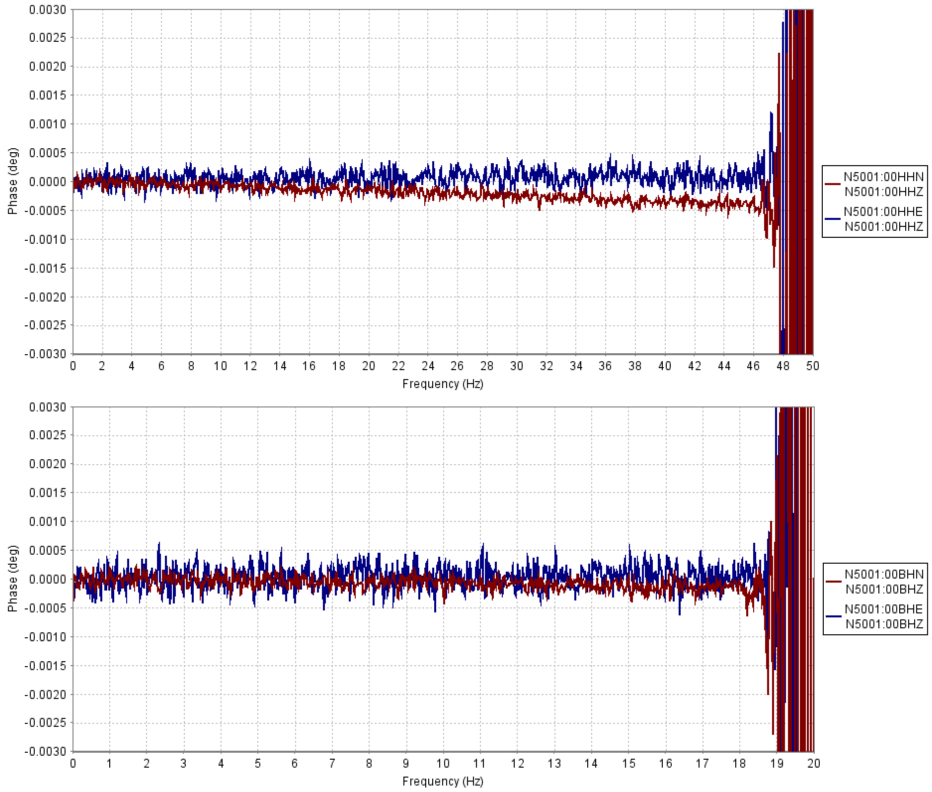

Figure 77 Relative Transfer Function: Centaur 5001, Gain 20

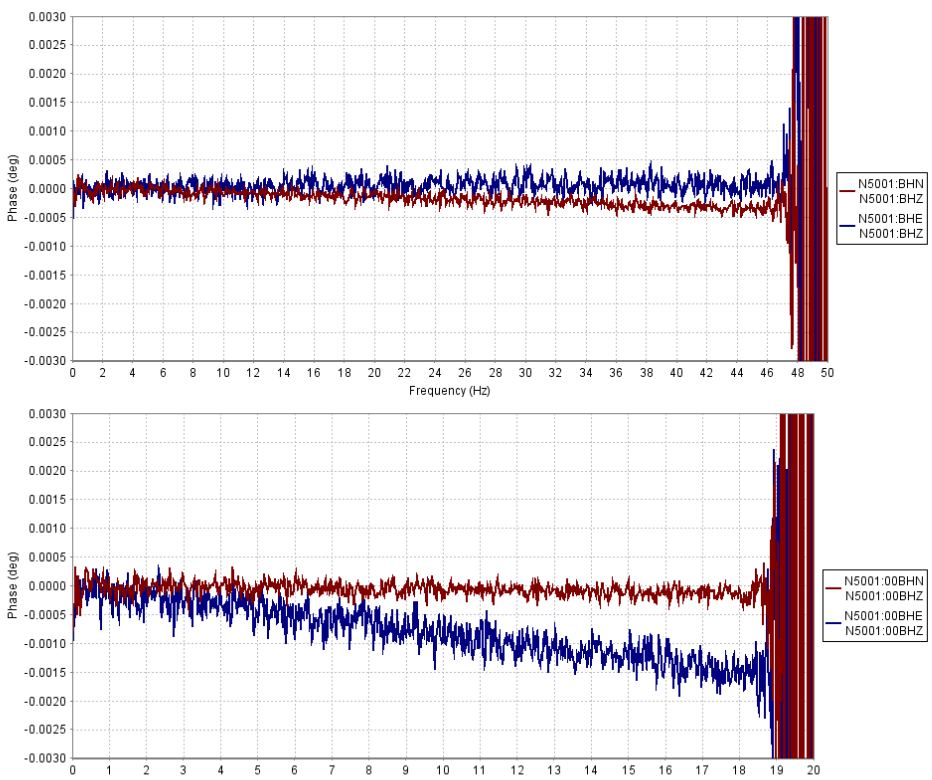

Figure 78 Relative Transfer Function: Centaur 5001, Gain 40

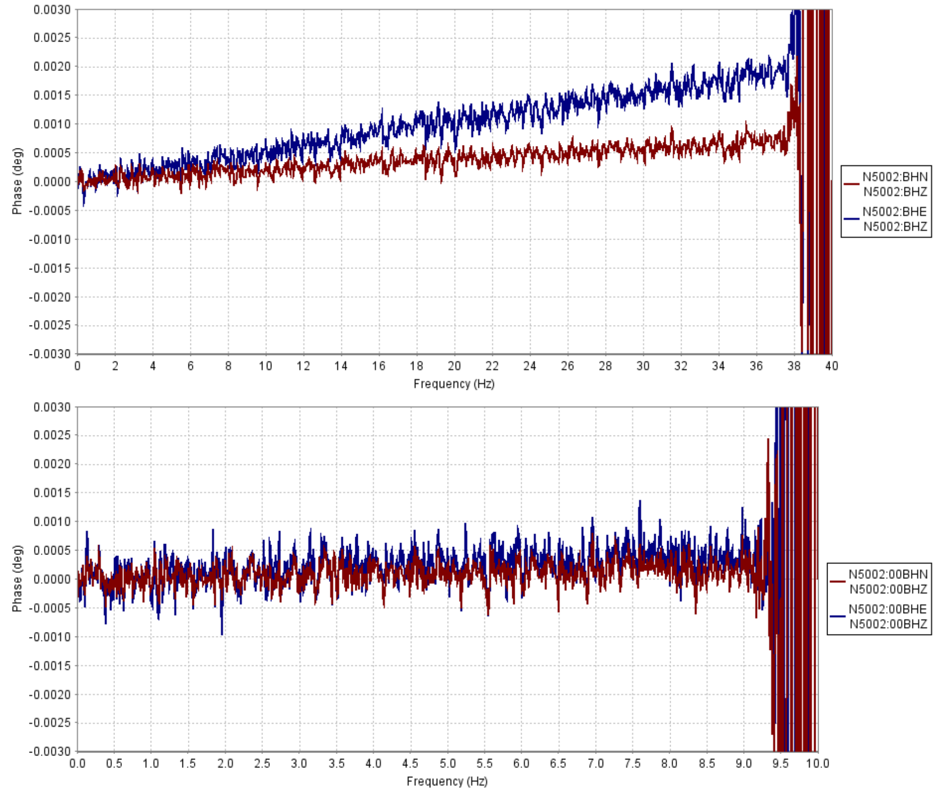

Figure 79 Relative Transfer Function: Centaur 5002, Gain 1

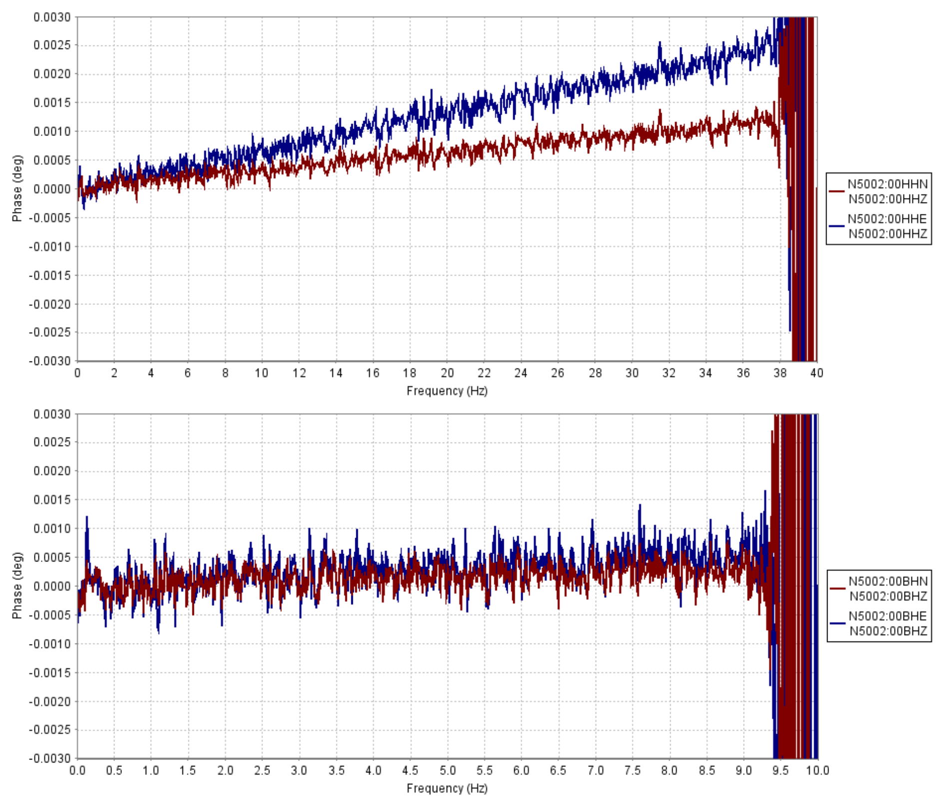

Figure 80 Relative Transfer Function: Centaur 5002, Gain 2

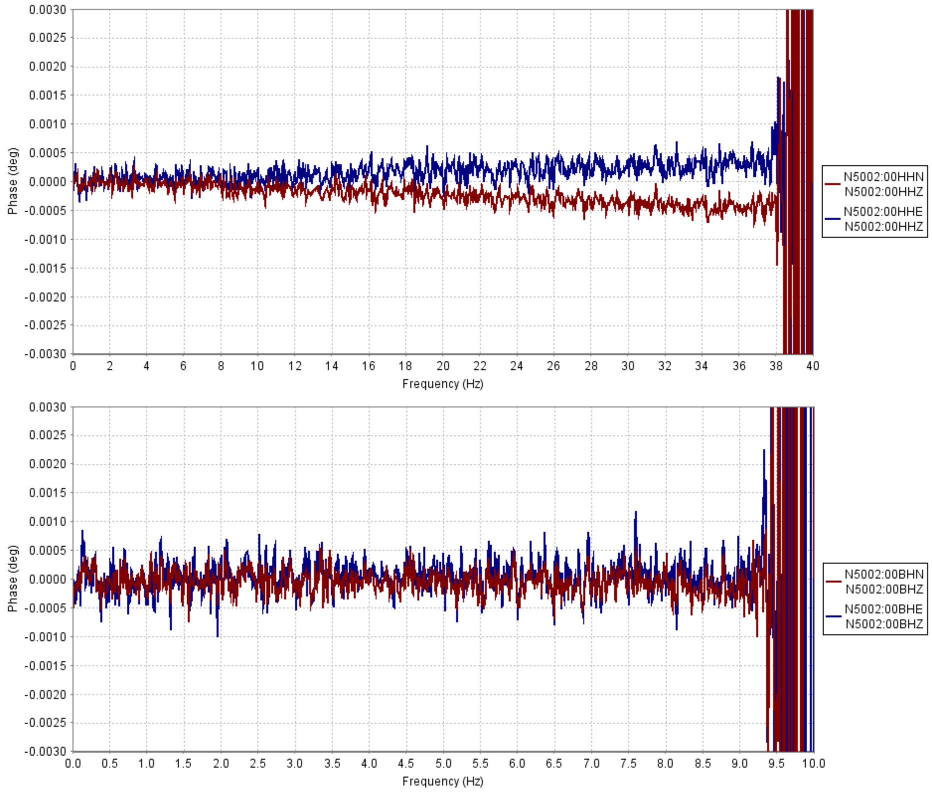

Figure 81 Relative Transfer Function: Centaur 5002, Gain 4

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 47 Relative Transfer Function Timing Skew relative to Channel 1 (Z): Centaur 5001

	100 Hz		40 Hz	
Gain	N - Z	E - Z	N - Z	E - Z
10x	-0.0224 us	0.0021 us	-0.0201 us	-0.0007 us
20x	-0.0233 us	0.0065 us	-0.0235 us	0.0053 us
40x	-0.0227 us	0.0021 us	-0.0256 us	-0.2405 us

Table 48 Relative Transfer Function Timing Skew relative to Channel 1 (Z): Centaur 5002

	80 Hz		20 Hz	
Gain	N - Z	E - Z	N - Z	E - Z
1x	0.0528 us	0.1403 us	0.0493 us	0.1280 us
2x	0.0868 us	0.1787 us	0.0908 us	0.1725 us
4x	-0.0345 us	0.0213 us	-0.0332 us	0.0164 us

All of the digitizer channels were observed to have a timing skew that was within less than 0.25 microsecond of one another.

3.14 Analog Bandwidth

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

3.14.1 Measurand

The quantity being measured is the upper limit of the frequency passband in Hertz.

3.14.2 Configuration

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

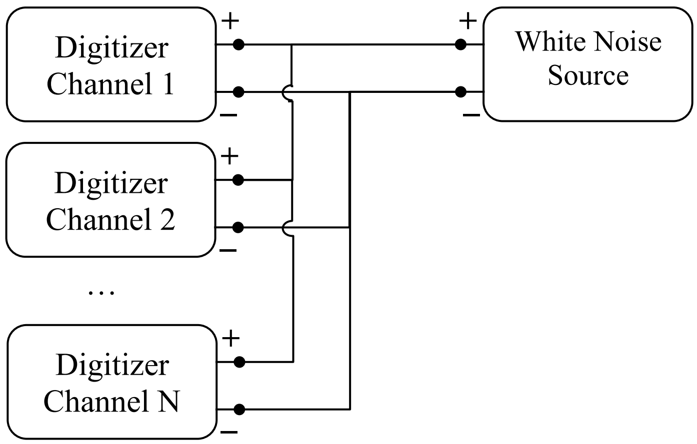

Figure 82 Analog Bandwidth Configuration Diagram

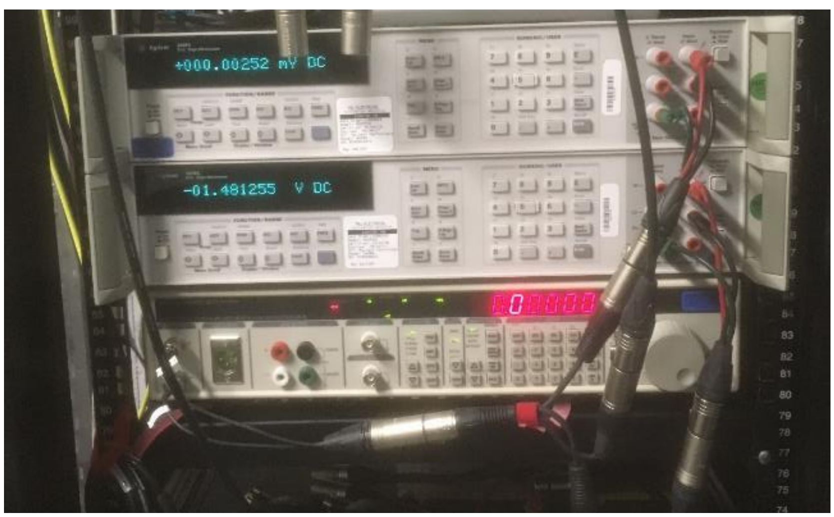

Figure 83 Analog Bandwidth Configuration Picture

Table 49 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:

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

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.

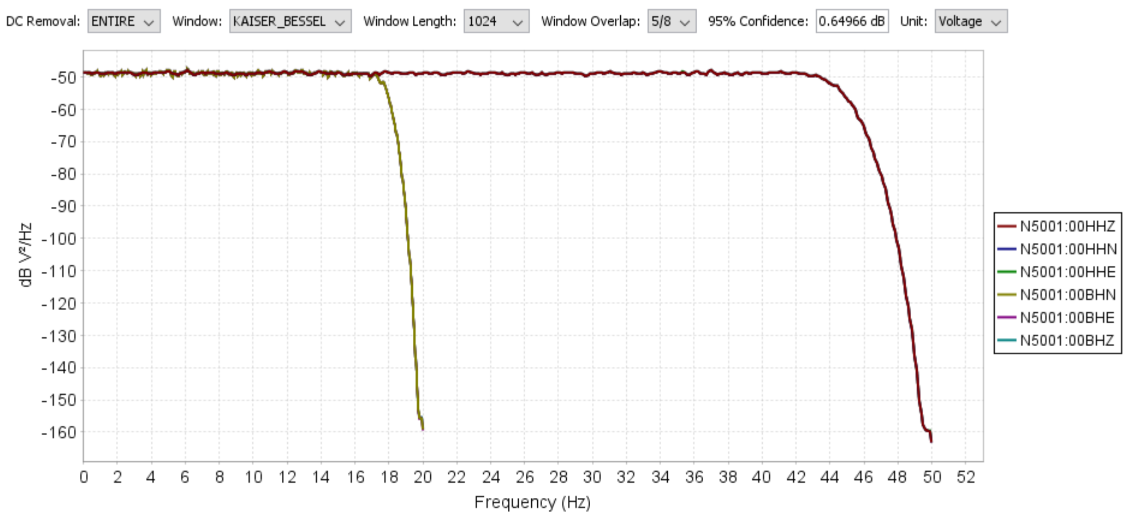

Figure 84 Analog Bandwidth Gain 10: 5001

Figure 85 Analog Bandwidth Gain 20: 5001

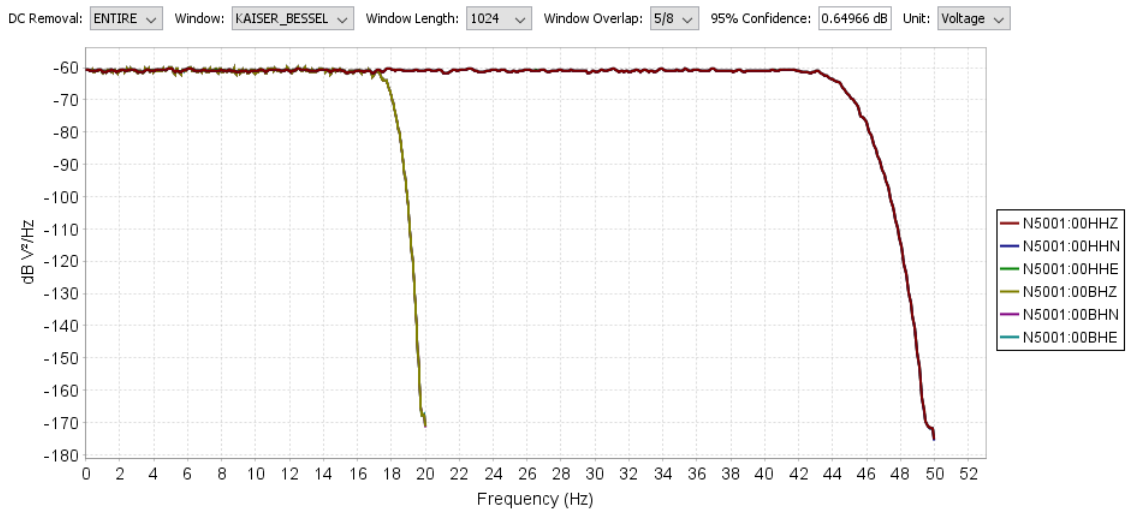

Figure 86 Analog Bandwidth Gain 40: 5001

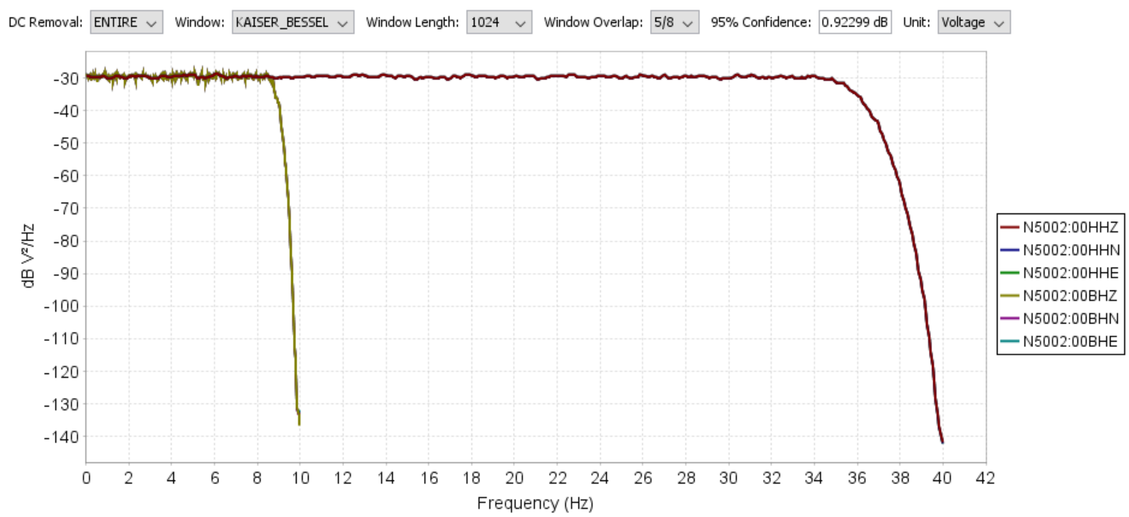

Figure 87 Analog Bandwidth Gain 1: 5002

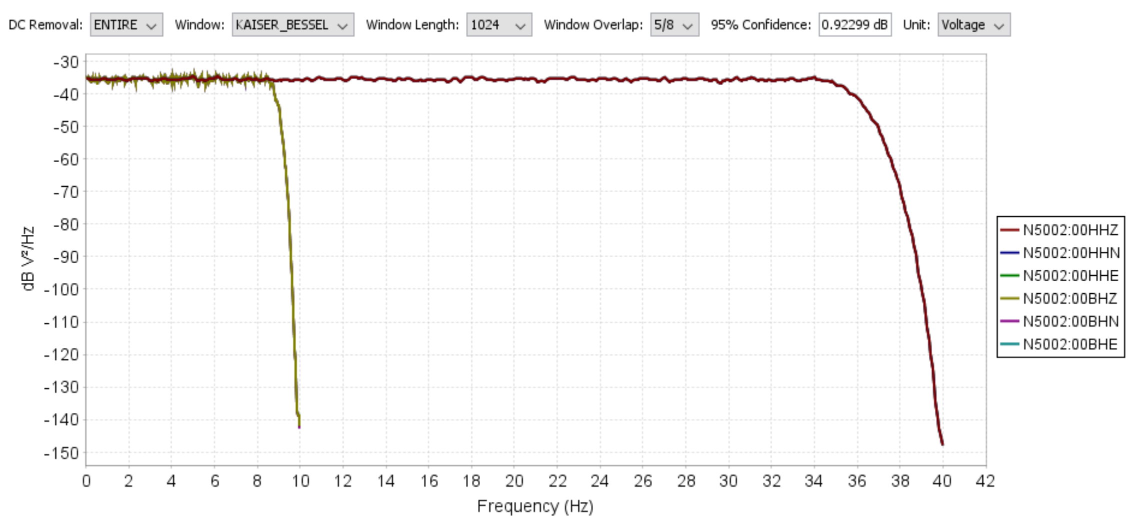

Figure 88 Analog Bandwidth Gain 2: 5002

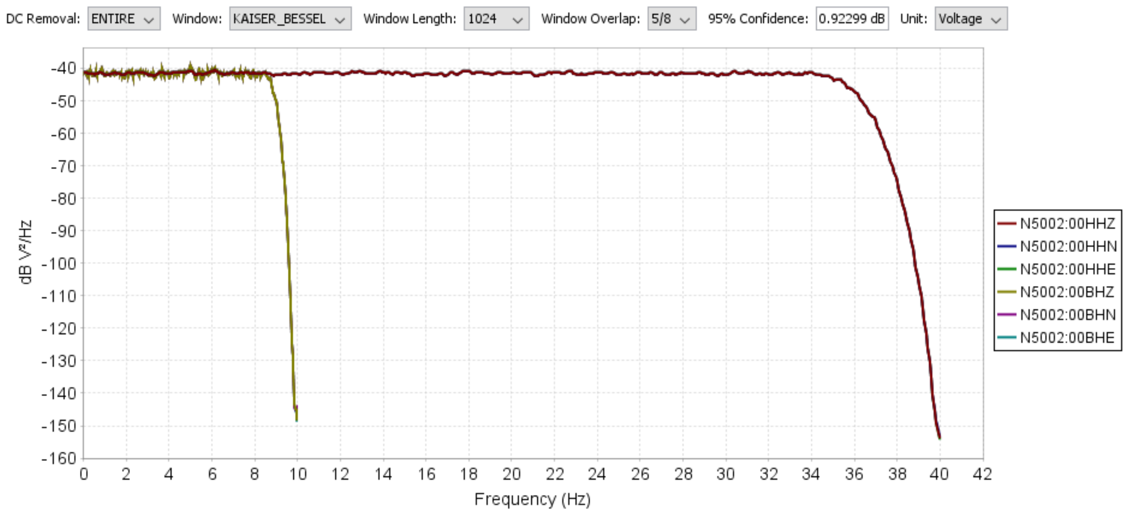

Figure 89 Analog Bandwidth Gain 4: 5002

The tables below contain the upper frequency at which the signal is 3 dB down from the flat portion of the power spectra.

Table 50 Analog Bandwidth: 5001

		Gain 10x		Gain 20x		Gain 40x	
Sample Rate	Channel	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist
40 Hz	Z	17.70 Hz	88.50%	17.70 Hz	88.50%	17.70 Hz	88.50%
	N	17.70 Hz	88.50%	17.70 Hz	88.50%	17.70 Hz	88.50%
	E	17.70 Hz	88.50%	17.70 Hz	88.50%	17.70 Hz	88.50%
100 Hz	Z	44.10 Hz	88.20%	44.10 Hz	88.20%	44.20 Hz	88.40%
	N	44.10 Hz	88.20%	44.10 Hz	88.20%	44.20 Hz	88.40%
	E	44.10 Hz	88.20%	44.10 Hz	88.20%	44.20 Hz	88.40%

Table 51 Analog Bandwidth: 5002

		Gain 1x		Gain 2x		Gain 4x	
Sample Rate	Channel	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist
20 Hz	Z	8.79 Hz	87.90%	8.79 Hz	87.90%	8.71 Hz	87.10%
	N	8.79 Hz	87.90%	8.79 Hz	87.90%	8.71 Hz	87.10%
	E	8.79 Hz	87.90%	8.79 Hz	87.90%	8.71 Hz	87.10%
80 Hz	Z	35.50 Hz	88.75%	35.50 Hz	88.75%	35.50 Hz	88.75%
	N	35.50 Hz	88.75%	35.50 Hz	88.75%	35.50 Hz	88.75%
	E	35.50 Hz	88.75%	35.50 Hz	88.75%	35.50 Hz	88.75%

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 between 87.1% and 88.75% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, 80 Hz, and 100 Hz. There was no significant different in passband across the gain levels.

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.

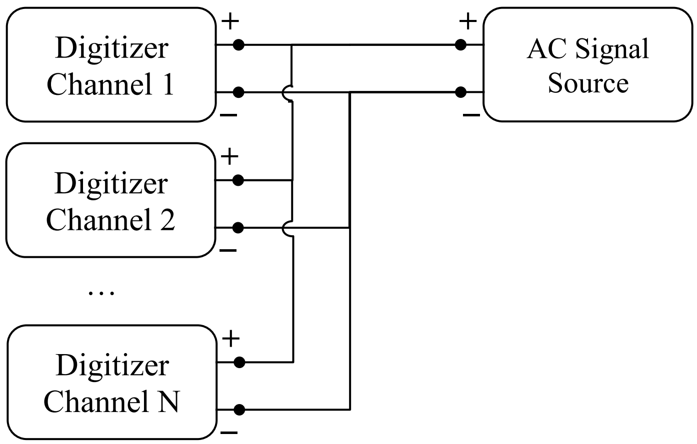

Figure 90 Incoherent Noise Configuration Diagram

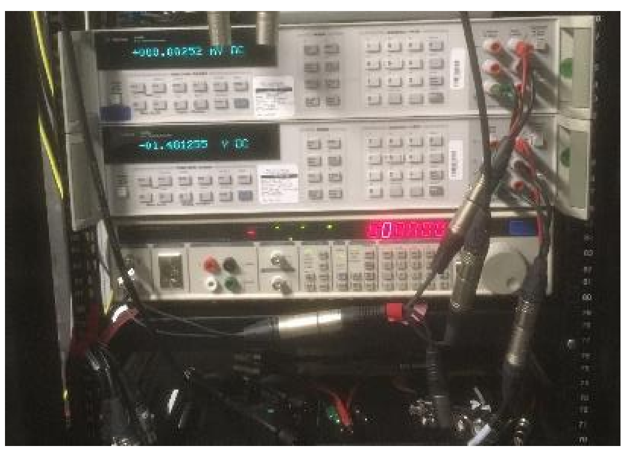

Figure 91 Incoherent Noise Configuration Picture

Table 52 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 bit weight, from the AC Accuracy at 1 Hz, is applied to the collected data:

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

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

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

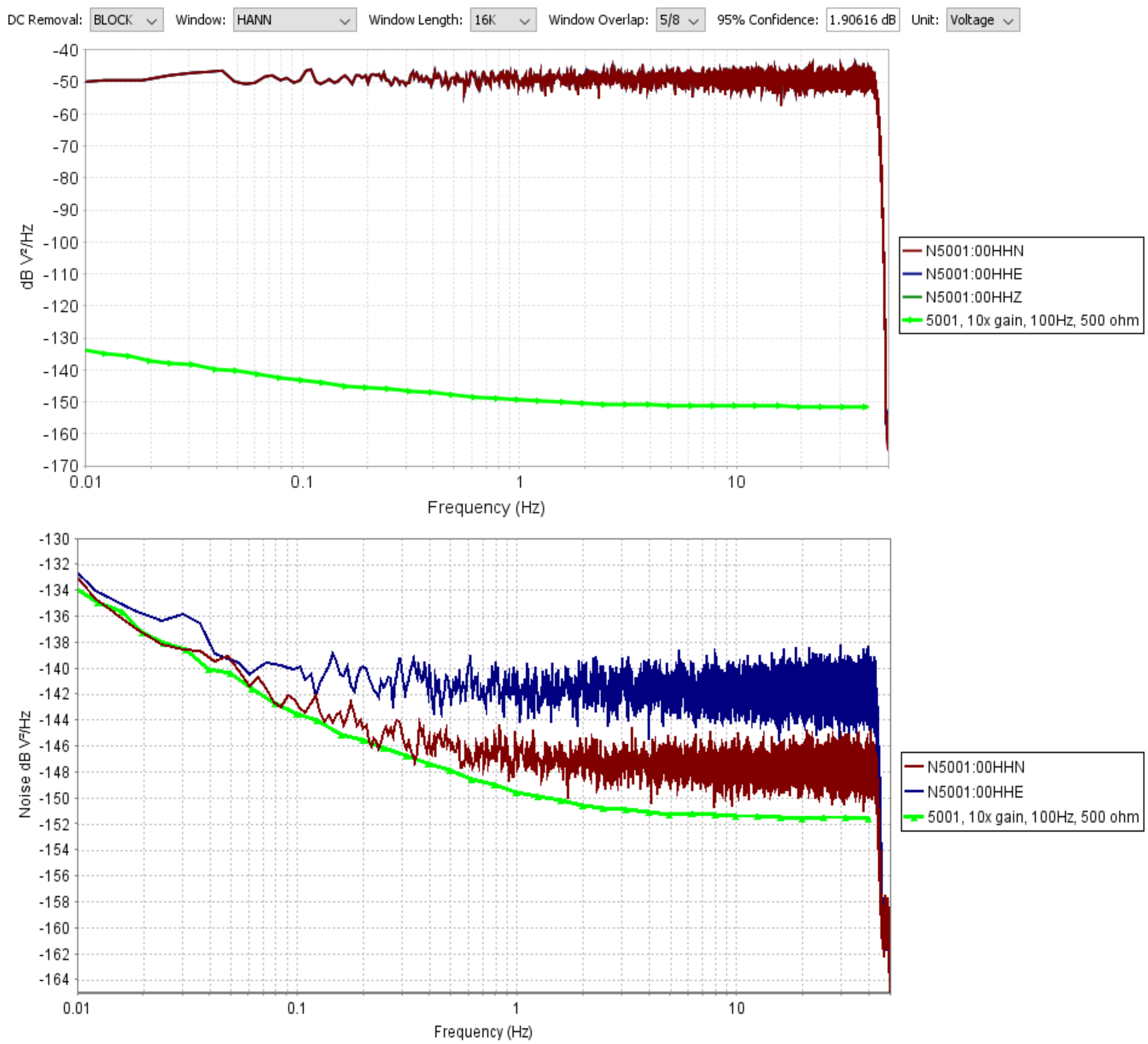

Figure 92 PSD and Incoherent Noise: Centaur 5001, gain 10x, 100 Hz

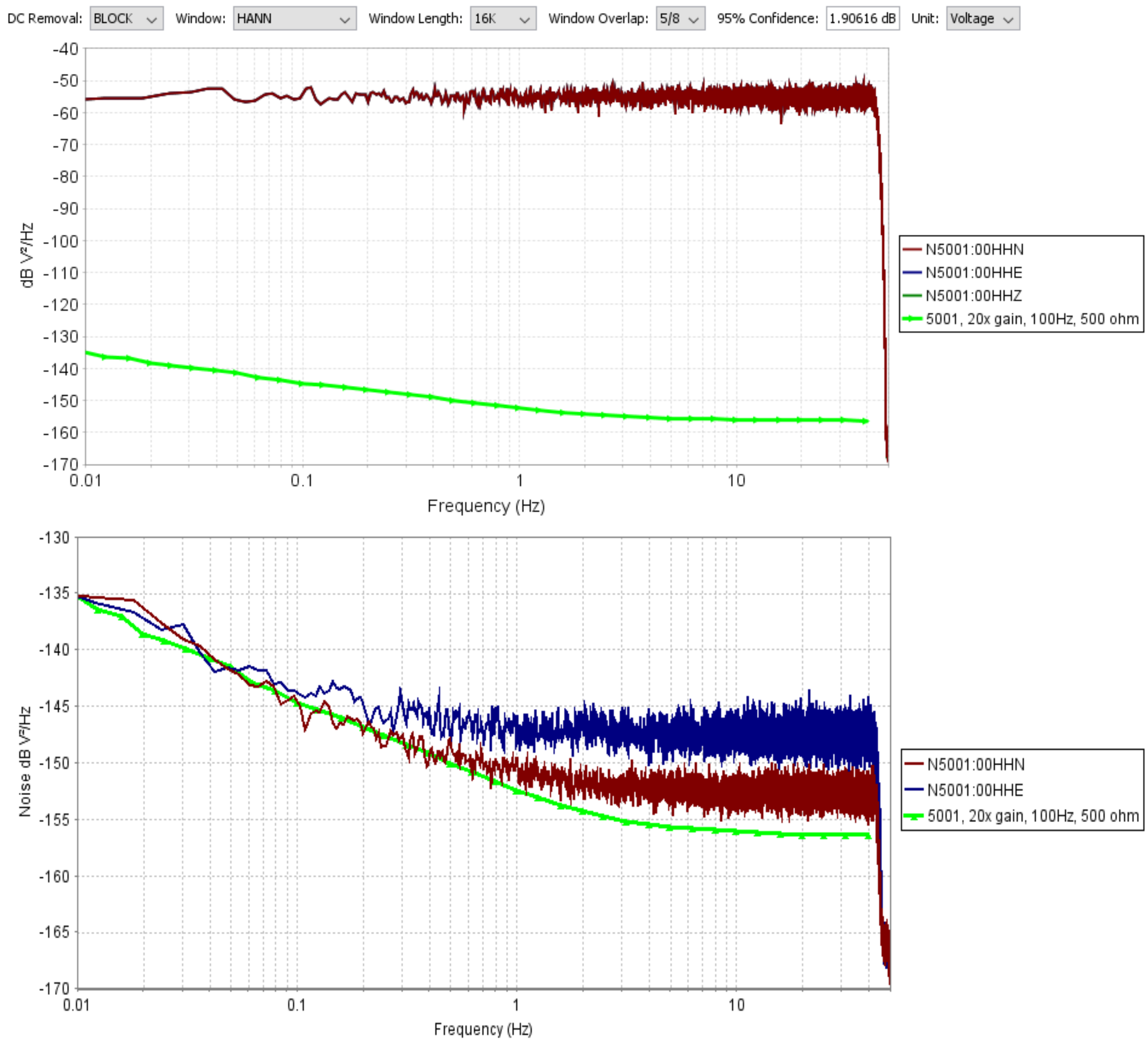

Figure 93 PSD and Incoherent Noise: Centaur 5001, gain 20x, 100 Hz

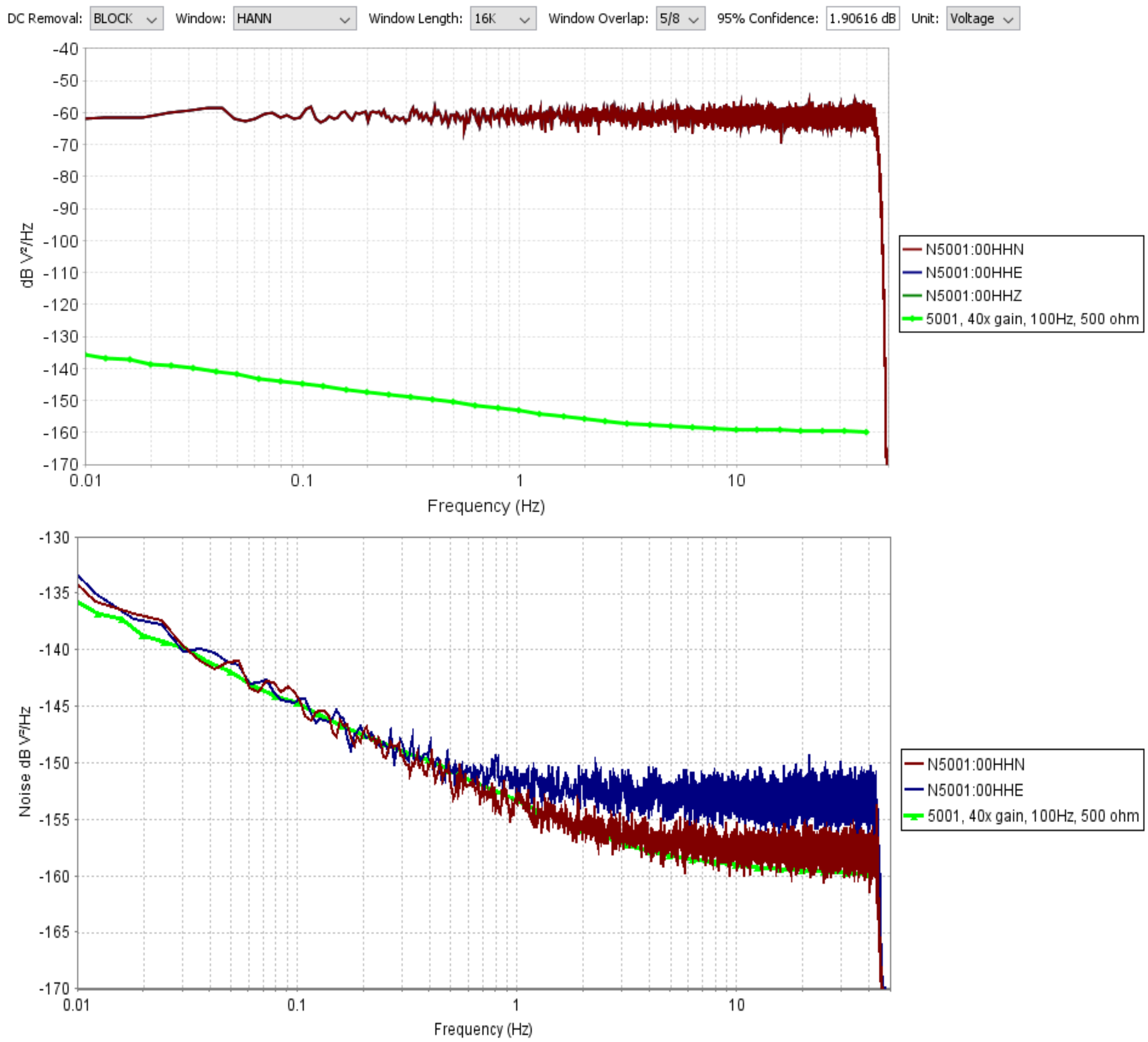

Figure 94 PSD and Incoherent Noise: Centaur 5001, gain 40x, 100 Hz

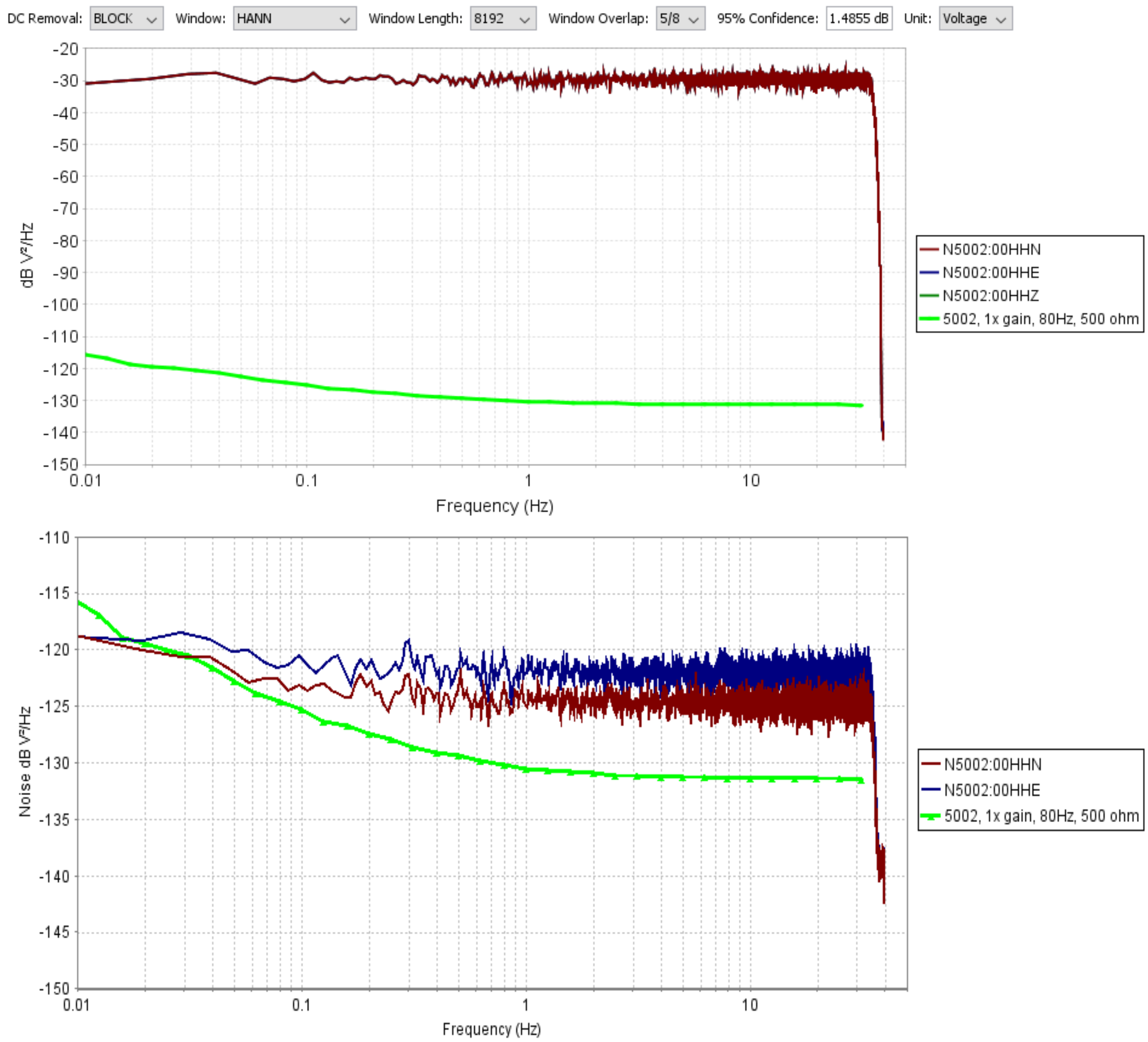

Figure 95 Incoherent Noise: Centaur 5002, gain 1x, 80 Hz

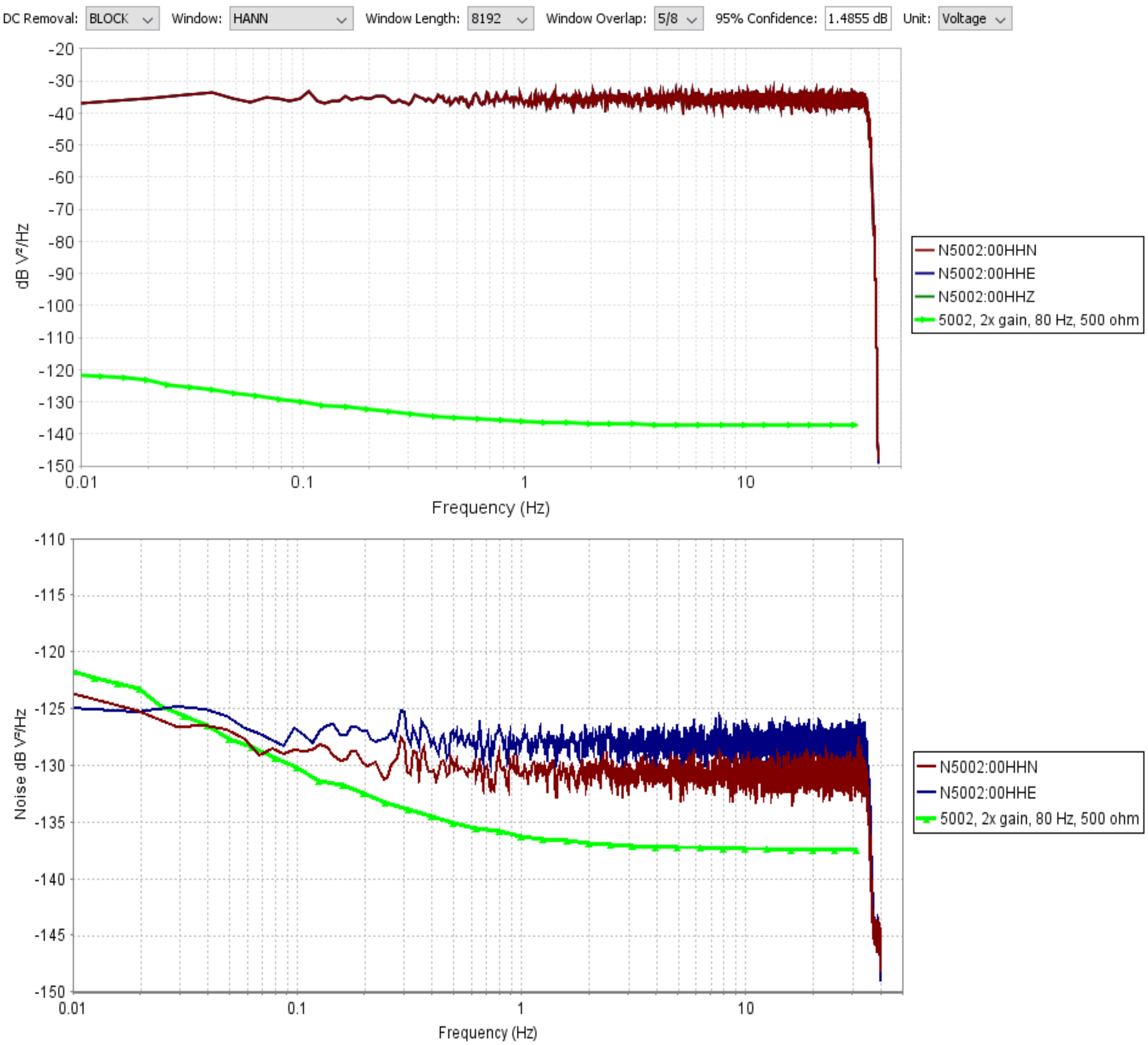

Figure 96 Incoherent Noise: Centaur 5002, gain 2x, 80 Hz

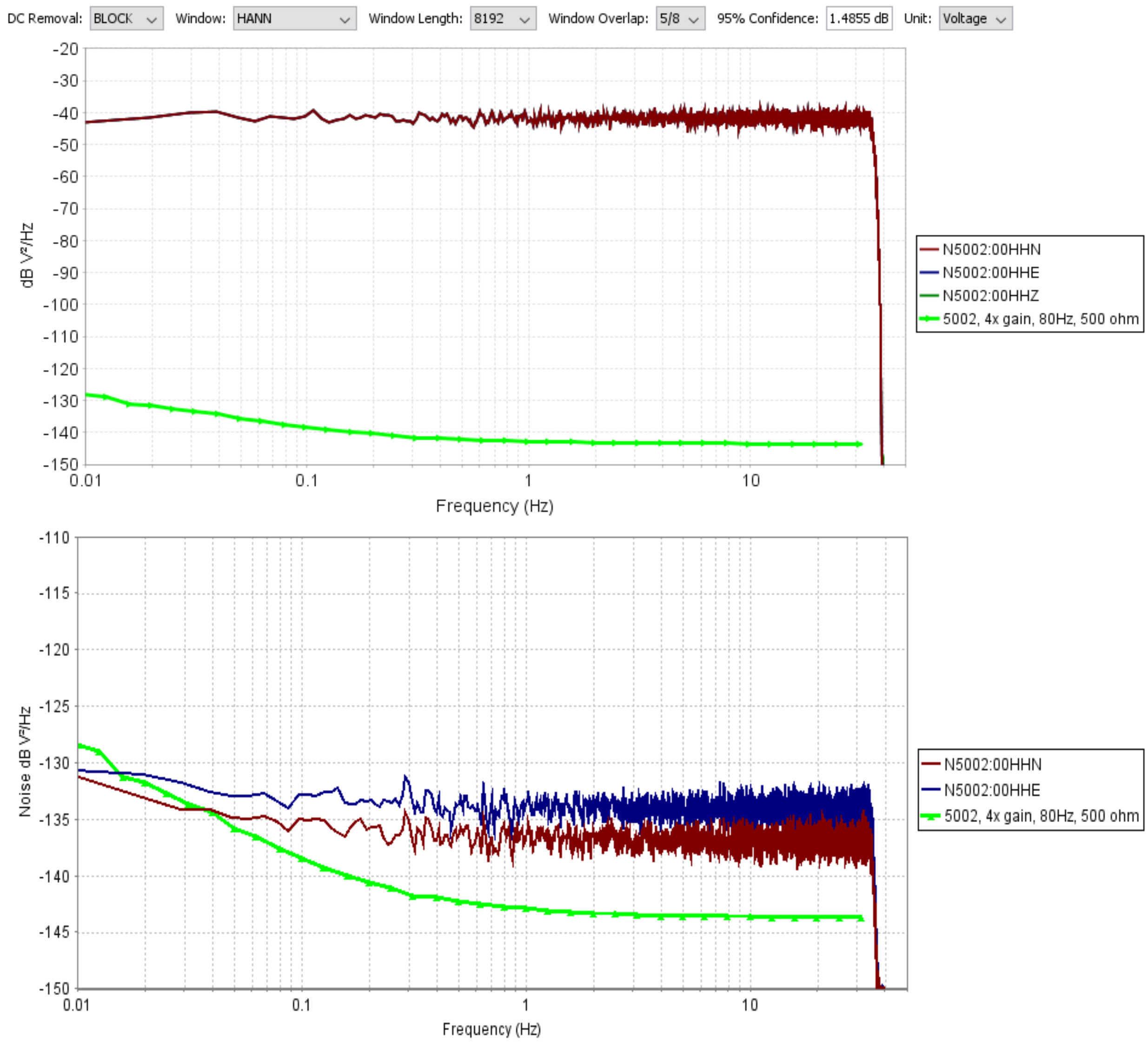

Figure 97 Incoherent Noise: 5002, gain 4x, 80 Hz

In all cases, the incoherence noise present while the digitizer channels were being actively driven by a broadband signal was slightly elevated above the observed self-noise while terminated. The white noise power was approximately 100 dB above the expected terminated self-noise at frequencies above 1 Hz.

It was observed that the incoherent portion of the white noise signal was as much as 10 dB higher than the earlier measurements of terminated self-noise.

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.

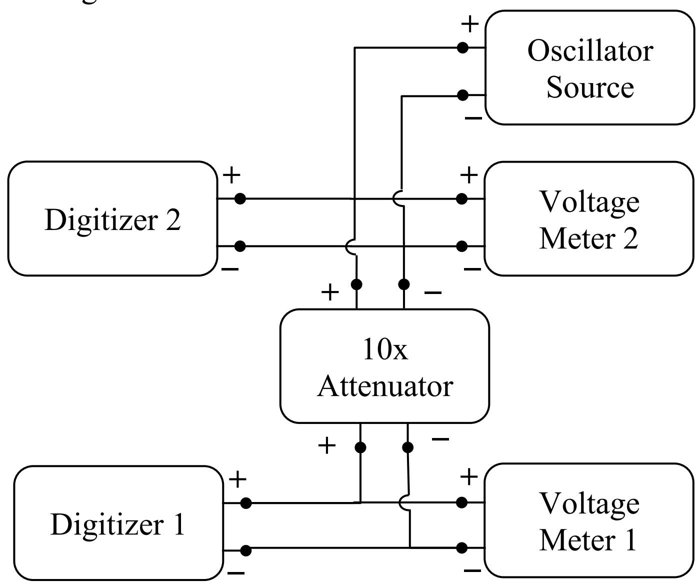

Figure 98 Total Harmonic Distortion Configuration Diagram

Table 53 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Oscillator	Quanterra Supertonal	123669	1.41 Hz, 50% Full Scale
Voltage Meter 1	Agilent 3458A	MY45048371	DC Voltage – for D5001
Voltage Meter 2	Agilent 3458A	MY45048372	DC Voltage – for D5002

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.

A 10x Attenuator and a second voltage meter were used so that the two digitizers being evaluated could be operated at different gain settings simultaneously. THD was measured on D5001 at gains of 10x, 20x, and 40x and on D5002 at gains of 1x, 2x, and 4x.

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:

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

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.

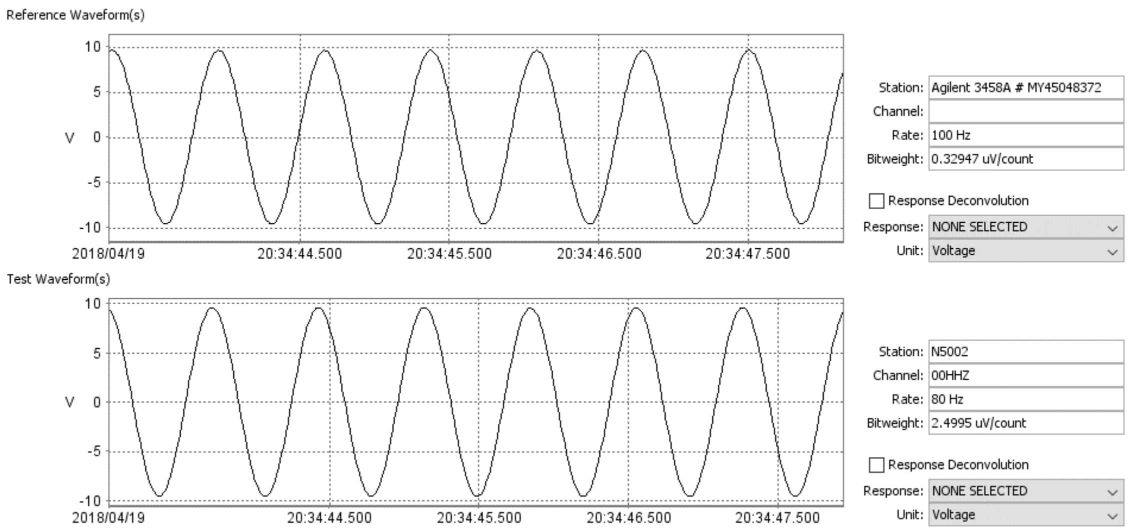

Figure 99 THD Waveform Time Series

The figures below show the THD for the channels evaluated. The two sample rates, 100 Hz and 40 Hz for 5001 and 80 Hz and 20 Hz for 5002, are shown together within each of the plots. Alongside the plots of power spectra are the noise models representing the noise floor of the reference meter in the mode in which it was used shown in green and the output noise floor of the Quanterra Supertonal that was used to generate the sinusoid shown in red.

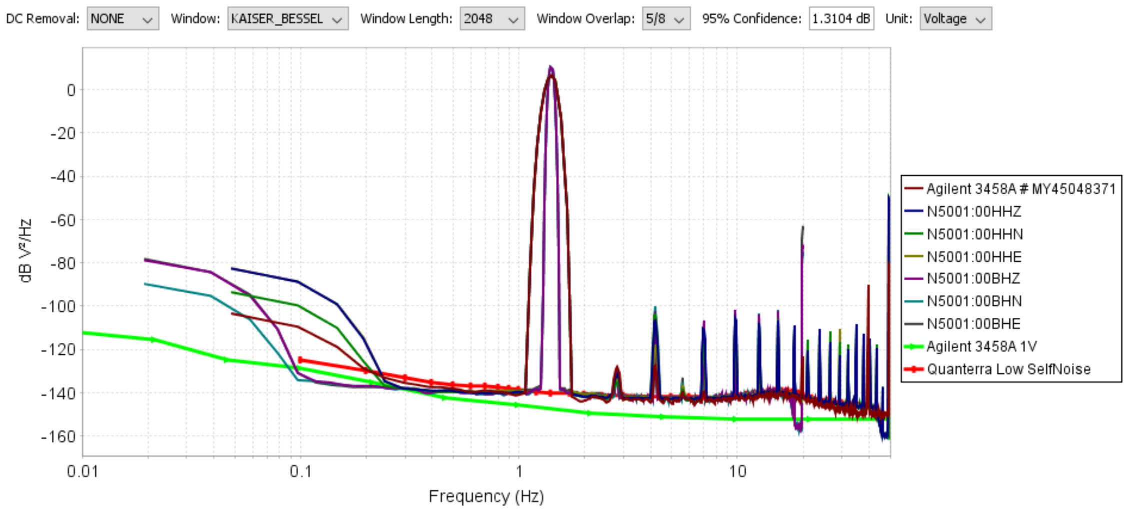

Figure 100 THD Power Spectra, 5001 gain 10x

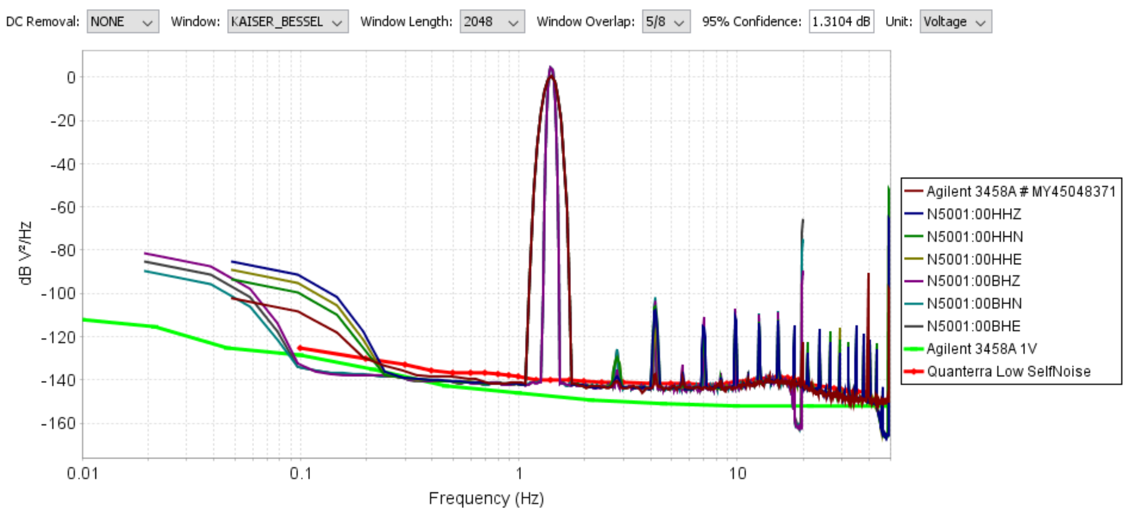

Figure 101 THD Power Spectra, 5001 gain 20x

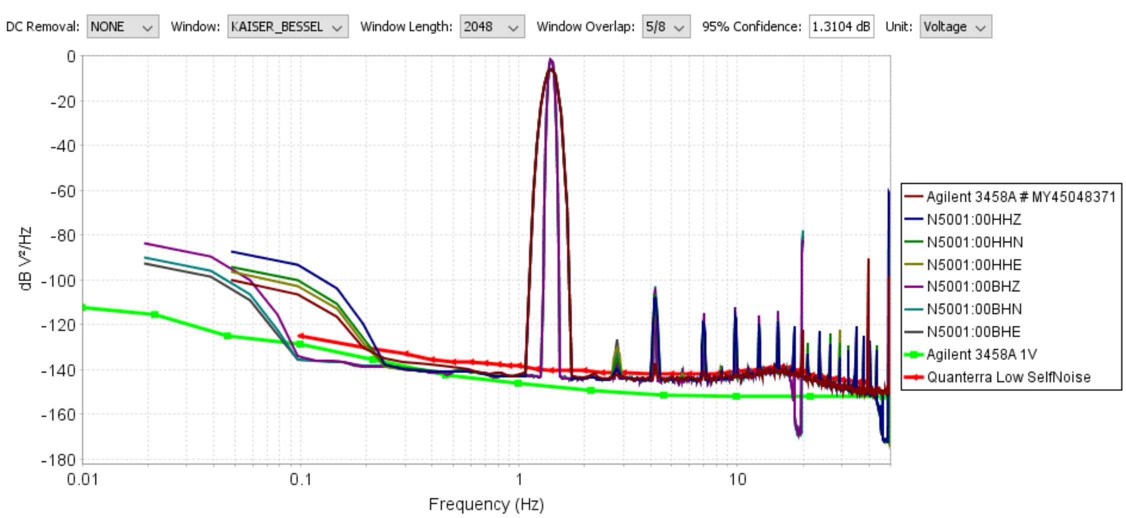

Figure 102 THD Power Spectra, 5001 gain 40x

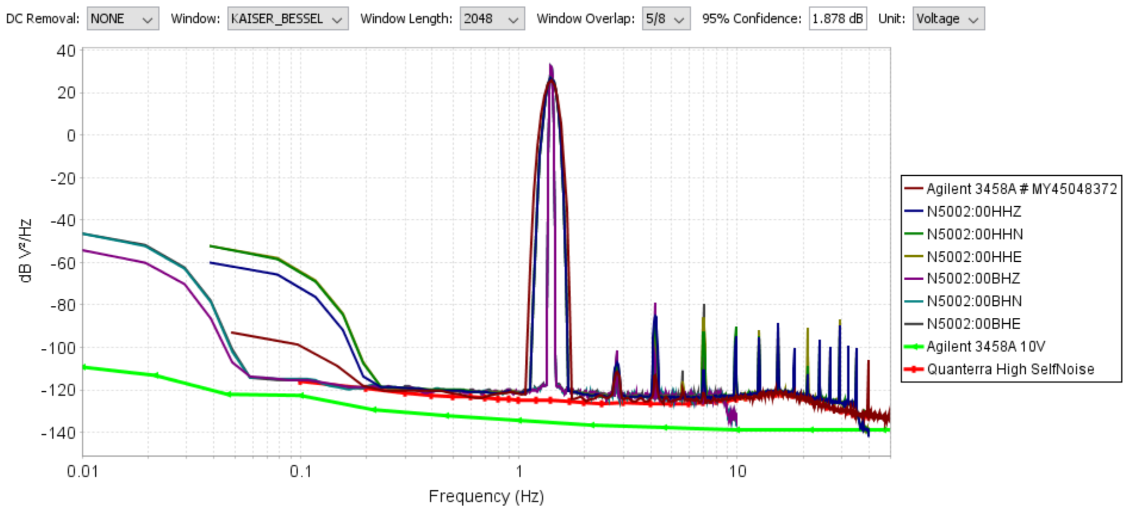

Figure 103 THD Power Spectra, 5002 gain 1x

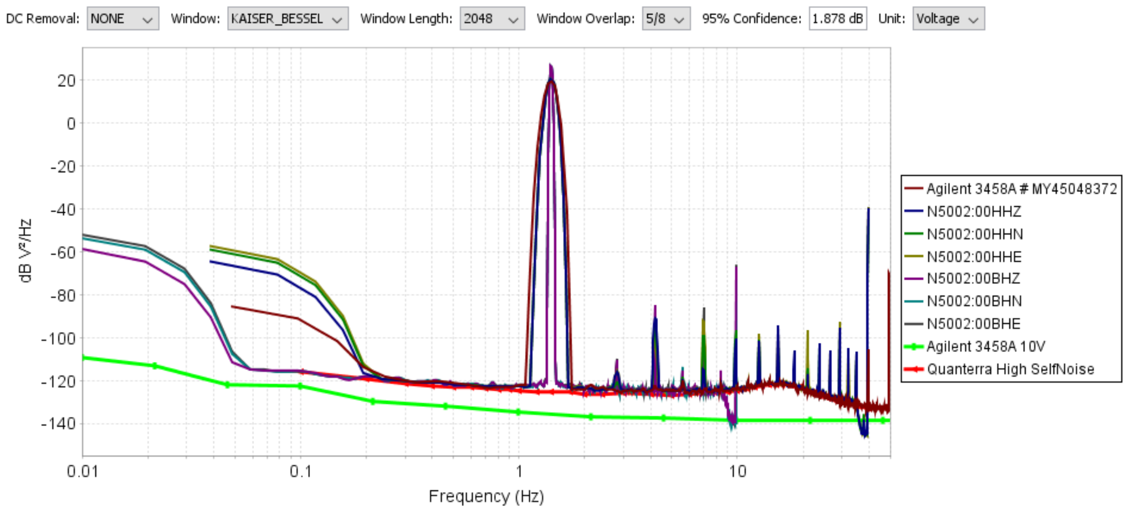

Figure 104 THD Power Spectra, 5002 gain 2x

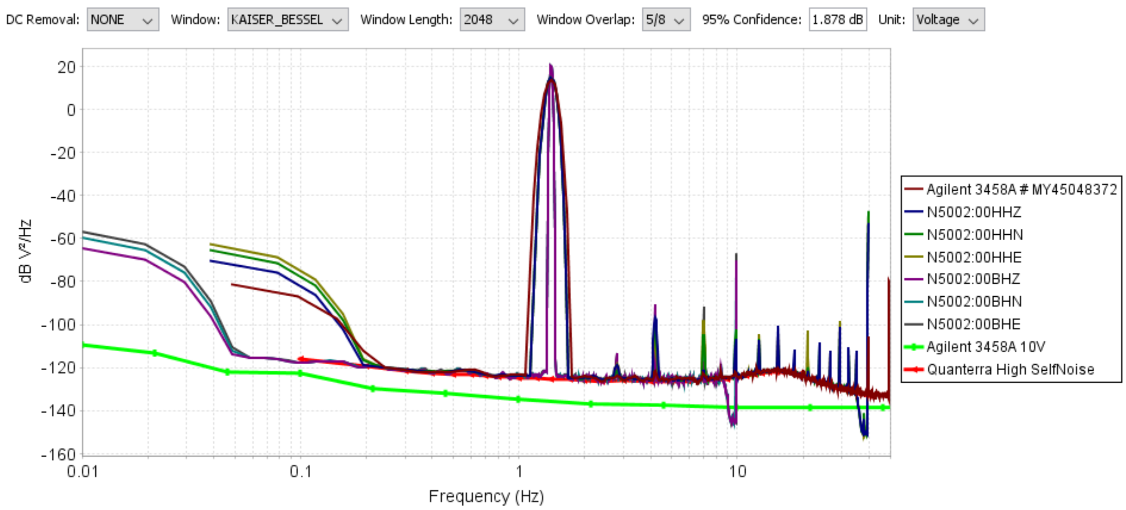

Figure 105 THD Power Spectra, 5002 gain 4x

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

Table 54 Total Harmonic Distortion: Centaur 5001

	Gain 10x	Gain 20x	Gain 40x
Reference	-126.27 dB	-121.46 dB	-115.45 dB
Channel 1 (Z) - 40 Hz	-106.59 dB	-105.77 dB	-101.88 dB
Channel 1 (Z) - 100 Hz	-106.01 dB	-105.77 dB	-101.30 dB
Channel 2 (N) - 40 Hz	-106.49 dB	-105.51 dB	-101.09 dB
Channel 2 (N) - 100 Hz	-105.70 dB	-105.51 dB	-101.07 dB
Channel 3 (E) - 40 Hz	-113.63 dB	-111.68 dB	-104.79 dB
Channel 3 (E) - 100 Hz	-113.44 dB	-111.66 dB	-104.76 dB

Table 55 Total Harmonic Distortion: Centaur 5002

	Gain 1x	Gain 2x	Gain 4x
Reference	-133.10 dB	-130.47 dB	-126.10 dB
Channel 1 (Z) - 20 Hz	-111.77 dB	-111.53 dB	-111.44 dB
Channel 1 (Z) - 80 Hz	-109.26 dB	-111.05 dB	-110.89 dB
Channel 2 (N) - 20 Hz	-114.91 dB	-114.75 dB	-114.62 dB
Channel 2 (N) - 80 Hz	-111.68 dB	-112.68 dB	-112.44 dB
Channel 3 (E) - 20 Hz	-111.75 dB	-112.01 dB	-112.28 dB
Channel 3 (E) - 80 Hz	-109.39 dB	-111.96 dB	-112.13 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 -114.91 dB and -109.26 dB at a gain of 1x, -114.75 dB and -111.05 dB at a gain of 2x, -114.62 dB and -110.89 dB at a gain of 4x, -113.63 and -105.70 dB at a gain of 10x, -111.68 dB and -105.51 dB at a gain of 20x, and -104.79 dB and -101.07 dB at a gain of 40x.

Note that the measured harmonic distortion is lower on the 20 Hz versus 80 Hz sample rate channels. This is simply due to their being fewer harmonic present in the narrower frequency passband.

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.

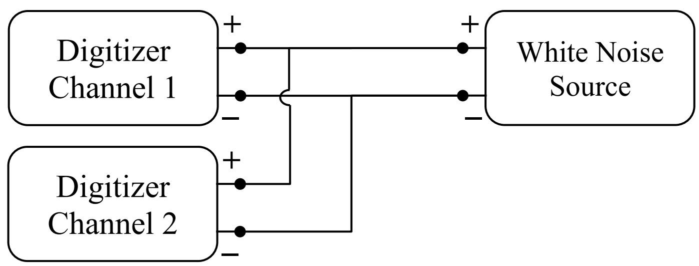

Figure 106 Modified Noise Power Ratio Configuration Diagram

Table 56 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:

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

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 5002 channels Z and N sampled at 100 Hz.

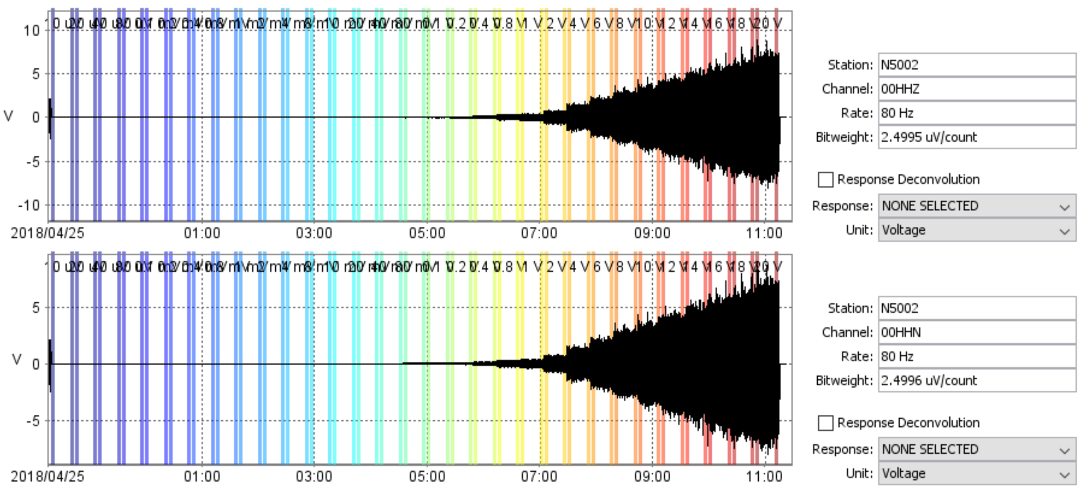

Figure 107 Modified Noise Power Ratio Time Series: Centaur 5002, Z and N, gain 1x

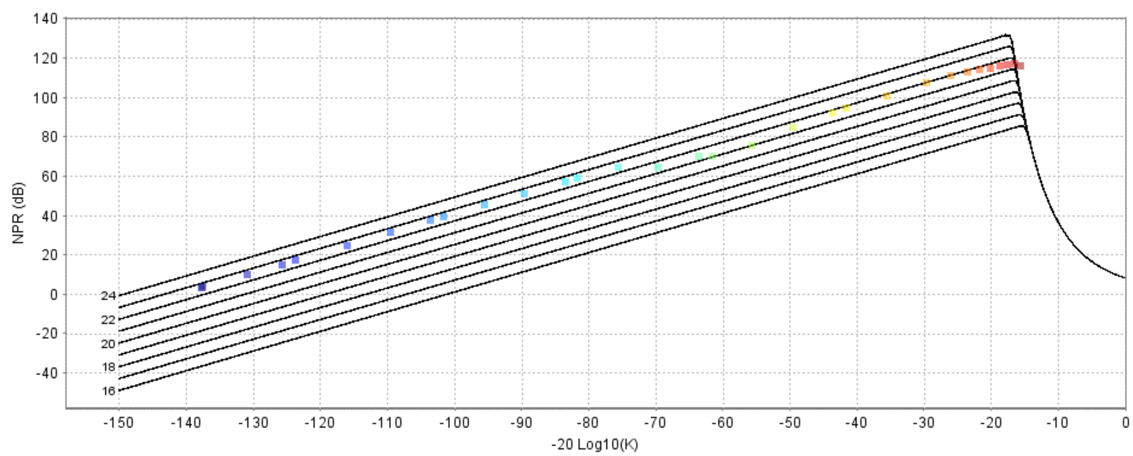

Figure 108 Modified Noise Power Ratio: 5001, Z and N, gain 10x

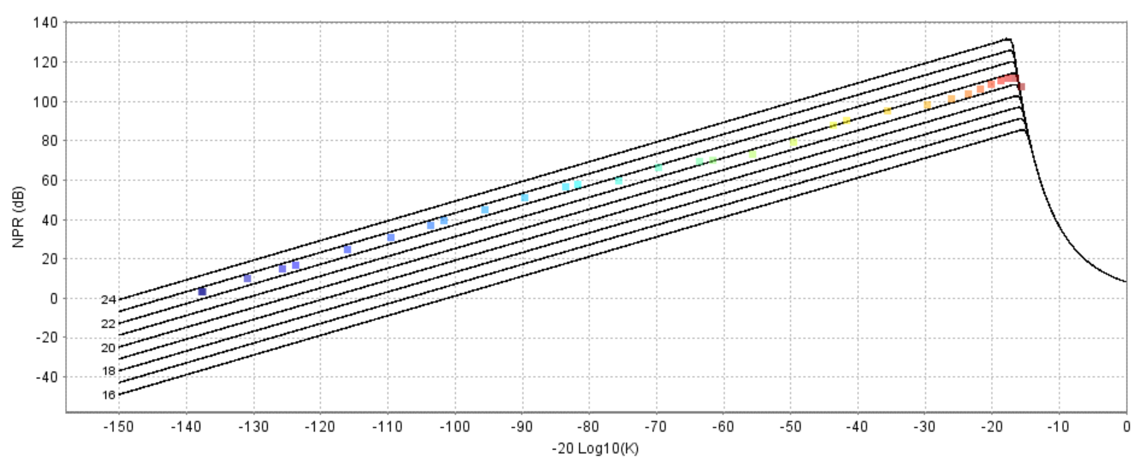

Figure 109 Modified Noise Power Ratio: 5001, Z and E, gain 10x

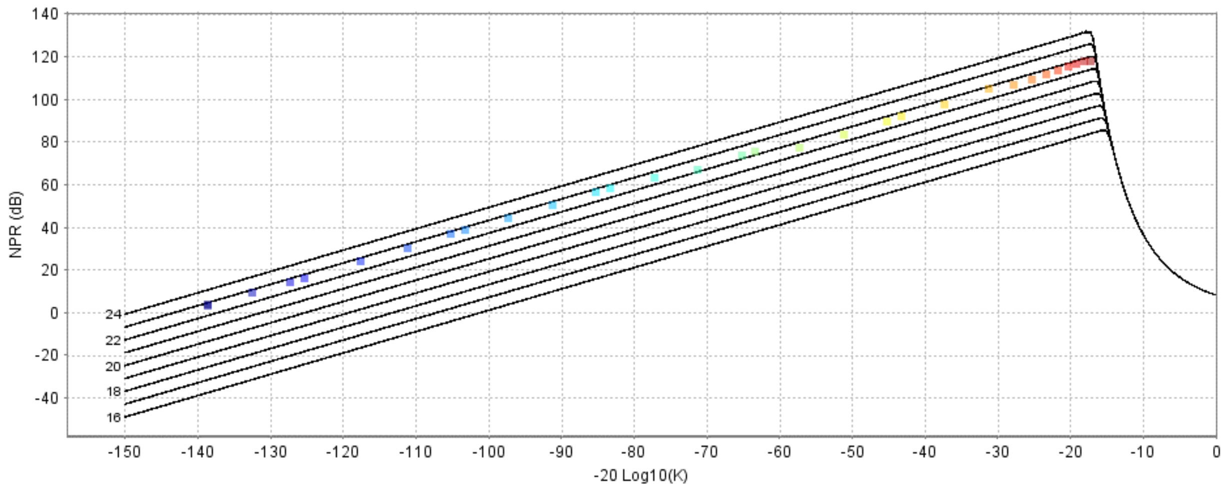

Figure 110 Modified Noise Power Ratio: 5002, Z and N, gain 1x

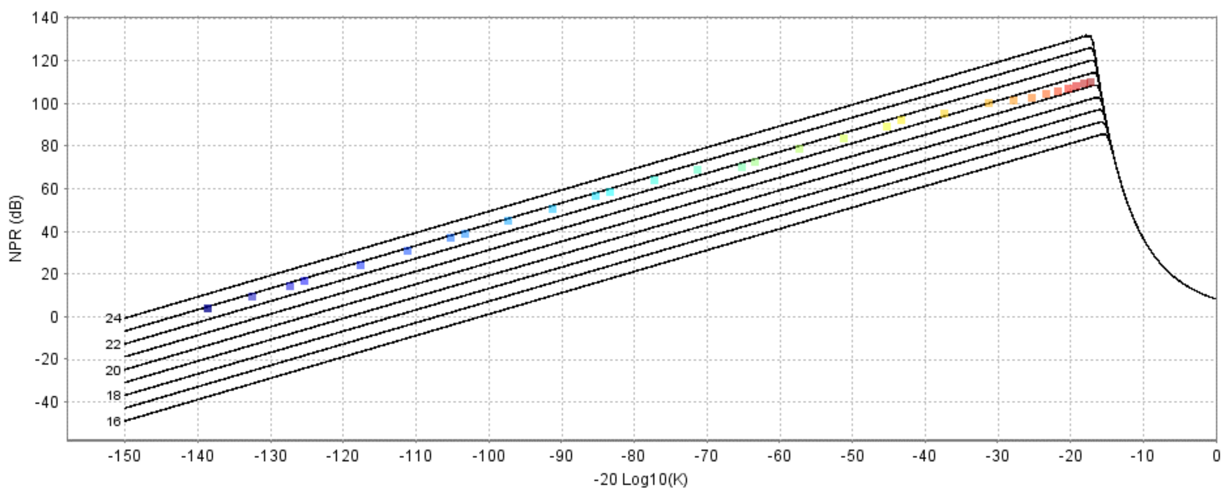

Figure 111 Modified Noise Power Ratio: 5002, Z and E, gain 1x

The Modified Noise Power Ratio results indicate that the two digitizers perform similarly with just under 23 bits of performance at low amplitudes. At higher amplitudes, both digitizers were observed to have a reduction in their linear range where they exhibited between 20.5 and 22 bits of performance.

Table 57 Modified Noise Power Ratio: 5001, gain 10x

RMS Amplitude	-20 log K	NPR: Z - N	NPR: Z - E
0.000000186 V rms	-137.61	3.55 dB	3.37 dB
0.000000184 V rms	-137.69	3.45 dB	3.34 dB
0.000000402 V rms	-130.93	9.91 dB	9.72 dB
0.000000732 V rms	-125.72	15.10 dB	14.89 dB
0.000000918 V rms	-123.75	17.04 dB	16.89 dB
0.000002240 V rms	-116.01	24.80 dB	24.67 dB
0.000004709 V rms	-109.55	31.26 dB	31.11 dB
0.000009404 V rms	-103.54	37.32 dB	37.09 dB
0.00001177 V rms	-101.59	39.28 dB	39.11 dB
0.00002350 V rms	-95.59	45.23 dB	44.99 dB
0.00004696 V rms	-89.58	51.27 dB	50.82 dB
0.00009397 V rms	-83.55	57.25 dB	56.29 dB
0.0001173 V rms	-81.63	59.18 dB	57.49 dB
0.0002349 V rms	-75.59	64.27 dB	59.91 dB
0.0004679 V rms	-69.61	64.60 dB	66.33 dB
0.0009365 V rms	-63.58	69.83 dB	69.60 dB
0.001168 V rms	-61.66	70.18 dB	69.84 dB
0.002337 V rms	-55.64	75.44 dB	72.90 dB
0.004681 V rms	-49.60	84.52 dB	79.25 dB
0.009350 V rms	-43.59	92.28 dB	87.89 dB
0.01170 V rms	-41.65	94.32 dB	90.54 dB
0.02341 V rms	-35.62	100.85 dB	95.41 dB
0.04682 V rms	-29.60	107.43 dB	98.33 dB
0.07015 V rms	-26.09	110.81 dB	101.08 dB
0.09353 V rms	-23.59	112.84 dB	103.76 dB
0.1169 V rms	-21.66	114.02 dB	106.45 dB
0.1403 V rms	-20.07	114.97 dB	108.83 dB
0.1639 V rms	-18.72	115.91 dB	110.73 dB
0.1870 V rms	-17.57	116.73 dB	112.00 dB
0.2107 V rms	-16.54	117.25 dB	111.83 dB
0.2336 V rms	-15.64	116.04 dB	107.44 dB

Table 58 Modified Noise Power Ratio: 5002, gain 1x

RMS Amplitude	-20 log K	NPR: Z - N	NPR: Z - E
0.000001653 V rms	-138.64	3.59 dB	3.66 dB
0.000001654 V rms	-138.64	3.54 dB	3.67 dB
0.000003378 V rms	-132.44	9.41 dB	9.46 dB
0.000006074 V rms	-127.34	14.46 dB	14.55 dB
0.000007626 V rms	-125.36	16.37 dB	16.50 dB
0.00001848 V rms	-117.68	23.90 dB	24.03 dB
0.00003881 V rms	-111.23	30.44 dB	30.59 dB
0.00007749 V rms	-105.23	36.64 dB	36.66 dB
0.00009698 V rms	-103.28	38.59 dB	38.63 dB
0.0001937 V rms	-97.27	44.58 dB	44.63 dB
0.0003870 V rms	-91.26	50.64 dB	50.63 dB
0.0007746 V rms	-85.23	56.71 dB	56.74 dB
0.0009664 V rms	-83.31	58.58 dB	58.45 dB
0.001936 V rms	-77.27	63.41 dB	63.73 dB
0.003864 V rms	-71.27	66.80 dB	68.95 dB
0.007733 V rms	-65.24	73.47 dB	70.21 dB
0.009654 V rms	-63.32	75.45 dB	72.20 dB
0.01931 V rms	-57.29	77.32 dB	78.31 dB
0.03867 V rms	-51.26	83.26 dB	83.41 dB
0.07723 V rms	-45.26	89.94 dB	89.09 dB
0.09662 V rms	-43.31	92.27 dB	91.83 dB
0.1934 V rms	-37.28	97.82 dB	95.17 dB
0.3868 V rms	-31.26	104.80 dB	99.87 dB
0.5797 V rms	-27.75	106.96 dB	101.21 dB
0.7726 V rms	-25.25	109.02 dB	102.67 dB
0.9655 V rms	-23.32	111.41 dB	104.23 dB
1.159 V rms	-21.73	113.46 dB	105.60 dB
1.354 V rms	-20.38	115.21 dB	106.93 dB
1.544 V rms	-19.24	116.59 dB	108.18 dB
1.740 V rms	-18.20	117.63 dB	109.42 dB
1.931 V rms	-17.30	117.79 dB	109.97 dB

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.

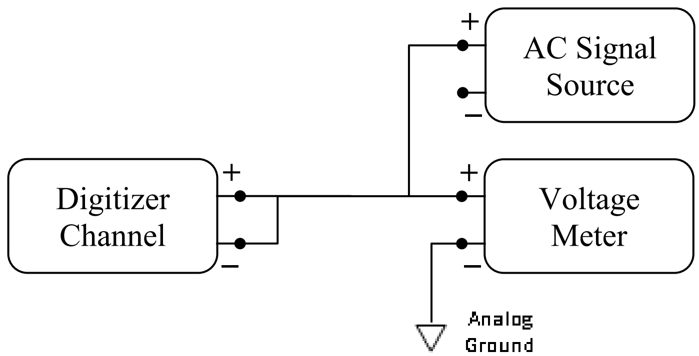

Figure 112 Common Mode Rejection Configuration Diagram

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 59 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:

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

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

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

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

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

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.

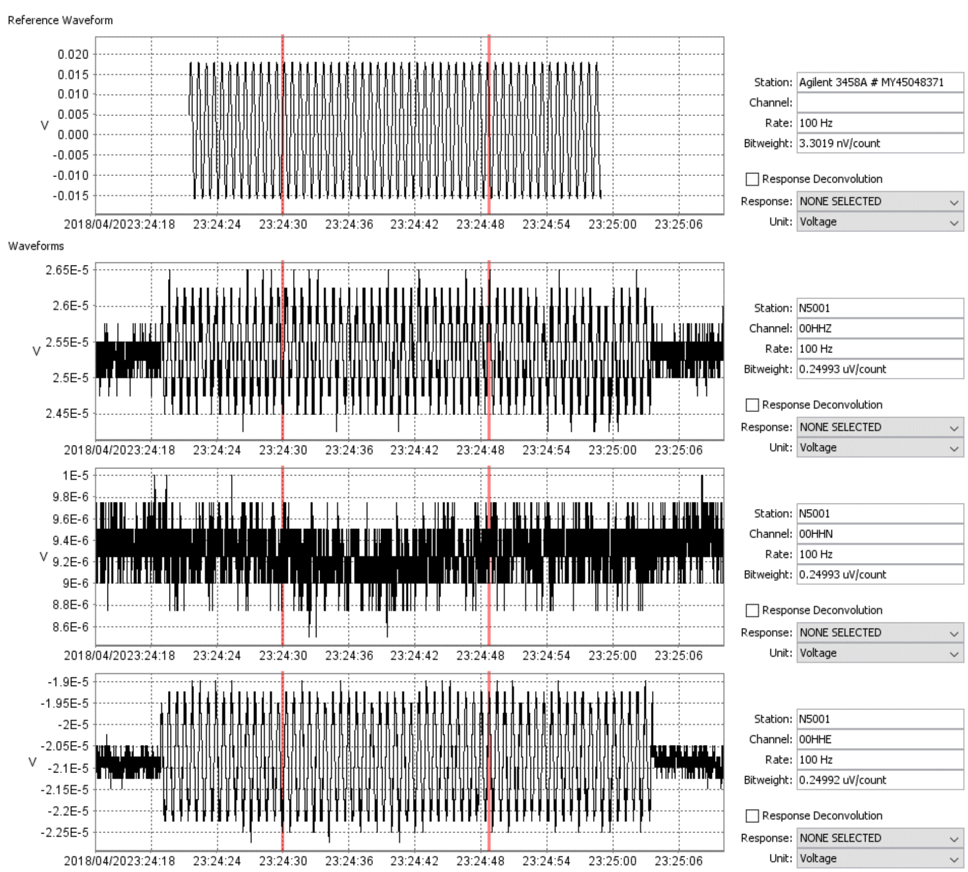

Figure 113 Common Mode Rejection Time Series, 5001 gain 10

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

Table 60 Common Mode Rejection: 5001

	Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Signal Amplitude	0.1680 V	83.98 mV	41.94 mV	16.78 mV	8.396 mV	4.193 mV
Z - 40 Hz	69.36 dB	79.12 dB	80.09 dB	88.15 dB	94.57 dB	95.58 dB*
N - 40 Hz	73.60 dB	99.66 dB*	93.17 dB	108.02 dB*	110.59 dB*	105.51 dB*
E - 40 Hz	76.48 dB	76.13 dB	73.76 dB	82.07 dB	88.29 dB	100.59 dB*
Z - 100 Hz	69.35 dB	79.11 dB	80.10 dB	88.21 dB	94.34 dB	95.62 dB*
N - 100 Hz	73.59 dB	99.60 dB*	93.25 dB	107.89 dB*	109.66 dB*	105.78 dB*
E - 100 Hz	76.51 dB	76.14 dB	73.77 dB	82.04 dB	88.29 dB	100.79 dB*

*Observed Common Mode noise amplitude was very low, on the order of the channel self-noise, making an estimate of amplitude problematic.

Table 61 Common Mode Rejection: 5002

	Gain 1x	Gain 2x	Gain 4x	Gain 10x	Gain 20x	Gain 40x
Signal Amplitude	0.1680 V	83.98 mV	41.94 mV	16.78 mV	8.396 mV	4.193 mV
Z - 20 Hz	80.09 dB	77.89 dB	85.13 dB	87.26 dB	87.86 dB	88.11 dB
N - 20 Hz	75.81 dB	80.37 dB	85.60 dB	91.82 dB	96.08 dB	97.80 dB*
E - 20 Hz	93.04 dB	100.58 dB*	83.66 dB	89.33 dB	92.53 dB	95.63 dB*
Z - 80 Hz	80.14 dB	77.88 dB	85.11 dB	87.19 dB	87.76 dB	88.04 dB
N - 80 Hz	75.78 dB	80.38 dB	85.58 dB	91.79 dB	95.82 dB	97.72 dB*
E - 80 Hz	93.03 dB	100.51 dB*	83.67 dB	89.27 dB	92.64 dB	95.59 dB*

*Observed Common Mode noise amplitude was very low, on the order of the channel self-noise, making an estimate of amplitude problematic.

The observed common mode rejection was typically between 80 and 90 dB.

An earlier test of Common Mode noise had been performed at an amplitude of 10% of input channel full-scale, which would correspond to a peak amplitude of 2 V at a gain of 1x. This test demonstrated similar levels of amplitude rejection of the common mode signals. However, at this amplitude level, there was some observed distortion that would present itself as harmonics of the common mode signal. The amplitude at which the test results above were reported was at 0.84 % of full scale.

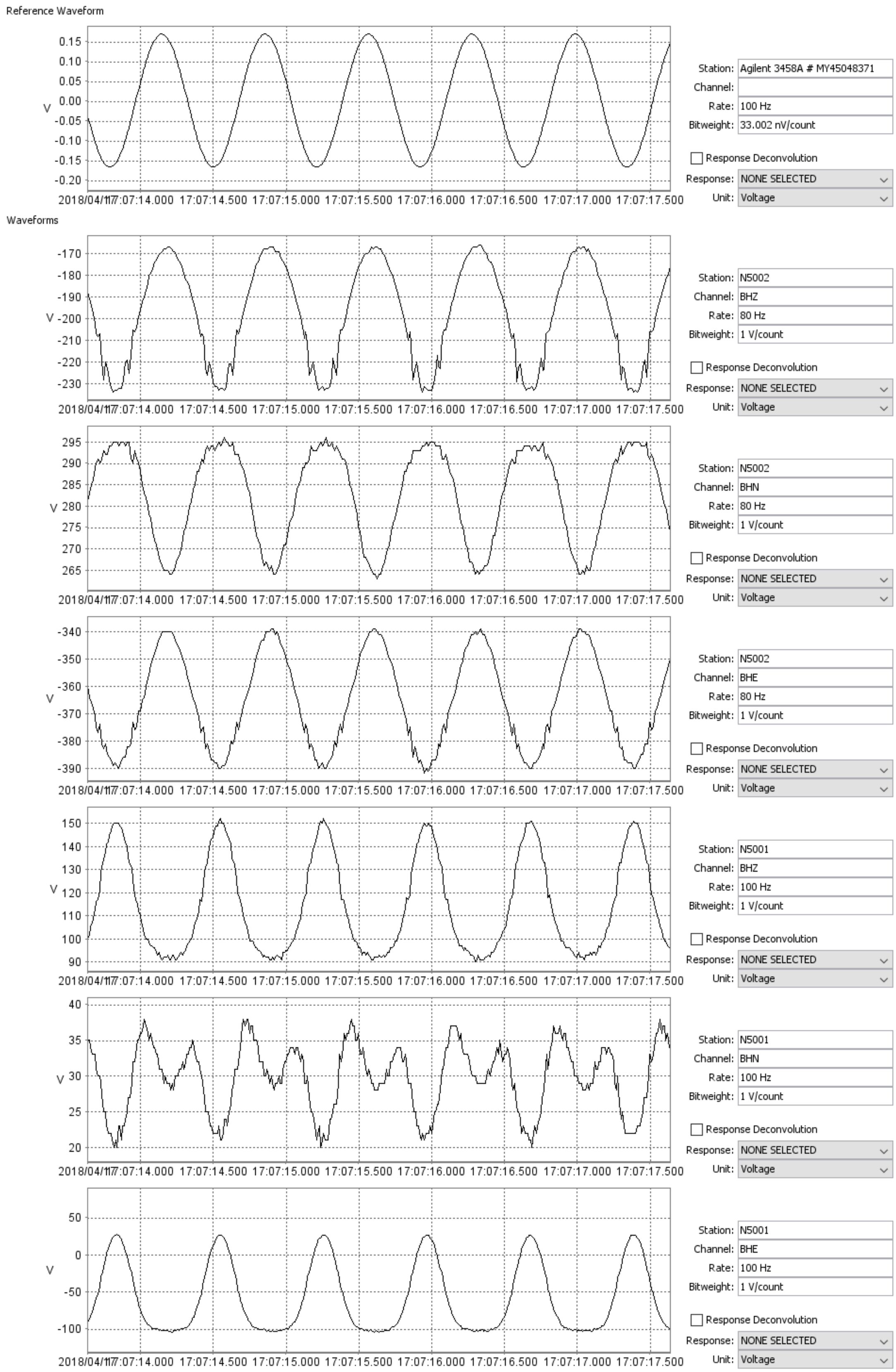

Figure 114 Common Mode Distortion observed at 10% Full Scale, Gain 10x

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.

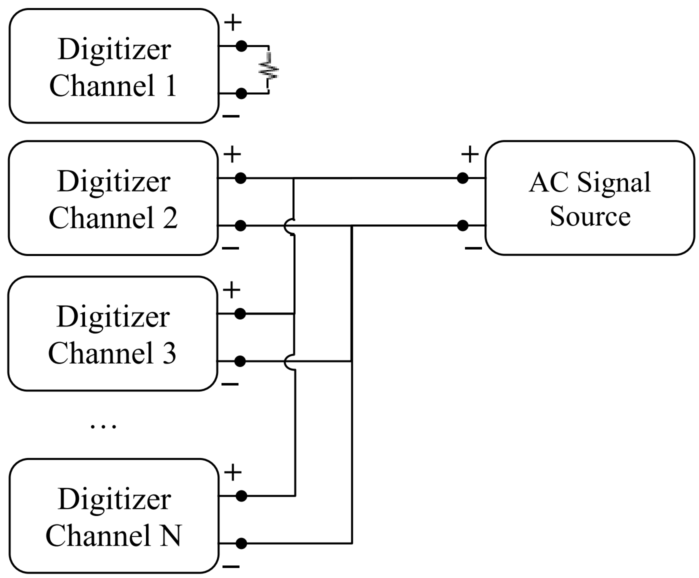

Figure 115 Crosstalk Configuration Diagram

Table 62 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:

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

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

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

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

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

3.19.4 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.

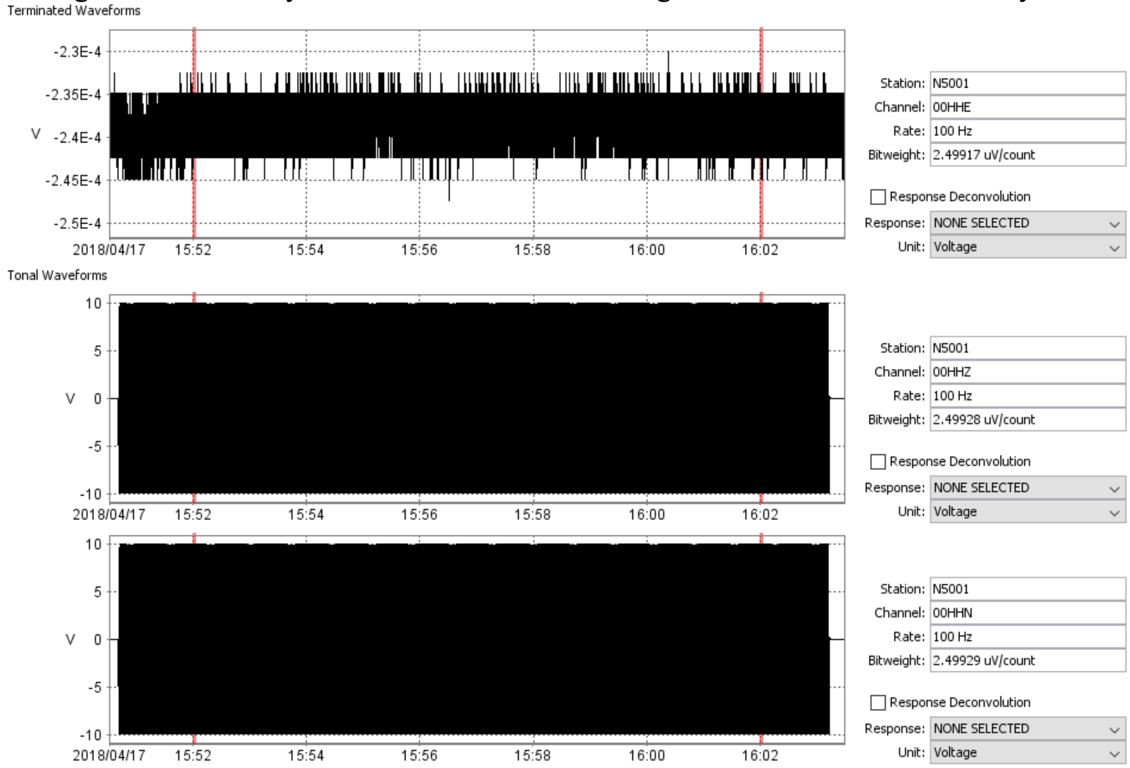

Figure 116 Crosstalk Representative Waveform Time Series

The figures below show representative power spectra of the terminated and tonal channels at a gain of 1x.

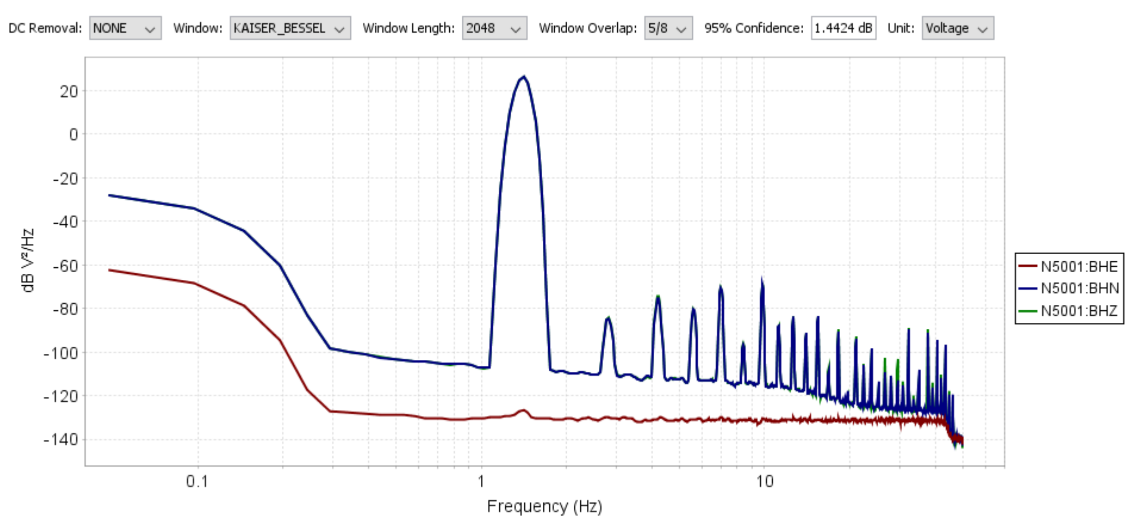

Figure 117 Crosstalk Power Spectra, 5001, 100 Hz, gain 1x, E Terminated

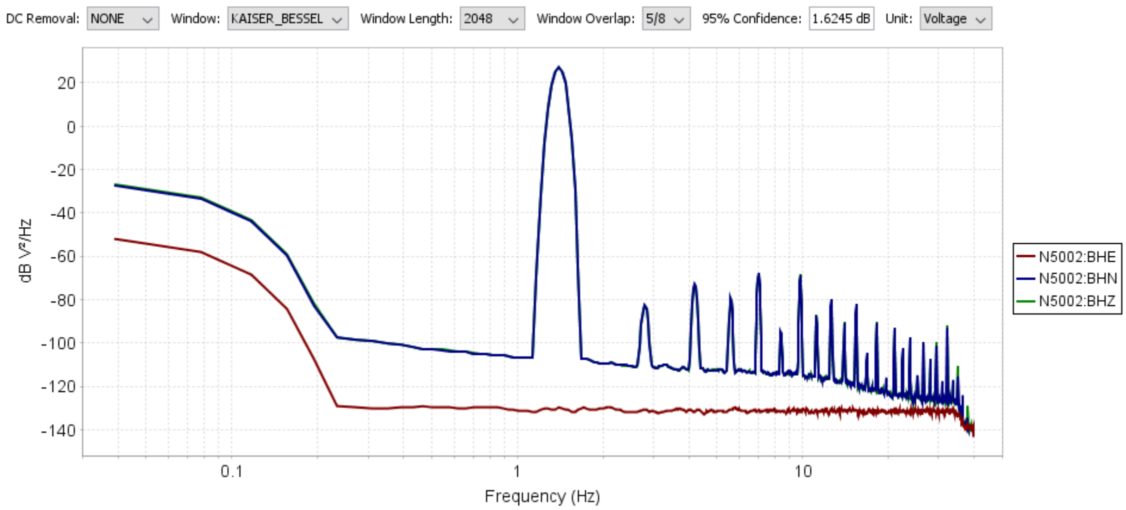

Figure 118 Crosstalk Power Spectra, 5002, 100 Hz, gain 1x, E Terminated

Table 63 Crosstalk, gain of 1x

			Terminated Channel		
	Gain	Sample Rate	Z	N	E
5001	1x	40 Hz	-158.59 dB	-159.37 dB	-152.60 dB
		100 Hz	-157.66 dB	-157.61 dB	-152.50 dB
5002	1x	20 Hz	-156.60 dB	-156.77 dB	-157.13 dB
		80 Hz	-158.71 dB	-158.89 dB	-155.80 dB

The computed levels of crosstalk were all between -159.37 and -152.5 dB. Crosstalk levels were very consistent between the sample rates, which is to be expected as crosstalk is primarily affected by the physical circuitry layout. The slight difference between the sample rates is due to the difference in frequency resolution in the estimates of power spectra.

Note that the only channel that had any observable crosstalk was on digitizer 5001, channel E. The remaining channels 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.

3.20 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 timing source, either GPS or PTP.

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.

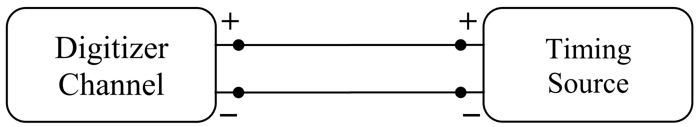

Figure 119 Time Tag Accuracy Configuration Diagram

Table 64 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/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.

Digitizer 5001 was configured to be time synchronized with the GPS rebroadcaster operating. Digitizer 5002 was configured to be time synchronized with a PTP clock on the local network.

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.

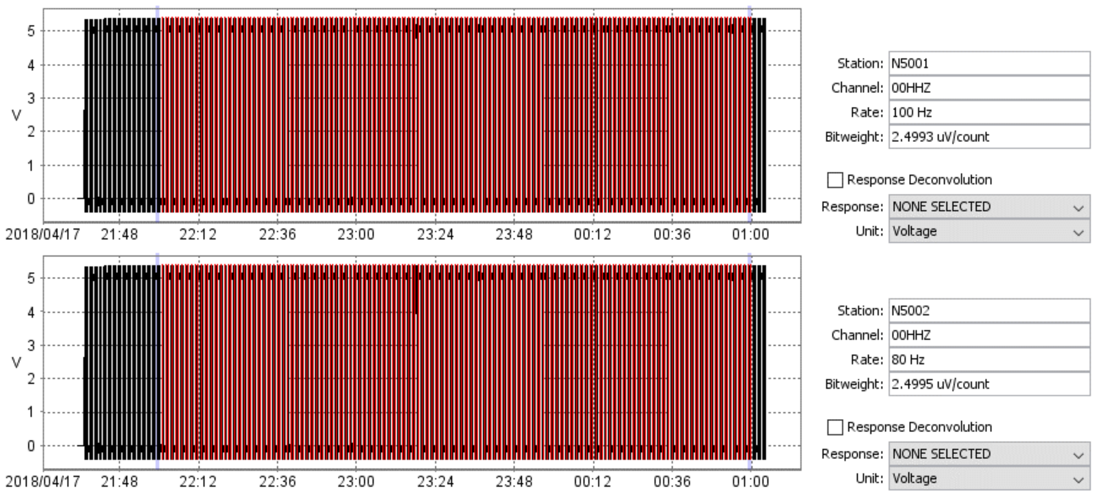

Figure 120 Time Tag Accuracy PPM Time Series

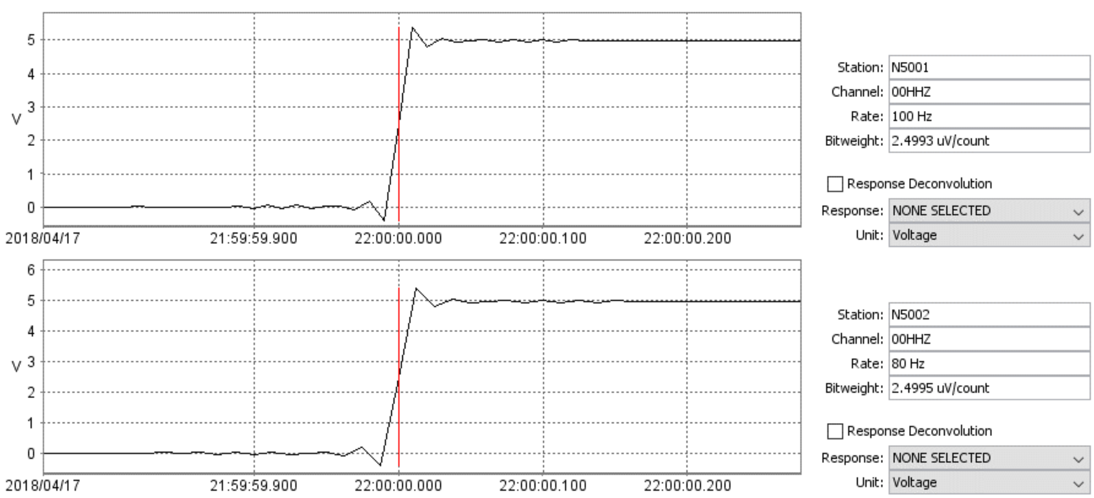

Figure 121 Time Tag Accuracy PPM Timing Pulse

The following table contains the computed timing accuracy results:

Table 65 Time Tag Accuracy

Digitizer	Configuration	Mean	Std
5002	3 hrs, PTP	36.73 us	13.09 us
5001	3 hrs, GPS	34.67 us	1.123 us
5001	1 hr, GPS, firmware 4.3.15 upgraded	2.384 us	0 us
5001	15 min, GPS, firmware 4.3.14 restored	31.50 us	0.1388 us

A distribution plot of the time tag accuracy results for both GPS and PTP are shown below.

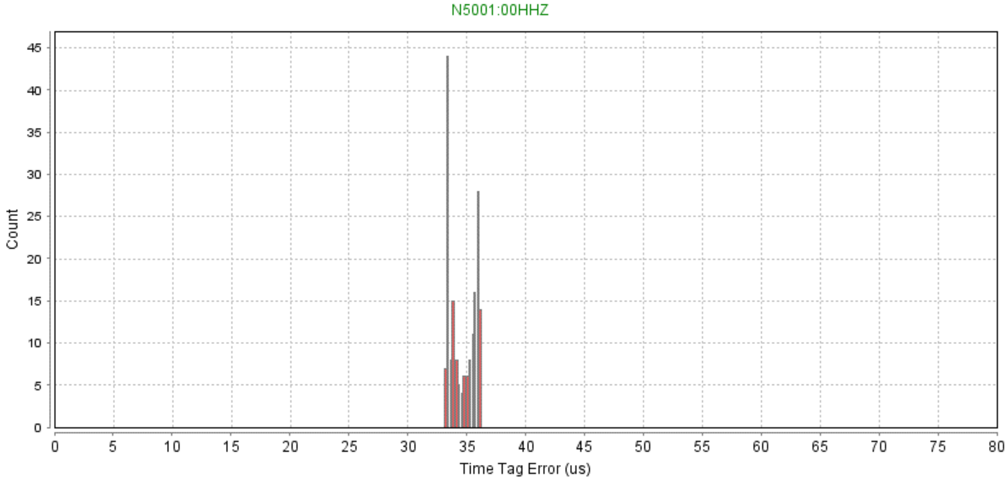

Figure 122 Time Tag Accuracy Histogram: 5001, GPS

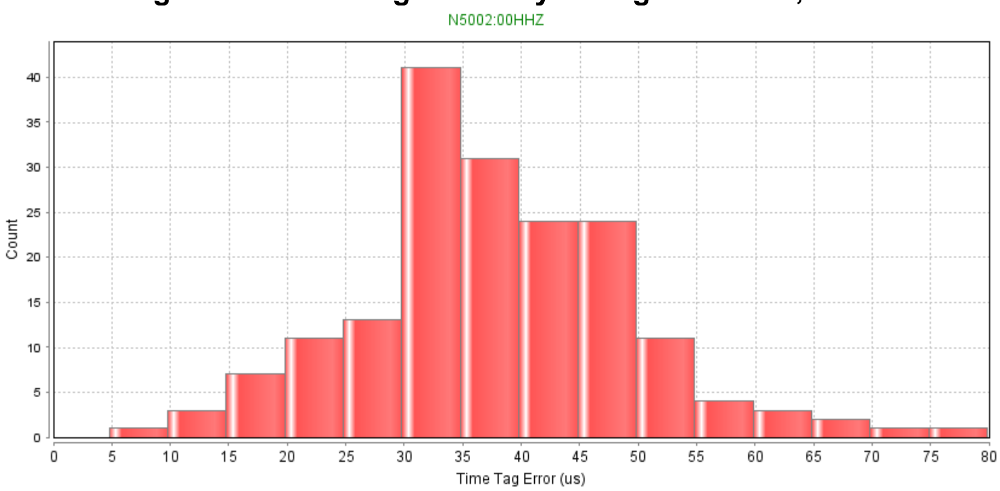

Figure 123 Time Tag Accuracy Histogram: 5002, PTP

As may be seen, the GPS time synchronized digitizer, 5001, had a tight tolerance in its timing results, with a mean value of 36.73 us. The PTP time synchronized digitizer, 5002, had a much broader variation in results, with a mean time accuracy of 34.67 us.

Nanometrics determined that there was a timing error in their firmware and provided SNL with an updated firmware revision, 4.3.15, that SNL used to perform retesting of GPS timing accuracy. The updated firmware improved the time accuracy to better than 2.5 us. PTP results with the revised firmware were not evaluated. Immediately after testing, the original firmware, 4.3.14, was restored to reconfirm the original results.

Note that the Centaur 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 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.

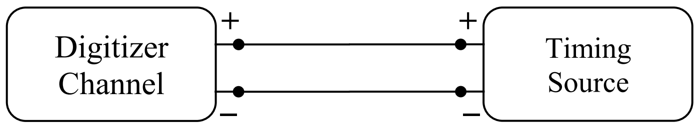

Figure 124 GPS & PTP Timing Drift Configuration Diagram

Table 66 GPS & PTP 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
Digitizer Timing Lock	PTP Masterclock	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 the GPS antenna is uncovered and allowed to regain its timing lock.

In order for the digitizer GPS to lose reception, it was necessary to wrap the GPS antennas in metal foil. In the case of the digitizer locked to the PTP Masterclock, the GPS antenna of the PTP server was covered.

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.

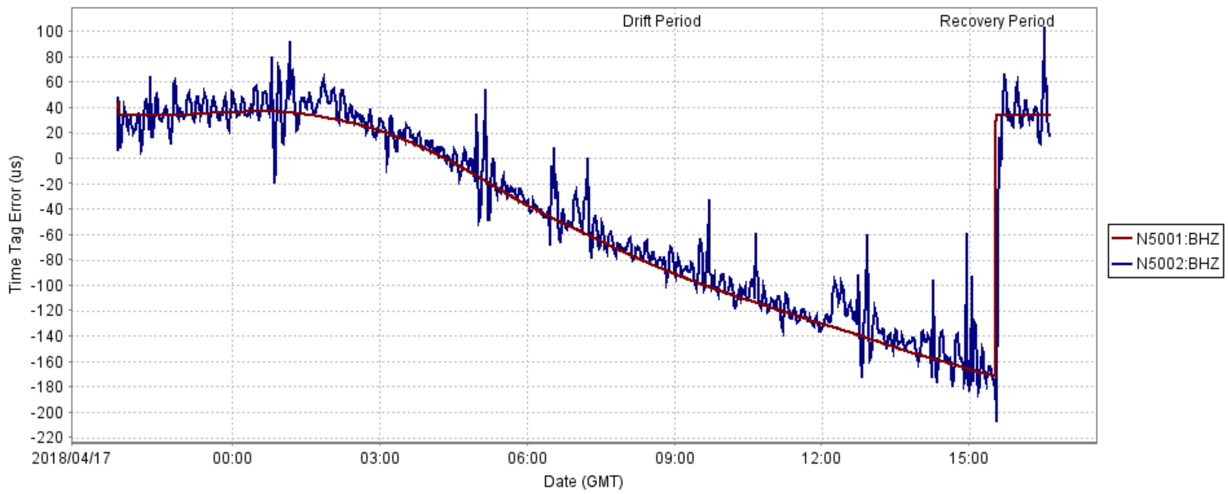

Figure 125 Time Tag Drift and Recovery: Centaur 5001 – GPS and 5002 – PTP

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 67 GPS Time Tag Drift and Recovery

	5001 - GPS	**5002 - PTP**
Lock Level	34 us	40 us, +/- 40 us
Drift Rate	15.873 us/h	15.548 us/h
Recovery Time	< 2 minutes	5 minutes
Stabilized Recovery Level	33.62 us	40 us, +/- 30 us

Both digitizers drifted at similar rates of between 15.548 us/h and 15.873 us/h during the period where the GPS antennas were covered. Most notable during this test was that the digitizer synchronized to PTP had a greater instantaneous variability in its timing accuracy when compared to the digitizer synchronized to GPS.

In addition, on Centaur 5002 that was synchronized to PTP over the local Ethernet network, a download from its internal storage was initiated after the time tag drive test had completed to stress the network connection and the digitizer's internal processor to observe whether there was any impact on the PTP timing accuracy. The download was initiated on April 18th at 17:00 UTC.

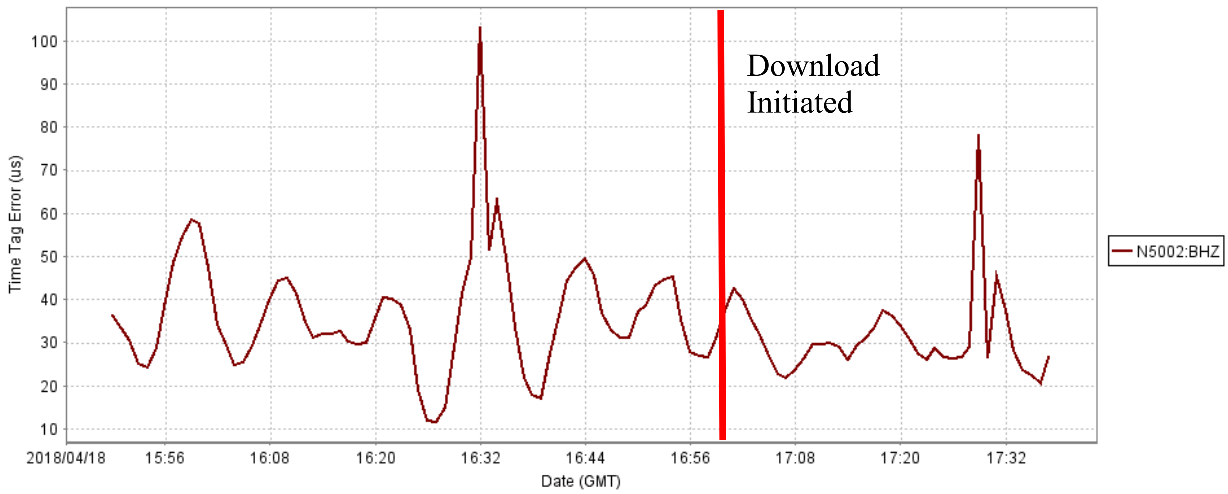

Figure 126 Time Tag Drift during data download: Centaur 5002 – PTP

As may be seen in the figure above, there was no apparent impact on the PTP timing accuracy for the 30 minutes that the data download was being performed.

3.22 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.

3.22.1 Measurand

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

3.22.2 Configuration

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

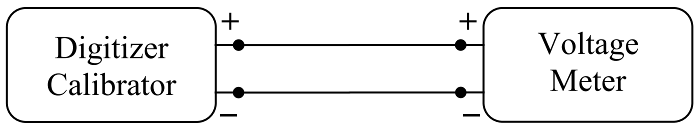

Figure 127 Calibrator Configuration Diagram

Table 68 Calibrator Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Voltage Meter	Agilent 3458A	MY45048371	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.

3.22.3 Analysis

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

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

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

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

For broadband calibration signals, the PSD is computed (Merchant, 2011) from the time series and observations made of the spectral characteristics.

3.22.4 Result

The Nanometrics Centaur CTR4-3A digitizers with firmware 4.3.14 includes an improved calibrator system. Earlier Centaur digitizers provided the ability to generate a calibration signal solely from a user pre-generated waveform file. The current digitizers continue to support this capability and have added the ability to generate calibration signals by specifying the signal parameters including signal types such as sinusoid and random binary.

Note that the Centaur digitizers do not provide a loopback recording of the calibration signal. It would therefore necessary to either assume the correctness of the signal being generated or to utilize one of the recording channels and externally loopback the calibration signal.

3.22.4.1 Sine Amplitude

The calibrator performance was demonstrated on the Centaur #5001 digitizer using sinusoids at 1 Hz over a range of amplitudes. The figures and tables below show the reference meter recording of the calibrator output.

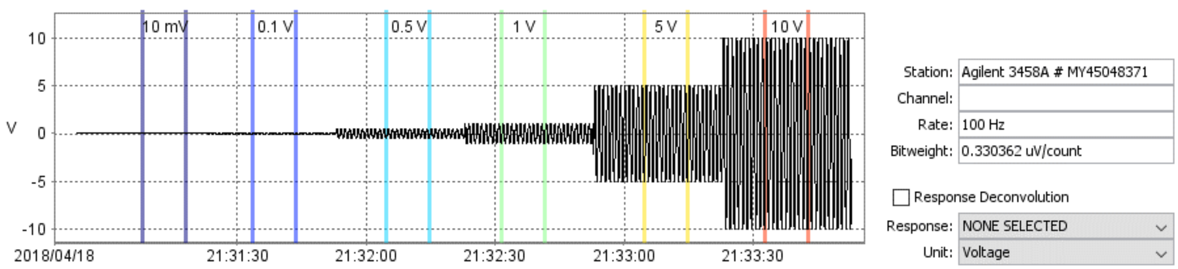

Figure 128 Calibrator Sine Amplitude at 1 Hz

Table 69 Calibrator Sine Amplitude at 1 Hz

Programmed Amplitude	Measured Amplitude	Percent Difference
10 mV	9.9931 mV	-0.07%
0.1 V	0.10018 V	0.17%
0.5 V	0.50084 V	0.17%
1 V	0.99772 V	-0.23%
5 V	4.9871 V	-0.26%
10 V	9.9697 V	-0.30%

The calibrator sinusoid amplitudes were measured to be between -0.3 % and 0.17% of the values programmed into the digitizer.

3.22.4.2 Sine Frequency

The calibrator performance was demonstrated on the Centaur #5001 digitizer using sinusoids at 1 V over a range of frequencies. The figures and tables below show the reference meter recording of the calibrator output.

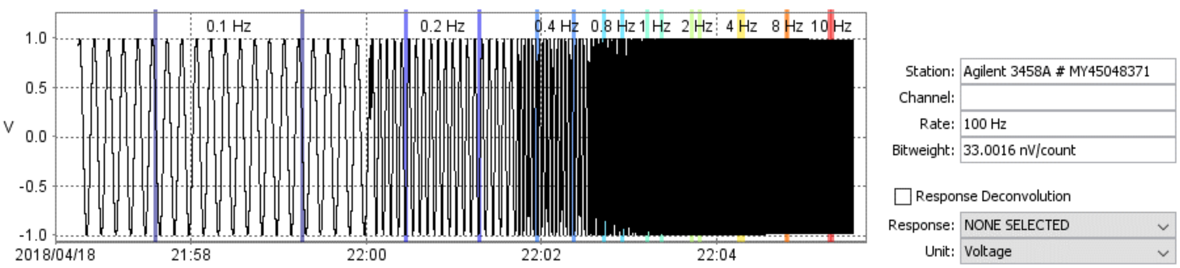

Figure 129 Calibrator Sine Frequency at 1 V

Table 70 Calibrator Sine Frequency at 1 V

Programmed Frequency	Measured Frequency	Percent Difference
0.1 Hz	0.100001 Hz	0.0010%
0.2 Hz	0.200002 Hz	0.0010%
0.4 Hz	0.400004 Hz	0.0010%
0.8 Hz	0.800009 Hz	0.0011%
1 Hz	1.00001 Hz	0.0010%
2 Hz	2.00002 Hz	0.0010%
4 Hz	4.00005 Hz	0.0012%
8 Hz	8.00009 Hz	0.0011%
10 Hz	10.0001 Hz	0.0010%

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

3.22.4.3 Harmonic Distortion

The harmonic distortion of the calibrator on Centaur #5001 was measured while the calibrator was generating a 1 Hz sinusoid. A 5-minute recording of the sinusoid was made on the reference meter sampled at 100 Hz. The figure and table below show the reference meter recording of the calibrator output.

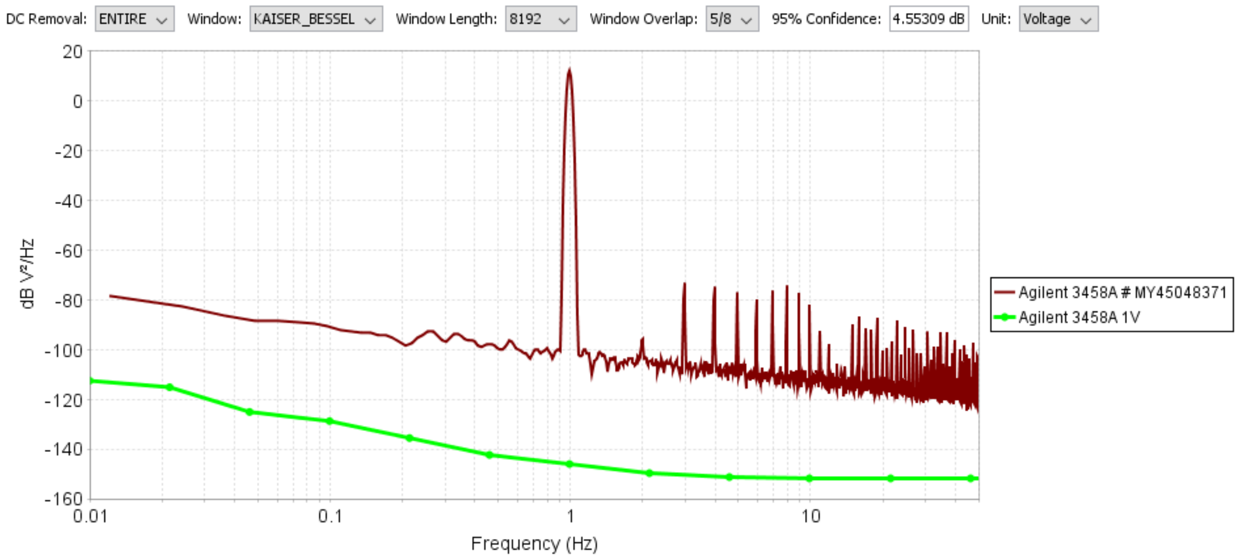

Figure 130 Calibrator THD at 1 Hz and 1 V

Table 71 Calibrator THD at 1 Hz and 1 V

Frequency	Amplitude	THD
1 Hz	1 V	-78.97 dB

The calibrator was observed to have a THD of just under -79 dB at 1 Hz and 1 V.

3.22.4.4 Random Binary

The calibrator performance was demonstrated on the Centaur #5001 digitizer using a random binary signal at +/- 5 V. A 3-minute recording of the sinusoid was made on the reference meter sampled at 100 Hz. The figures below show the reference meter recording of the calibrator output.

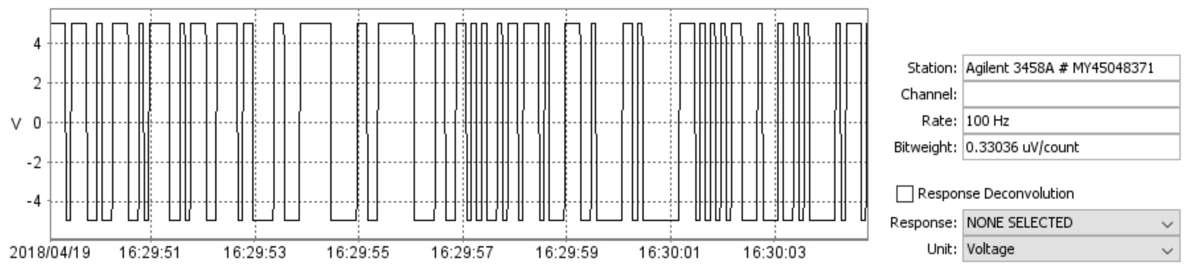

Figure 131 Calibrator Random Binary Time Series

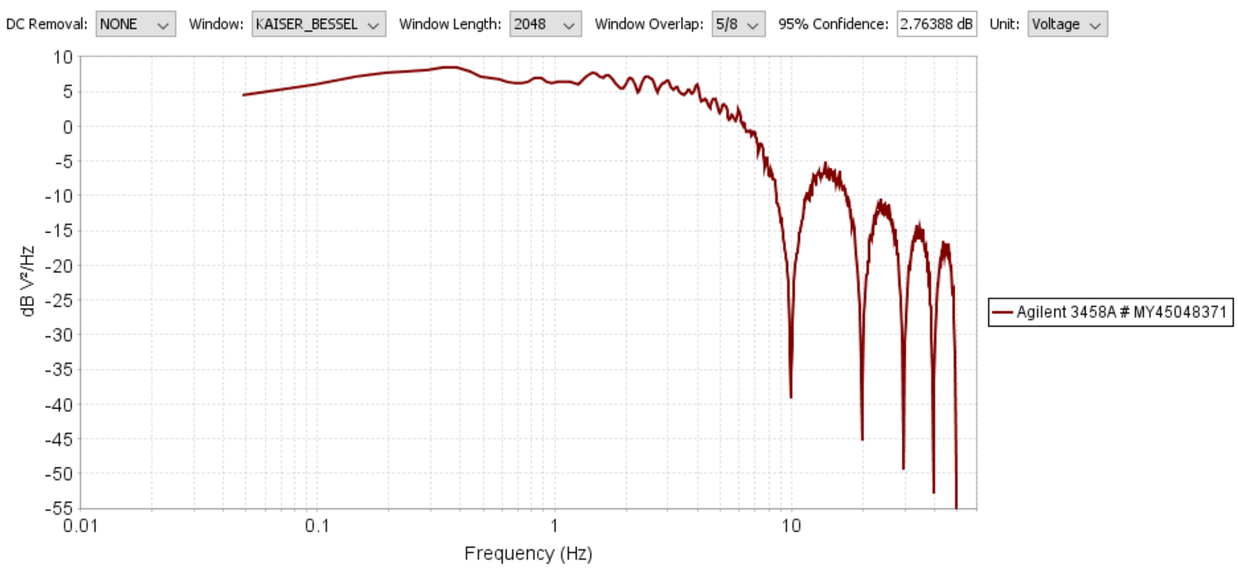

Figure 132 Calibrator Random Binary Power Spectra

The power spectra was consistent with what would be expected from a random binary signal with null points at harmonics of 10 Hz.

3.22.4.5 Red Noise - Seismowave

The calibrator performance was demonstrated on the Centaur #5002 digitizer using a red noise waveform file provided by Seismowave for the purpose of calibrating an MB3a infrasound sensor. The figures below show the calibrator output recording while it was looped back to one of the digitizer channels on Centaur #5002.

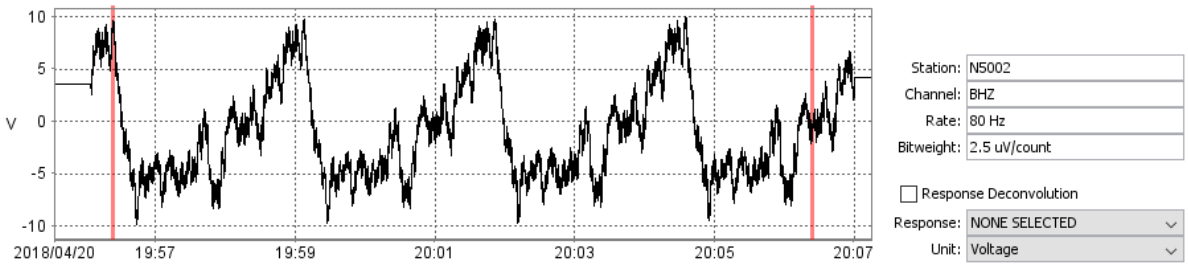

Figure 133 Calibrator Red Noise Seismowave Time Series

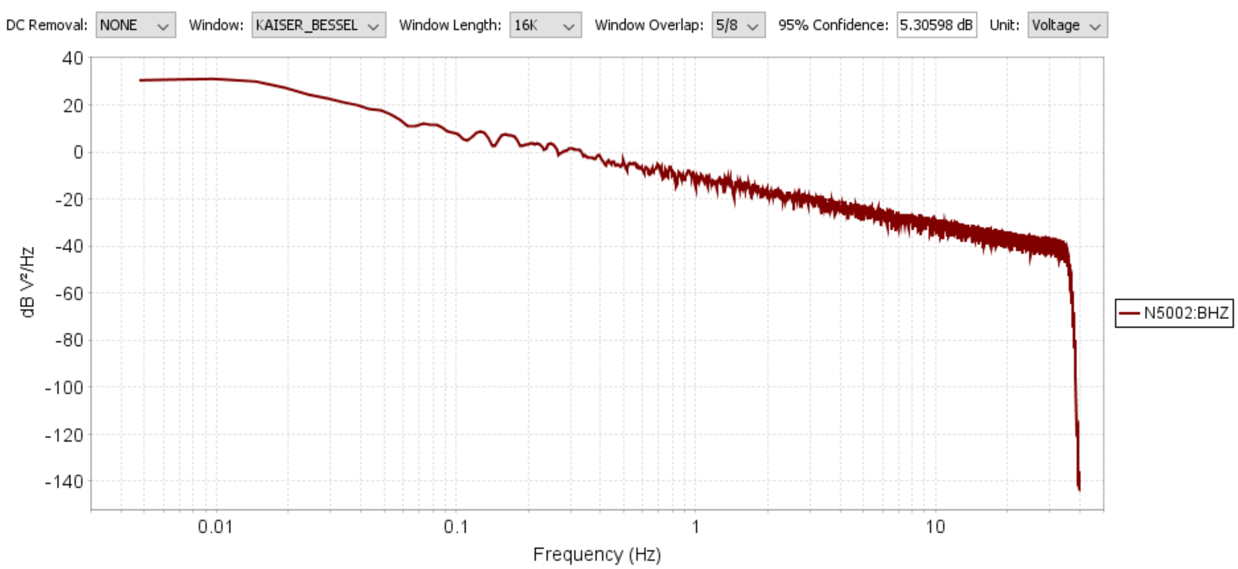

Figure 134 Calibrator Red Noise Seismowave Power Spectra

The red noise waveform being played back appears to be optimized to have more power at low frequencies, which would be suitable for performing an electrical calibration on an infrasound sensor in the presence of infrasound background noise.

3.22.4.6 Red Noise – Nanometrics

The calibrator performance was demonstrated on the Centaur #5002 digitizer using a red noise waveform file provided by Nanometrics for the purpose of calibrating an MB3a infrasound sensor. The figures below show the calibrator output recording while it was looped back to one of the digitizer channels on Centaur #5002.

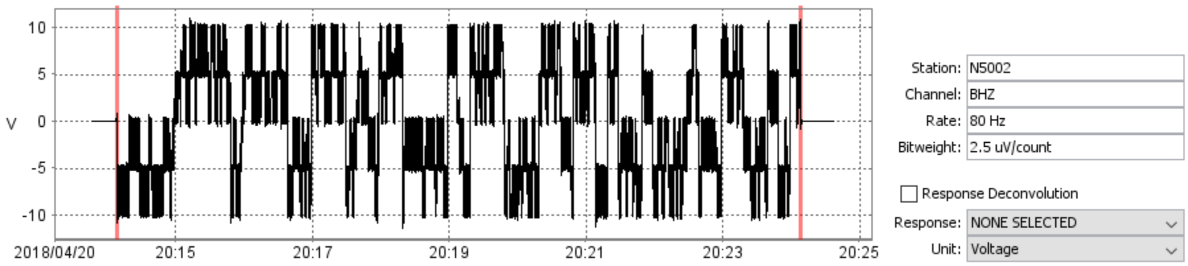

Figure 135 Calibrator Red Noise Nanometrics Time Series

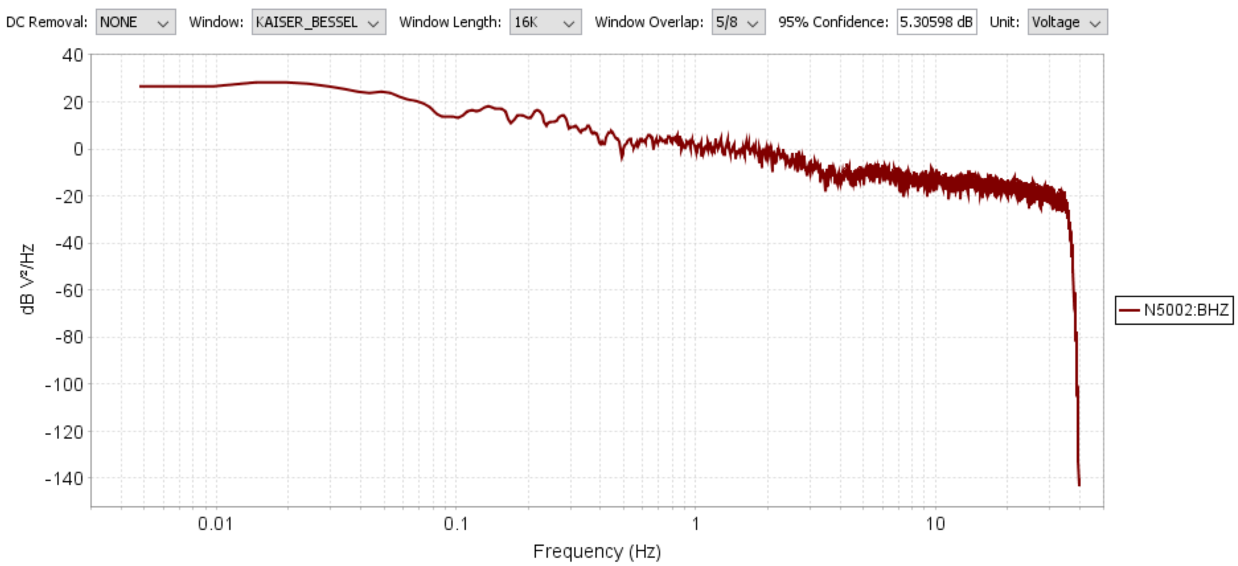

Figure 136 Calibrator Red Noise Nanometrics Power Spectra

The red noise waveform being played back appears to be optimized to have an equal amount of total power as the red noise file provided by Seismowave. However, it is flatter with more power at high frequencies and less power at low frequencies, which would not be as suitable for performing an electrical calibration on an infrasound sensor in the presence of infrasound background noise.

3.23 Sensor Compatibility Verification

The Centaur 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.

3.23.1 Nanometrics Trillium 240

The Centaur 5001 was connected to a Trillium 240 Seismometer, SN7400, and operated to collect site background noise, a sine calibration, and a broadband calibration as described in the following sections.

3.23.1.1 Site Background

The T240 seismometer and Centaur digitizer collected background signal as shown in the power spectra plot below:

Figure 137 T240 Background Power Spectra

The power spectra properly represents the local site noise, indicating that the seismometer and digitizer and collecting valid signals.

3.23.1.2 Broadband Calibration

A random binary calibration was performed using the Centaur digitizer. Since the Centaur does not provide a loopback on the calibration, there is no reference calibration signal against which to compare the signal coherence or relative response. The calibration was performed on all (U, V, and W) channels of the Trillium 240 simultaneously for 1 hour. The time series and power spectra are shown in the figures below.

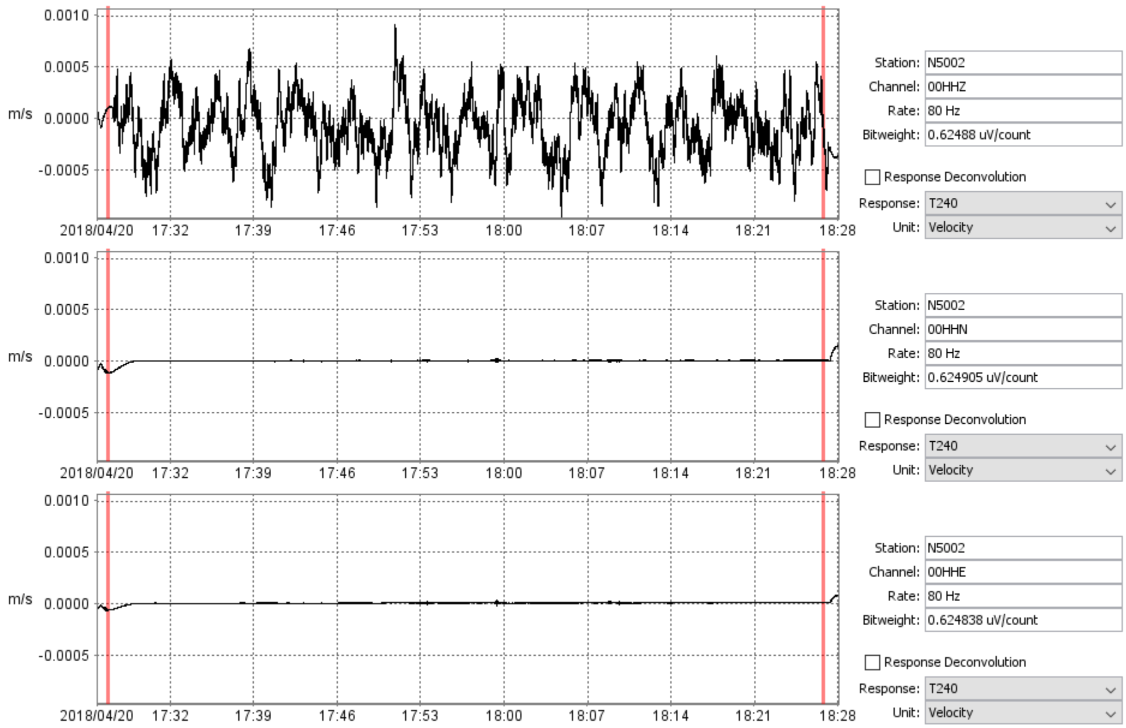

Figure 138 Trillium 240 Calibration Time Series

As expected from performing a calibration on all U, V, and W channels simultaneously, the output is principally on the Trillium 240 Z output channel. The horizontal channels have minimal output.

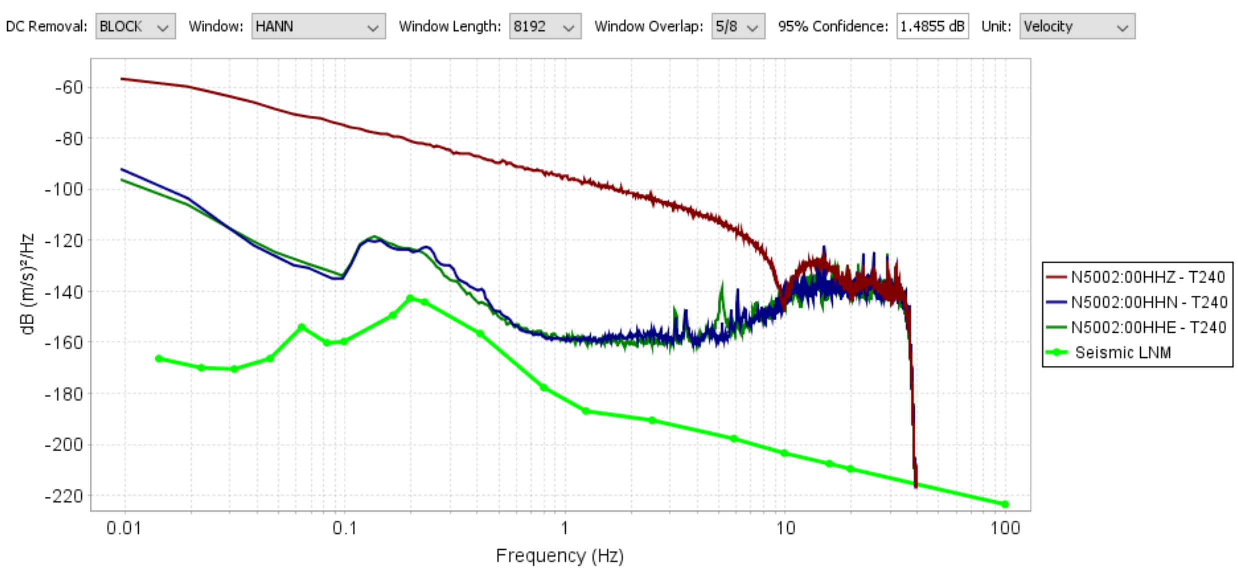

Figure 139 Trillium 240 Calibration Power Spectra

The power spectra plot above shows the sensor output channels, corrected for the Trillium 240 response, indicating that the calibration signal is visible on the Z channel.

3.23.2 Kinematrics STS-2

The Centaur 5001 was connected to a Kinematrics STS-2 seismometer and operated to collect site background noise and a broadband calibration as described in the sections below.

3.23.2.1 Site Background

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

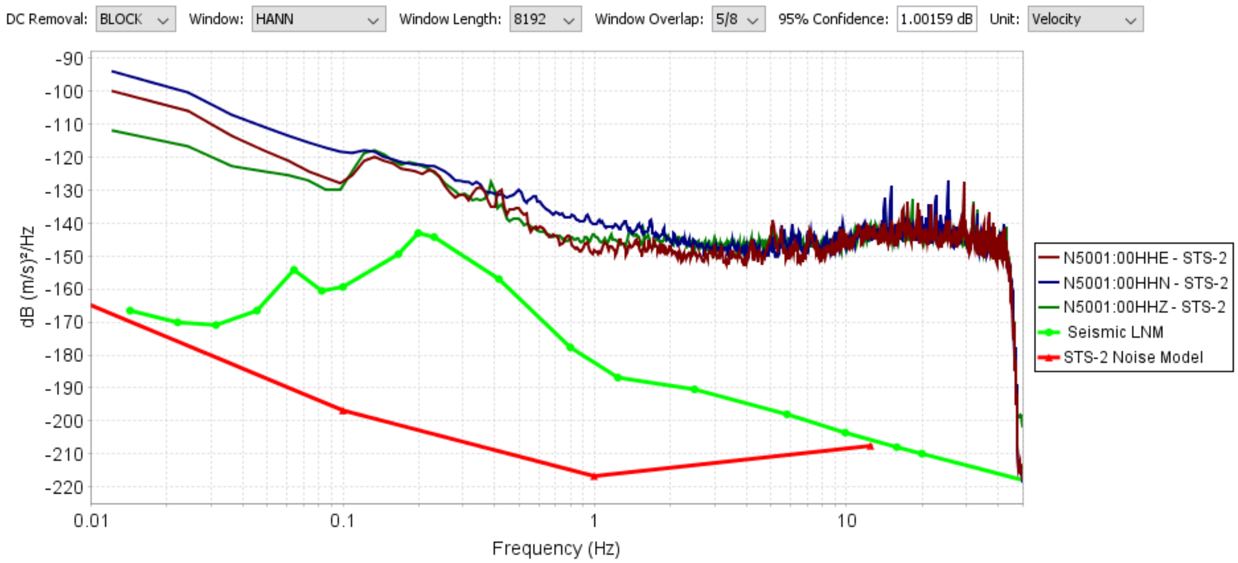

Figure 140 STS-2 Background Power Spectra

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

3.23.2.2 Broadband Calibration

A random binary calibration was performed using the Centaur digitizer. Since the Centaur does not provide a loopback on the calibration, there is no reference calibration signal against which to compare the signal coherence or relative response. The calibration was performed on all (U, V, and W) channels of the STS-2 simultaneously for 1 hour. The time series and power spectra are shown in the figures below.

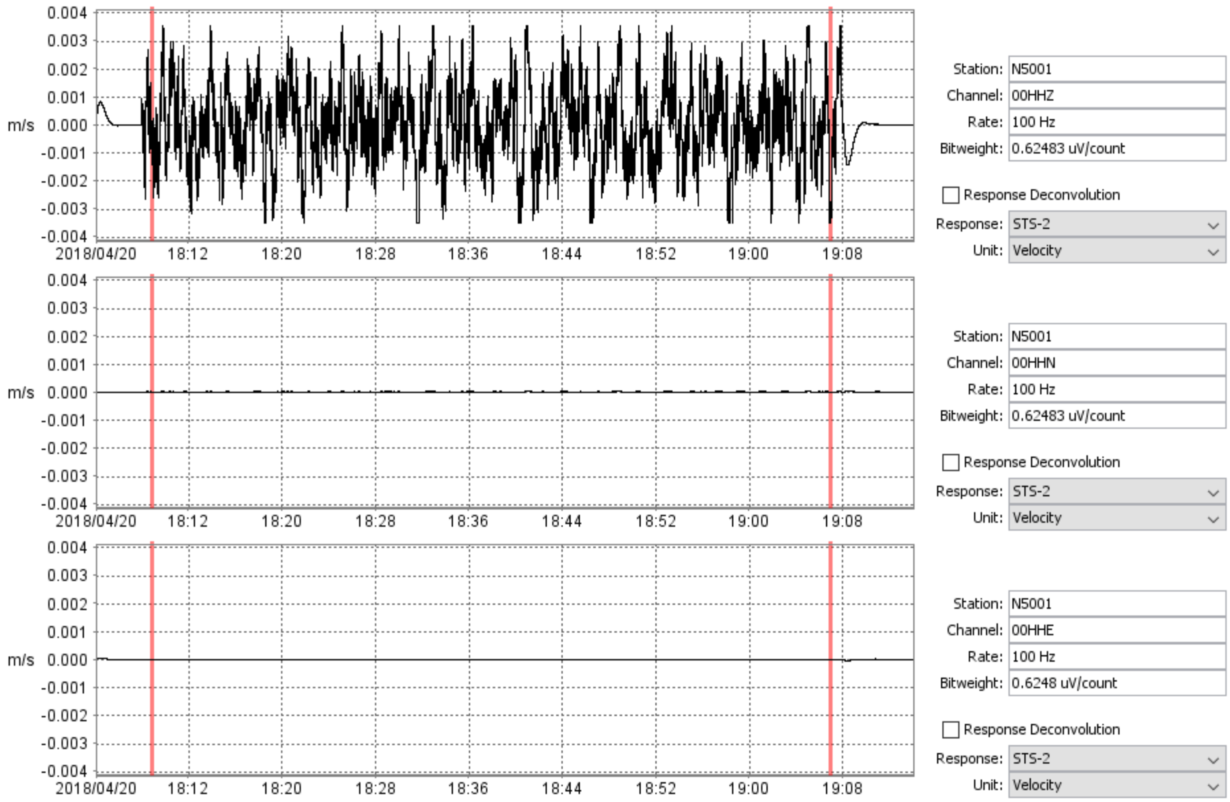

Figure 141 STS-2 Calibration Time Series

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.

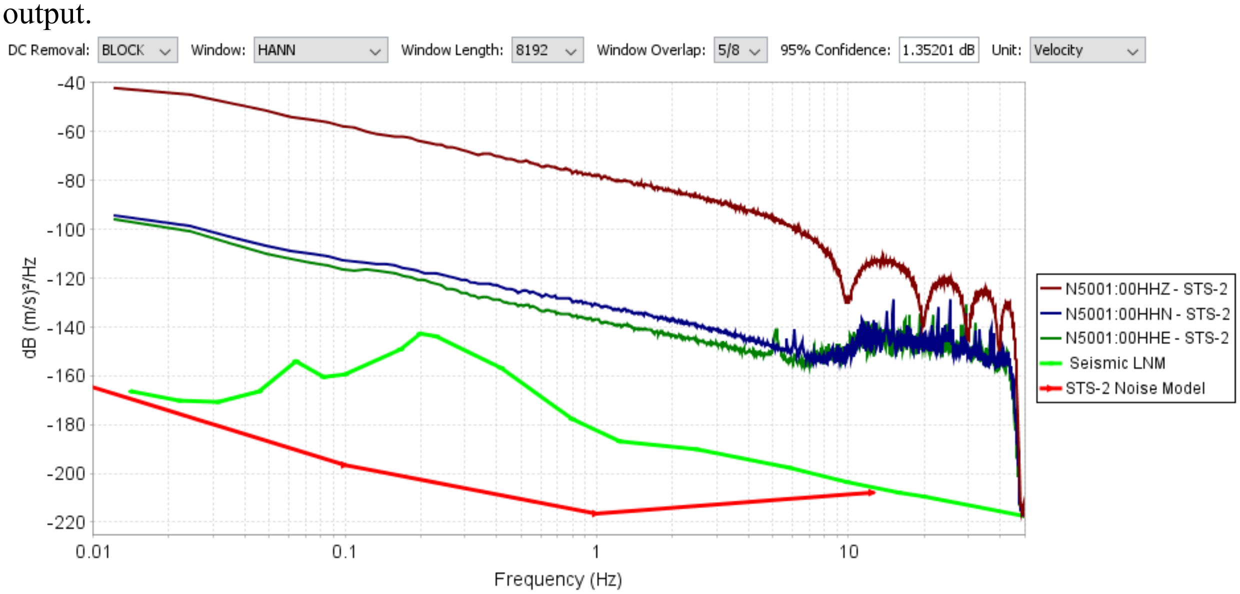

Figure 142 STS-2 Calibration Power Spectra

The power spectra plot above shows the sensor output channels, corrected for the STS-2 response, indicating that the calibration signal is visible on the Z channel.

3.23.3 MB3a

The Centaur 5002 was connected to an MB3a infrasound sensor, as shown in the figure below.

Figure 143 Centaur 5002 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.

3.23.3.1 Site Background

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

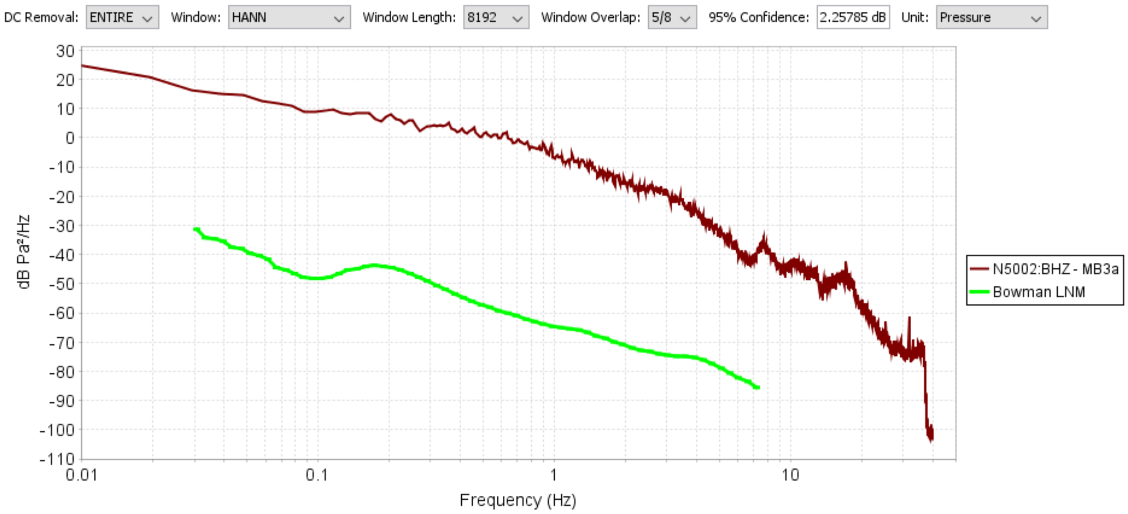

Figure 144 MB3a Open Background Power Spectra

The Centaur recorded the MB3a output which is consistent with the expected background in the area.

3.23.3.2 Sine Calibration

A sine calibration was performed using the Centaur 5002 digitizer to generate a 1 Hz sinusoid. The amplitude was increased to its maximum output level of 10 V peak to maximize the signal to noise ratio. Note that the Centaur digitizer does not loopback the calibration signal, therefore the amplitude of the calibration signal is assumed to be the 10 V that was programmed in.

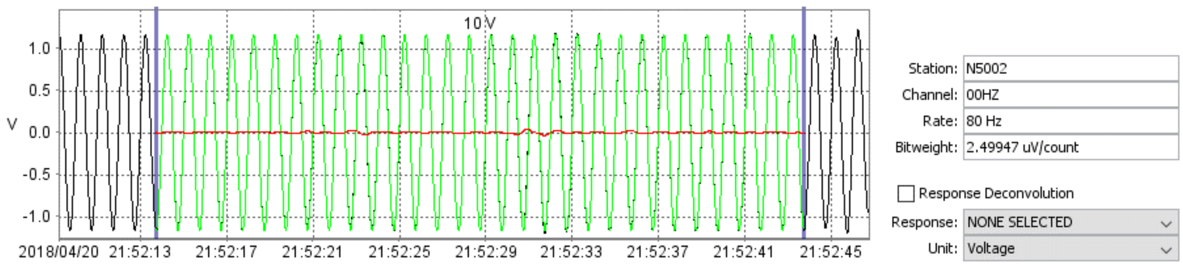

Figure 145 MB3a Sine Calibration Time Series

The MB3a calibrator sensitivity of 6 Pa/V (or 0.1667 V/Pa) was applied to the input calibration amplitude to convert it from voltage to a pressure of 60 Pa. Computing the ratio of the sensor voltage output and the calibration pressure results in an observed MB3a sensitivity at 1 Hz of 19.35 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 Centaur was able to generate a calibration signal that matched very closely with the theoretical MB3a response at 1 Hz.

3.23.3.3 Red Noise Calibration

A broadband calibration was performed using the Centaur 5002 digitizer to generate a red noise signal from a file provided by Seismowave. The coherence between a separate recording of the calibration signal and the sensor output was calculated to determine the relative amplitude response.

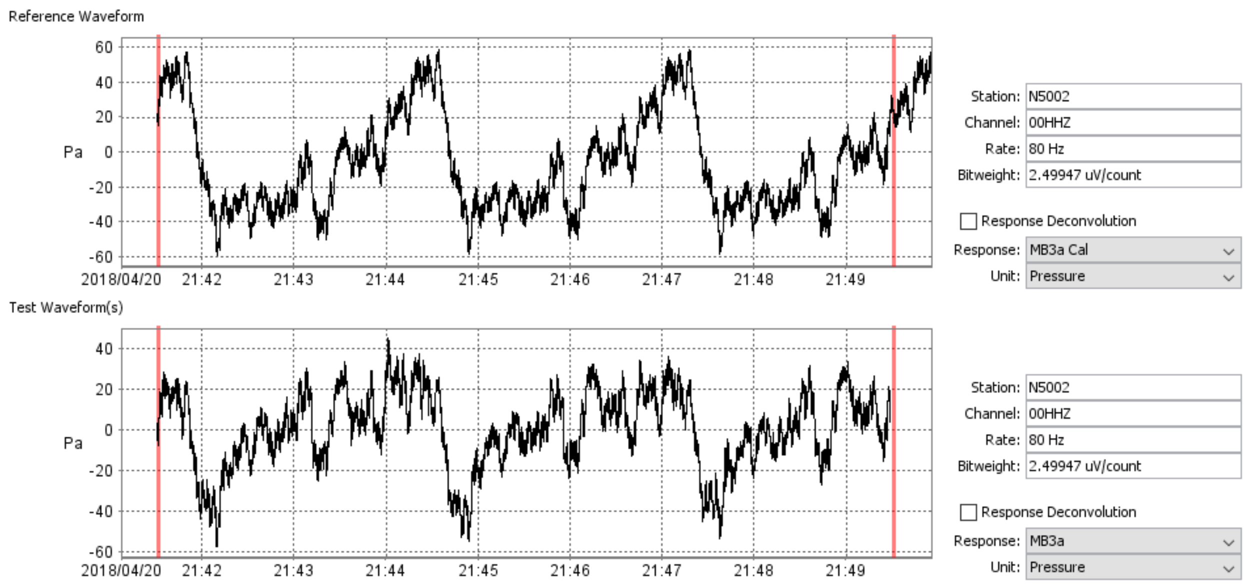

Figure 146 MB3a Red Noise Calibration Time Series

The MB3a calibrator sensitivity of 6 Pa/V (or 0.1667 V/Pa) was applied to the input calibration signal to convert it from voltage to pressure. Computing the power spectra of both the calibration signal and the sensor output, there is good agreement between the two.

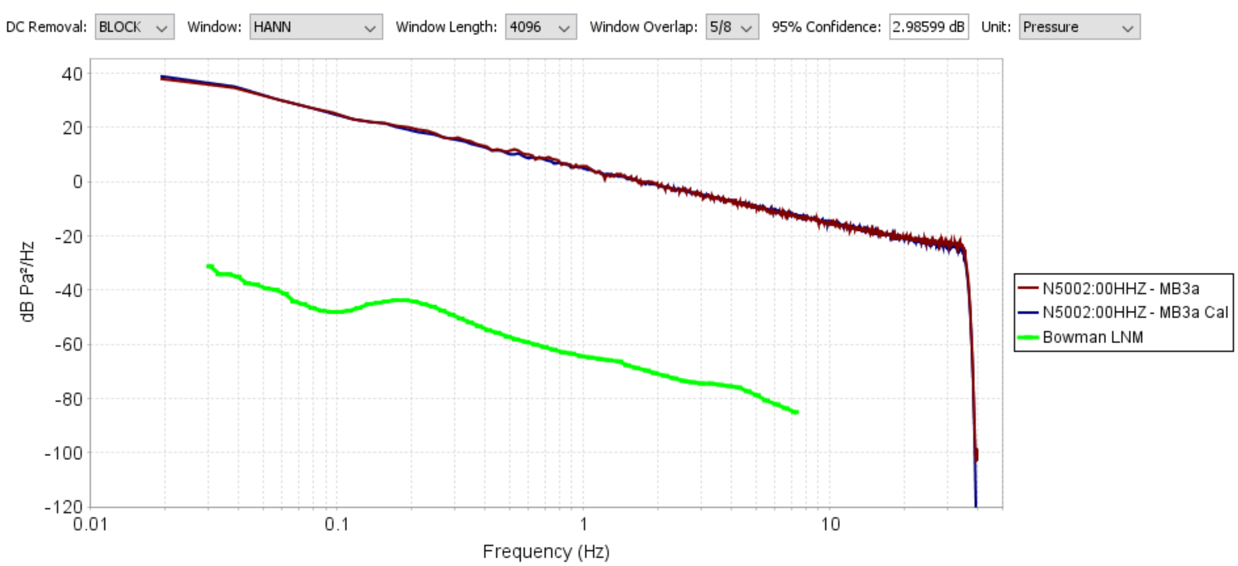

Figure 147 MB3a Red Noise Calibration Power Spectra

The plots below contain the coherence and relative amplitude between the signal provided to the MB3a calibrator and the MB3a output:

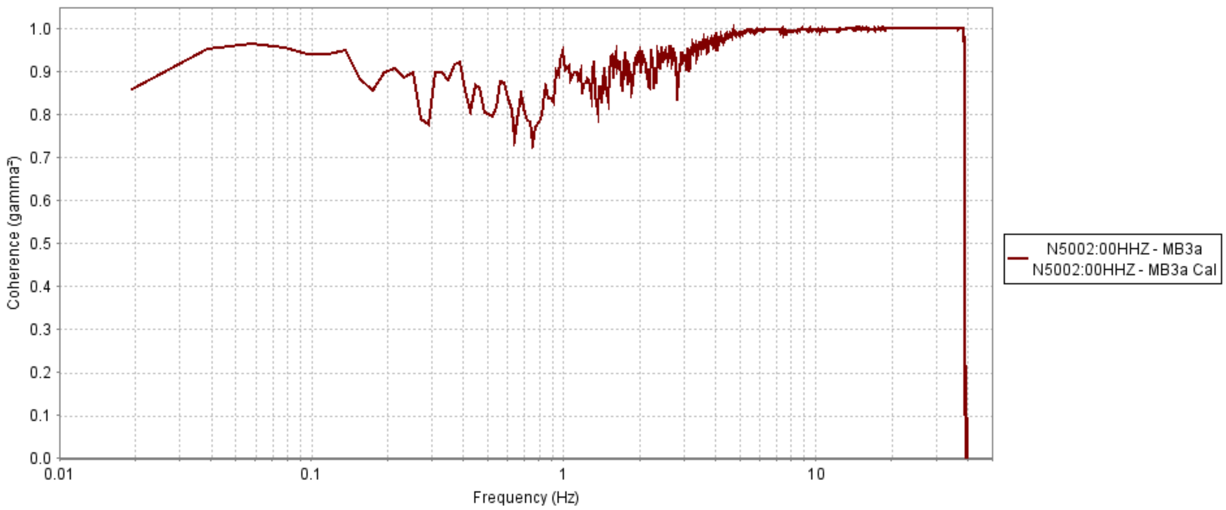

Figure 148 MB3a Red Noise Calibration Coherence

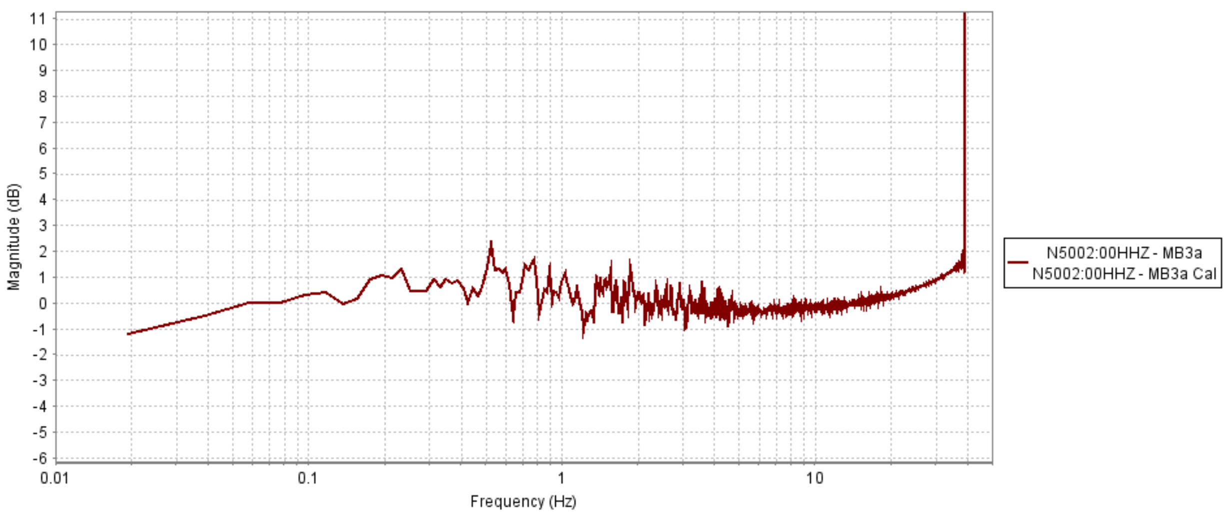

Figure 149 MB3a Red Noise Calibration Relative Amplitude

The coherence is reduced below 4 Hz, presumably where the background noise present on the MB3a output is visible. It is worth noting that the MB3a inlet is simply open to the ambient environment and not connected to a wind noise reduction system. Such a system would reduce the impact of the background noise and result in improved coherence.

The relative amplitude response between calibration signal and the MB3a output is flat to within less than +/- 1 dB at frequencies below 20 Hz, discontinuing the frequency region where the coherence is reduced due to background noise.

3.23.4 MB2005

The Centaur 5002 was connected to an MB2005 infrasound sensor, as shown in the figure below.

Figure 150 MB2005 infrasound sensor

The MB2005 was operated to collect site background noise and compared against an MB3a.

The MB2005 and Centaur digitizer collected background signals with the sensor ports open as shown in the power spectra plots below:

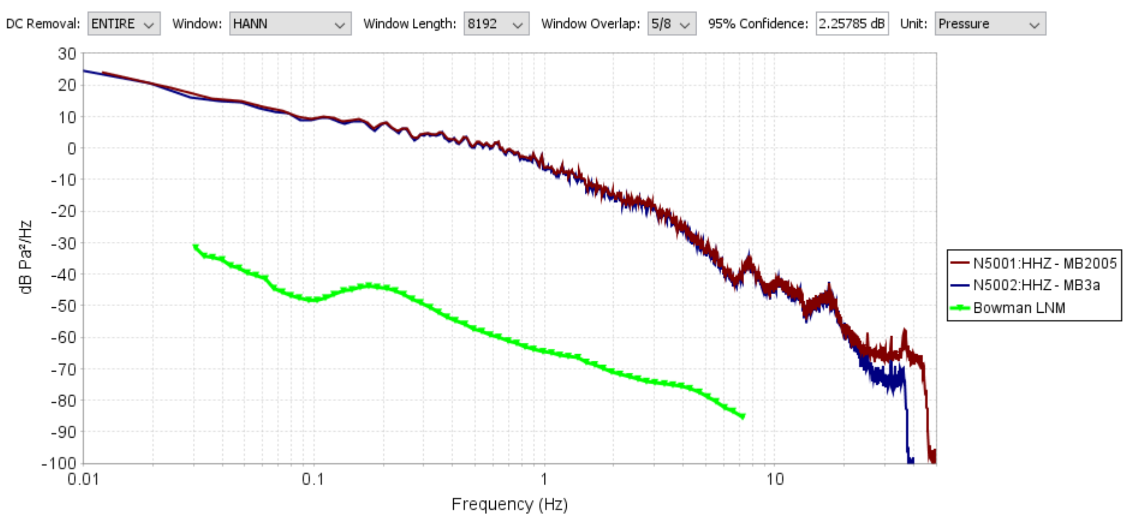

Figure 151 MB3a and MB2005 Open Background Power Spectra

The two Centaurs recorded both the MB3a and MB2005 signals and, when corrected for each of the sensors nominal sensitivity of 20 mV/Pa, the two signals overlay completely across 0.01 Hz – 10 Hz.

3.24 CD1 Status Flag Verification

During the evaluation of the Centaur 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 both Centaur 5001 and 5002. As a baseline, the CD1 status flags being reported during normal operation were observed to be:

```
Channel status: 32/0x01 0x00 0x07 0x00 0x00 0x00 0x00 0x00 "2018109 23:59:50.000" 1
    equipment housing open
    digitizing equipment open
    vault door opened
```

Indicating that the relay for the vault door was not connected to anything and that the GPS was locked with 1 micro-seconds of offset. There were no relays connected to the equipment housing, digitizer equipment, or vault door pins; therefore, these flags were being reported.

3.24.1 Calibration underway

A calibration was initiated from the webpage of the Centaur 5001 on April 18, 2018 at 21:30 (UTC) to generate a sine calibration signal for 30 seconds. The following was observed on the CD1 status:

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 796
    Number of samples: 1000
    Time stamp: "2018108 21:30:30.000" [1524087030.000000 2018/04/18 21:30:30.000000]
    Authentication offset (bytes): 792
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x08 0x07 0x00 0x00 0x00 0x00 0x00 "2018108 21:30:30.000" 1
        calibration underway
        equipment housing open
        digitizing equipment open
        vault door opened
    Data format: s4
    Data size (bytes): 688
```

The proper *calibration underway* flag was set. At the completion of the calibration signal, the CD1 status flags reverted to the baseline condition:

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 820
    Number of samples: 1000
    Time stamp: "2018108 21:34:00.000" [1524087240.000000 2018/04/18 21:34:00.000000]
    Authentication offset (bytes): 816
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x07 0x00 0x00 0x00 0x00 0x00 "2018108 21:34:00.000" 1
        equipment housing open
        digitizing equipment open
        vault door opened
    Data format: s4
    Data size (bytes): 712
```

3.24.2 GPS Unlocked

The Centaur 5001 GPS antenna was covered with metal foil and placed within a steel cabinet, without disconnecting the antenna from the digitizer, to recreate conditions in which the GPS antenna did not have reception. In addition, the GPS antenna of the PTP master that Centaur 5002 was time synchronized to was also covered with metal foil. The drift test was initiated on April 17, 2018 at approximately 22:43 UTC.

At 22:45 UTC, Centaur 5001 reported that its GPS receiver was unlocked.

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 780
    Number of samples: 1000
    Time stamp: "2018107 22:45:30.000" [1524005130.000000 2018/04/17 22:45:30.000000]
    Authentication offset (bytes): 776
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x07 0x04 0x00 0x00 0x00 0x00 "2018107 22:45:29.000" 2
        equipment housing open
        digitizing equipment open
        vault door opened
        GPS receiver unlocked
    Data format: s4
    Data size (bytes): 672
```

Centaur 5002, which was synchronized to the PTP master, never reported that its timing was unlocked.

3.24.3 GPS Drift

Both the Centaur 5001, synchronized to GPS, and 5002, synchronized to PTP, were allowed to drift overnight from April 17, 2018 at 22:43 UTC until April 18, 2018 at 15:31 UTC.

The Centaur 5001 digitizer correctly reported during the entire drift test that its last lock time occurred at 22:45:29 UTC and the estimate of the timing offset increased throughout the drift period. At the end of the drift period, the CD1 status flags were indicating a timing offset of 39,647 microseconds and that the clock differential was too large.

```
Time stamp: "2018108 15:32:10.000" [1524065530.000000 2018/04/18 15:32:10.000000]
Authentication offset (bytes): 708
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [100.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5001/BHZ/
Channel status: 32/0x01 0x00 0x07 0x05 0x00 0x00 0x00 0x00 "2018107 22:45:29.000" 39647
    equipment housing open
    digitizing equipment open
    vault door opened
    clock differential too large
    GPS receiver unlocked
```

The subsequent data frame showed that the GPS receiver had regained lock and the time offset had been reduced to 1462 microseconds.

```
Time stamp: "2018108 15:32:20.000" [1524065540.000000 2018/04/18 15:32:20.000000]
Authentication offset (bytes): 772
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [100.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5001/BHZ/
Channel status: 32/0x01 0x00 0x07 0x00 0x00 0x00 0x00 0x00 "2018108 15:32:20.000" 1462
    equipment housing open
    digitizing equipment open
    vault door opened
```

The clock differential too large flag was first set on Centaur 5001 at April 18, 2018 at 01:40:30 UTC when the estimate of clock offset transitioned from 4989 microseconds to 4997 microseconds.

```
Time stamp: "2018108 01:40:30.000" [1524015630.000000 2018/04/18 01:40:30.000000]
Authentication offset (bytes): 776
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [100.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5001/BHZ/
Channel status: 32/0x01 0x00 0x07 0x05 0x00 0x00 0x00 0x00 "2018107 22:45:29.000" 4997
    equipment housing open
    digitizing equipment open
    vault door opened
    clock differential too large
    GPS receiver unlocked
```

The Centaur 5002 digitizer, synchronized to PTP, never indicated that it the PTP master was unlocked and kept updating its time of last lock in the CD1 status flags.

```
Time stamp: "2018108 15:32:00.000" [1524065520.000000 2018/04/18 15:32:00.000000]
Authentication offset (bytes): 652
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [80.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5002/BHZ/
Channel status: 32/0x01 0x00 0x07 0x00 0x00 0x00 0x00 0x00 "2018108 15:32:01.500" 176
    equipment housing open
    digitizing equipment open
    vault door opened
```

The time offset in microseconds varied throughout, but was not observed to increase significantly during the timing drift test.

One item of note that was noticed on 5002 later on was that it began reporting that the time of last timing fix was between 0.5 and 1.5 microseconds after the data frame timestamp. This behavior appeared to resolve itself after a few hours of operation.

```
Time stamp: "2018108 16:01:20.000" [1524067280.000000 2018/04/18 16:01:20.000000]
Authentication offset (bytes): 648
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [80.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5002/BHZ/
Channel status: 32/0x01 0x00 0x07 0x00 0x00 0x00 0x00 0x00 "2018108 16:01:21.499" 270
    equipment housing open
    digitizing equipment open
    vault door opened
```

3.24.4 GPS Off

To evaluate the GPS Off status flag, the GPS antenna on 5001, which was synchronized to GPS, was physically disconnected on April 18, 2018 at 15:07 UTC. The CD1 status flags updated to reflect that the GPS was off:

```
Time stamp: "2018108 15:07:00.000" [1524064020.000000 2018/04/18 15:07:00.000000]
Authentication offset (bytes): 776
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [100.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5001/BHZ/
Channel status: 32/0x01 0x00 0x07 0x07 0x00 0x00 0x00 0x00 "2018107 22:45:29.000" 39150
    equipment housing open
    digitizing equipment open
    vault door opened
    clock differential too large
    GPS receiver off
    GPS receiver unlocked
```

The GPS antenna was reconnected on April 18, 2018 at 15:21 UTC. The first CD1 frame that indicated that the GPS was no longer off occurred at 15:21:20 UTC:

```
Time stamp: "2018108 15:21:20.000" [1524064880.000000 2018/04/18 15:21:20.000000]
Authentication offset (bytes): 772
Subframe Time Length (mS): 10000
Nominal sample rate (s/sec): [100.000000]
Authentication switch: 0 [off]
Compression: 2 [Canadian after signing]
Sensor type: 0 [Seismic]
Calibration Information: not specified
Site/Channel/Location names: N5001/BHZ/
Channel status: 32/0x01 0x00 0x07 0x05 0x00 0x00 0x00 0x00 "2018107 22:45:29.000" 39443
    equipment housing open
    digitizing equipment open
    vault door opened
    clock differential too large
    GPS receiver unlocked
```

3.24.5 Tamper Switches

In order to test the CD1 status flags for the tampering, tamper switches were installed on Centaur 5001 on April 19, 2018 at 15:38 UTC. As may be seen, the associated tamper status flags were all cleared.

At 15:41 UTC, the equipment housing was opened and the corresponding status flag was set.

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 1136
    Number of samples: 1000
    Time stamp: "2018109 15:41:00.000" [1524152460.000000 2018/04/19 15:41:00.000000]
    Authentication offset (bytes): 1132
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x01 0x00 0x00 0x00 0x00 0x00 "2018109 15:41:00.000" 2
        equipment housing open
    Data format: s4
    Data size (bytes): 1028
```

At 15:42:30 UTC, the vault door open relay was tripped and the corresponding status flag was set.

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 1124
    Number of samples: 1000
    Time stamp: "2018109 15:42:30.000" [1524152550.000000 2018/04/19 15:42:30.000000]
    Authentication offset (bytes): 1120
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x05 0x00 0x00 0x00 0x00 0x00 "2018109 15:42:30.000" 1
        equipment housing open
        vault door opened
    Data format: s4
    Data size (bytes): 1016
```

At 15:46 UTC, the digitizer equipment open relay was tripped and the corresponding status flag was set.

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 1124
    Number of samples: 1000
    Time stamp: "2018109 15:46:00.000" [1524152760.000000 2018/04/19 15:46:00.000000]
    Authentication offset (bytes): 1120
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x07 0x00 0x00 0x00 0x00 0x00 "2018109 15:46:00.000" 1
        equipment housing open
        digitizing equipment open
        vault door opened
    Data format: s4
    Data size (bytes): 1016
```

At 15:50:50 UTC, all of the relays were closed again and the corresponding status flags all cleared.

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 1128
    Number of samples: 1000
    Time stamp: "2018109 15:50:50.000" [1524153050.000000 2018/04/19 15:50:50.000000]
    Authentication offset (bytes): 1124
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x00 0x00 0x00 0x00 0x00 0x00 "2018109 15:50:50.000" 1
    Data format: s4
    Data size (bytes): 1020
```

In addition, a quick toggling of vault door relay for less than 1 second at 15:53:00 UTC demonstrated that the CD1 status flag did catch a transient relay condition.

```
Channel # [1]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [100]
    Packet length (bytes): 1128
    Number of samples: 1000
    Time stamp: "2018109 15:53:00.000" [1524153180.000000 2018/04/19 15:53:00.000000]
    Authentication offset (bytes): 1124
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [100.000000]
    Authentication switch: 0 [off]
    Compression: 2 [Canadian after signing]
    Sensor type: 0 [Seismic]
    Calibration Information: not specified
    Site/Channel/Location names: N5001/BHZ/
    Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x00 0x00 0x00 "2018109 15:53:00.000" 1
        vault door opened
    Data format: s4
    Data size (bytes): 1020
```

4 SUMMARY

Power Consumption

The Centaur digitizer was found to consume between 2.5 and 2.63 watts of power in general operation. Power consumption was observed to increase with gain level by an additional 130 mW at 40x gain. Power consumption can be decreased by 175 mW by slowing the Ethernet connection speed to 10 Mbit. Power consumption was less than expected from the Centaur documentation.

Input Impedance

The Centaur digitizer channels were found to have an input impedance that was within 0.12% of the nominal 40 kOhms, except for at a 40x gain where the channels varied by as much as 3%.

DC Accuracy

The Centaur digitizer channels were found to have bit-weights that were consistent with the nominal values to within 0.011 % to 0.025 % of the nominal values across the 20 Hz, 40 Hz, 80 Hz, and 100 Hz sample rates and gains of 1x, 2x, 4x, 10x, 20x, and 40x.

AC Accuracy

The Centaur digitizer channels were found to have bit-weights that were consistent with the nominal values to within 0.016 % to 0.032 % of the nominal values across the 20 Hz, 40 Hz, 80 Hz, and 100 Hz sample rates and gains of 1x, 2x, 4x, 10x, 20x, and 40x.

AC Full Scale

The Centaur digitizer channels could fully resolve peak-to-peak amplitudes at or about their full scale of +/- 20V, +/- 10 V, +/- 5 V, +/- 2 V, +/- 1V, and +/- 0.5 V across the 20 Hz, 40 Hz, 80 Hz, and 100 Hz sample rates and gains of 1x, 2x, 4x, 10x, 20x, and 40x.

AC Over Scale

The Centaur digitizer channels all were determined to have a full-scale amplitude that exceeded by at least 5% the nominally specified full scale across the 20 Hz, 40 Hz, 80 Hz, and 100 Hz sample rates and gains of 1x, 2x, 4x, 10x, 20x, and 40x.

Input Shorted Offset

The Centaur digitizer channels were found to have a DC offset that ranged from between -0.7042 mV and 0.369 mV at a gain of 1x to between -43.73 uV to 17.98 uV at a gain of 4x. Offsets were not impacted by the selection of sample rate. Offsets appeared to scale inversely with the gain level for gains of 1x, 2x, and 4x. No such relationship was observed for gains of 10x, 20x, and 40x.

Self-Noise

The Centaur digitizers were observed to have noise free bits at a gain of 1x of 23.45 bit, 23.5 bits, 23.35 bits, and 23.3 bits at sample rates of 20 Hz, 40 Hz, 80 Hz, and 100 Hz, respectively. Increasing gain levels from 1x to 2x, 4x, 10x, 20x, and 40x resulted in reductions in the effective number of bits of 0 bits, 0 bits, 0.1 bits, 0.2 bits, and 0.6 bits, respectively. Interestingly, the PSD levels at higher sample rates is less than at lower sample rates, indicating that the self-noise contains very little electronic noise and is dominated by the fundamental quantization noise.

Dynamic Range
At 100 Hz sampling rate dynamic ranges varied from as low as 130 dB at a gain of 40x up to 138.4 dB at a gain of 1x-4x. At 40 Hz, dynamic ranges varied from as low as 131 dB at a gain of 40 x up to 141 dB at a gain of 1x-4x. At 80 Hz, dynamic ranges varied from as low as 131 dB at a gain of 40x up to 139 dB at a gain of 1x-4x. At 20 Hz, dynamic ranges varied from as low as 135 dB at a gain of 40x up to 143 dB at gains of 1x-4x.

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 Centaur digitizer channels exhibited no observable change in self-noise power spectra levels at temperatures between -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 Centaur 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 Centaur digitizer channels exhibited less than 0.25 microsecond of timing skew from channel to channel.

Analog Bandwidth
The Centaur digitizer channels exhibited a bandwidth of between 87.1% and 88.75% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, 80 Hz, and 100 Hz. Bandwidth was not observed to vary with gain level.

Incoherent Noise
The Centaur digitizer channels exhibited incoherent noise while recording a white noise signal that was as much as 10 dB higher than the self-noise that had been measured previously. This indicates that there is slightly less resolution due to increased noise when recording high amplitude signals. Note that there remains over 90 dB of SNR between the white noise signal power and the incoherent noise power.

Total Harmonic Distortion
The Centaur digitizer channels exhibited total harmonic distortion ranged between -114.91 dB and -109.26 dB at a gain of 1x, -114.75 dB and -111.05 dB at a gain of 2x, -114.62 dB and -110.89 dB at a gain of 4x, -113.63 and -105.70 dB at a gain of 10x, -111.68 dB and -105.51 dB at a gain of 20x, and -104.79 dB and -101.07 dB at a gain of 40x.

Modified Noise Power Ratio
The Centaur digitizer channels exhibited a modified noise power ratio, measured at a sample rate of 100 Hz and gain of 10x and a sample rate of 80 Hz and gain of 1x, indicating that both digitizers perform consistently with nearly 23 bits of performance at low amplitudes and between 20.5 bits and 22 bits of performance at high amplitudes.

Common Mode Rejection
The Centaur digitizer channels exhibited common mode rejection ratios of between 80 and 90 dB. As expected, the common mode levels were unchanged for each unique physical digitizer channel and did not vary with sample rate or gain. Note that for common mode signals at 10% of full scale amplitude, although the signal amplitudes were still reduced by the expected rejection ratio, there was some distortion in the observed common mode signal observed at harmonics of the common mode frequency.

Crosstalk
The Centaur digitizer channels exhibited crosstalk that was measured to be better than between -159.37 dB and -152.5 dB. The measurement was limited due to there being minimal observable crosstalk present on the channel self-noise.

Time Tag Accuracy
The Centaur digitizers were measured to have time tag accuracy values with a mean level of 36.73 us for GPS and 34.67 us for PTP. Nanometrics provided an updated firmware by the end of the testing period that had improved GPS time tag accuracy to better than 2.4 us.

Time Tag Drift
The Centaur digitizers drifted by 15.548 us/hr and 15.873 us/hr when using GPS and PTP, respectively, for time synchronization. Both digitizers recovered back to their original time tag accuracy within minutes of regaining GPS lock. Network traffic and digitizer process workload due to a data download was not observed to have any impact on PTP time tag accuracy.

Calibrator
The Centaur digitizer 5001 demonstrated the ability to accurately generate sinusoids at amplitudes of between 0.01 V and 10.0 V with an amplitude accuracy of between -0.3% and 0.17%. Sinusoid with frequencies between 0.1 Hz and 10 Hz were generated with a frequency accuracy of better than 0.0012%. Harmonic distortion of the calibrator sinusoid was measured to be just under -79 dB at 1 Hz and 1 V. The Centaur was confirmed to be able to generate Pseudo Random Binary with selectable amplitude, pulse width and duration. The Centaur was also confirmed to be able to generate arbitrary broadband signals contained within a waveform file.

Sensor Compatibility Verification
The Centaur digitizer was able to demonstrate the proper operation and calibration of a Nanometrics T240 seismometer, a Kinemetrics STS-2 high gain seismometer, an MB2005 infrasound sensor, and an MB3a infrasound sensor.

CD1 Status Flag Verification

The Centaur digitizer demonstrated the transmission of CD1 status flags for a calibration underway, GPS receiver unlocked, GPS off, clock differential too large, and the various tamper flags. It should be noted that there were no status flags to indicate that a PTP time master was unlocked and there were some very slight discrepancies observed in the timestamp for the last time fix.

REFERENCES

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

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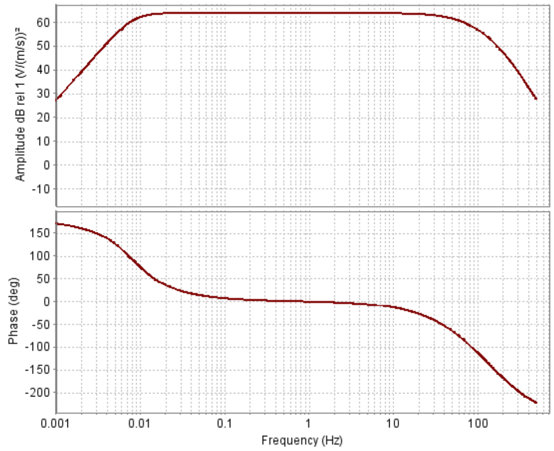
7. Sleeman, R., Wettum, A., Trampert, J. (2006), *Three-Channel Correlation Analysis: A New Technique to Measure Instrumental Noise of Digitizers and Seismic Sensors*, Bulletin of the Seismological Society of America, Vol. 96, No. 1, pp. 258-271, February 2006.

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:

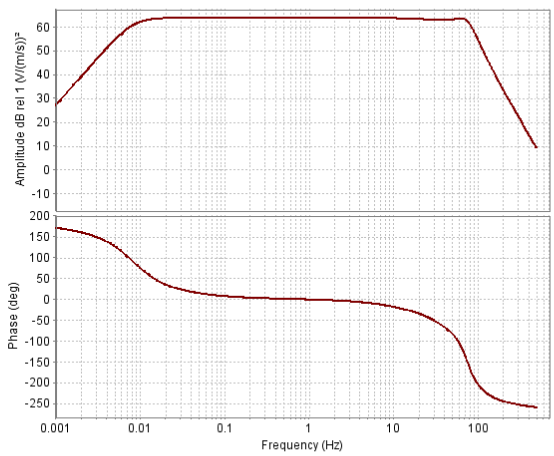
-1130.0	0.0
-1010.0	0.0
-503.0	0.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
861,208.00814 MV·s/m

Kinematrics STS-2 Low Gain Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

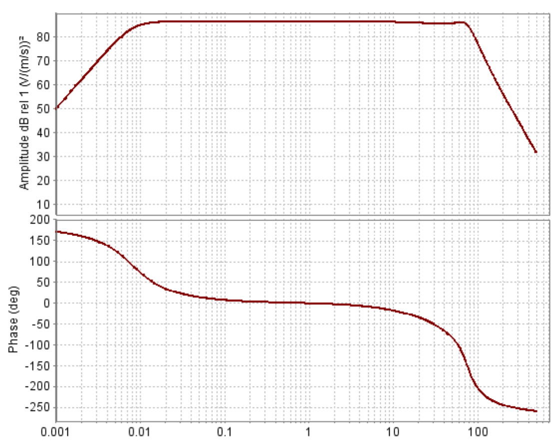
-251.0	0.0
-131.0	467.0
-131.0	-467.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
88,586.67303 MV·s/m

Kinematrics STS-2 High Gain Seismometer



Sensitivity:
20 kV·s/m at 1.0 Hz

Poles:

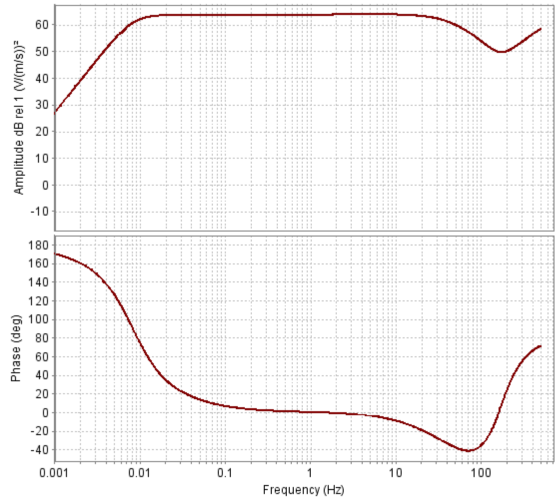
-251.33	0.0
-131.04	467.29
-131.04	-467.29
-0.035647	0.036879
-0.035647	-0.036879

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:

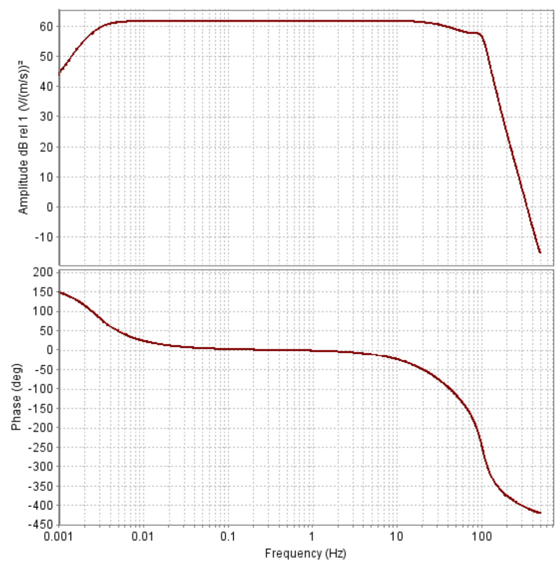
-961.0	0.0
-339.0	116.0
-339.0	-116.0
-16.0	0.0
-16.0	0.0
-0.037	-0.037
-0.037	0.037

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:

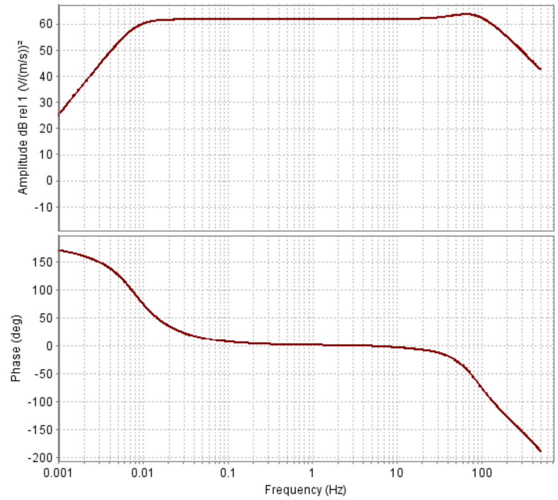
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-351.858	0.0
-121.58	647.231
-121.58	-647.231
-22.3068	0.0
-22.3068	0.0
-0.01231	0.01206
-0.01231	-0.01206

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:

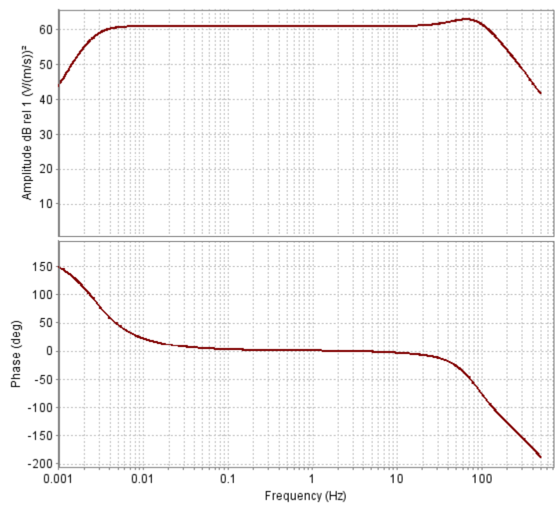
-7100.0	1700.0
-7100.0	-1700.0
-4900.0	5204.0
-4900.0	-5204.0
-1260.0	0.0
-364.0	404.0
-364.0	-404.0
-142.0	0.0
-32.55	0.0
-0.036614	0.037059
-0.036614	-0.037059

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:

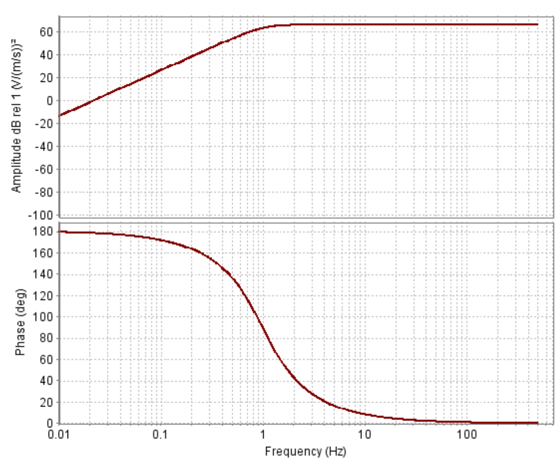
-7200.0	1700.0
-7200.0	-1700.0
-4900.0	5200.0
-4900.0	-5200.0
-1234.0	0.0
-360.0	405.0
-360.0	-405.0
-146.0	0.0
-0.01189	0.01189
-0.01189	-0.01189

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:

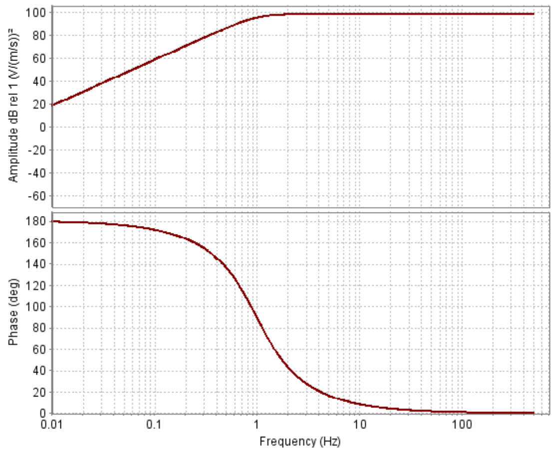
-4.443	4.443
-4.443	-4.443

Zeros:

0.0	0.0
0.0	0.0

A:
2,001.59953 V·s/m

Geotech GS13 Seismometer and 40x Preamplifier



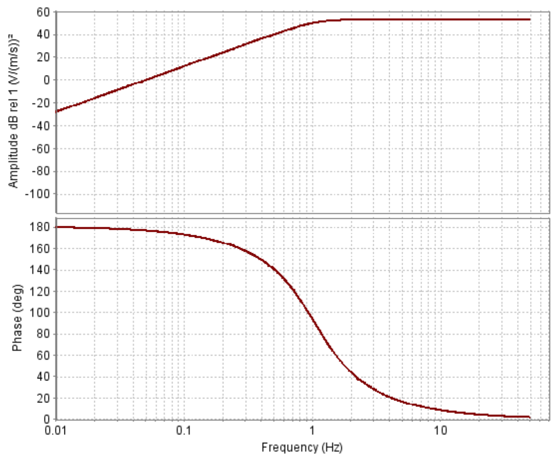
Sensitivity:
80 kV·s/m at 5.0 Hz

Poles:
-4.443 4.443
-4.443 -4.443

Zeros:
0.0 0.0
0.0 0.0

A:
80.06398 kV·s/m

Geotech GS21 Seismometer



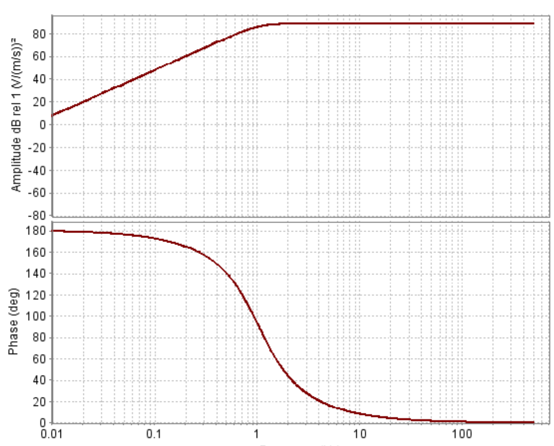
Sensitivity:
418 V·s/m at 5.0 Hz

Poles:
-4.4138 4.9251
-4.4138 -4.9251

Zeros:
0.0 0.0
0.0 0.0

A:
416.38503 V·s/m

Geotech GS21 Seismometer and 61.39x Preamplifier



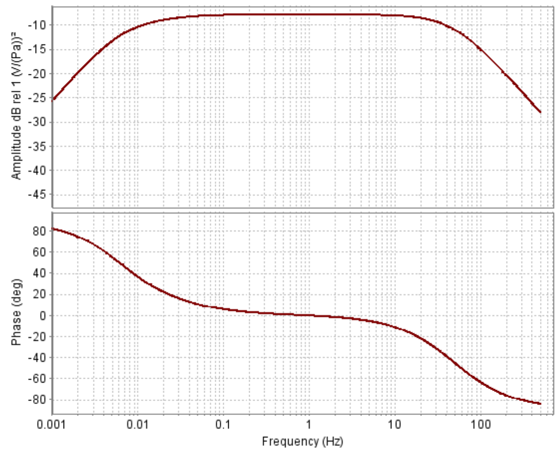
Sensitivity:
25.661 kV·s/m at 20.0 Hz

Poles:
-4.4138 4.9251
-4.4138 -4.9251

Zeros:
0.0 0.0
0.0 0.0

A:
25.65334 kV·s/m

Chaparral 50A Infrasound Sensor



Sensitivity:
0.4 V/Pa at 1.0 Hz

Poles:

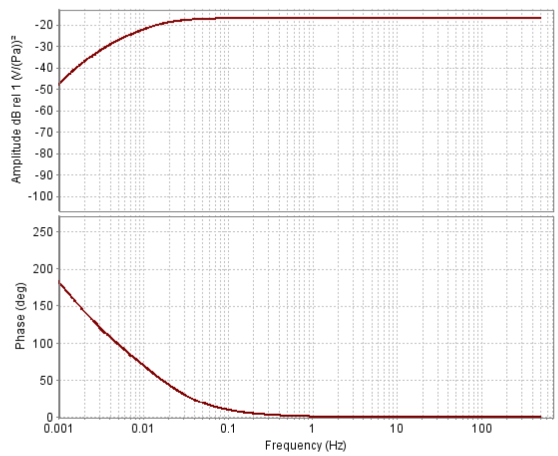
-314.0	0.0
-0.188	0.0
-0.044	0.0
0.0	0.0

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:

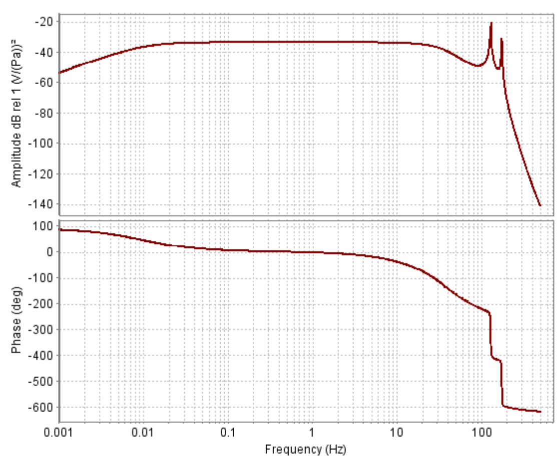
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
0.14002 V/Pa

MB2005 Infrasound Sensor



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

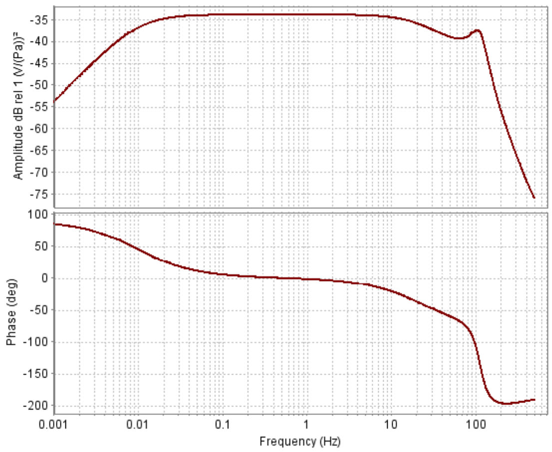
-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.06283	0.0

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

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Limited Calibration Certificate
Document #: 6652541_11726859

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 06752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1044
Date of Receipt	November 07, 2017
Dates Tested (Start – End)	November 29, 2017 - November 29, 2017
Date Approved	November 29, 2017
Calibration Expiration Date	November 29, 2018

Calibration Description

Calibration Lab	PSL-ELECTRICAL
Calibration Procedure, rev.	HP 3458A, 4.2
Temperature	23 ± 2 deg C
Humidity	40 ± 20 %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

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6652541_11726859

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:

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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:	6652541	Test Type:	FOUND-LEFT
Serial Number:	MY45048371	Calibration Date:	11/29/2017
Procedure Name:	HP 3458A	Temperature:	23 °C
Revision:	4.2	Humidity:	40 %
Calibrated By:	Jason Chance		

- 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
- 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	8/10/2018
20563	FLUKE 5790A CALIBRATOR	10/19/2018
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/15/2018
6664631	Fluke 5730A Multifunction Calibrator	12/4/2017

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 36.1 deg.C

DC Volts

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99812	100.00028	100.00188	mV	2.26#	15	
-100.00000 mV		-100.00188	-100.00030	-99.99812	mV	2.26#	16	
1.00000000 V		0.99998965	1.00000458	1.00001035	V	2.97#	44	
-1.00000000 V		-1.00001035	-1.00000474	-0.99998965	V	2.97#	46	
-10.0000000 V		-10.0000987	-10.0000510	-9.9999013	V	3.92#	52	
-5.0000000 V		-5.0000501	-5.0000262	-4.9999499	V	3.71#	52	
-2.0000000 V		-2.0000209	-2.0000090	-1.9999791	V	3.24#	43	
2.0000000 V		1.9999791	2.0000095	2.0000209	V	3.24#	45	
5.0000000 V		4.9999499	5.0000265	5.0000501	V	3.71#	53	
10.0000000 V		9.9999013	10.0000501	10.0000987	V	3.92#	51	
100.000000 V		99.998821	100.000715	100.001179	V	3.51#	61	

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
1000.00000 V		999.98900	1000.00799	1000.01100	V	2.42#	73	
DC Current								
100.000 nA		91.597	100.049	108.403	nA	1.85#	1	
1.000000 µA		0.969900	1.000067	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999948	10.030100	µA	5.2	0	
100.00000 µA		99.95000	99.99883	100.05000	µA	5.7	2	
1.0000000 mA		0.9997500	0.9999948	1.0002500	mA	7.6	2	
10.000000 mA		9.997500	9.999983	10.002500	mA	8.1	1	
100.00000 mA		99.97500	100.00057	100.02500	mA	6.1	2	
1.0000000 A		0.9995000	1.0000207	1.0005000	A	7.6	4	
Resistance								
10.00000 Ohm	10.000277	9.99918	10.00030	10.00138	Ohm	5.8	2	
100.00000 Ohm	100.003650	99.99815	100.00422	100.00915	Ohm	6.5	10	
1.0000000 kOhm	0.99998440	0.9999334	0.9999891	1.0000354	kOhm	9.1	9	
10.000000 kOhm	9.9998260	9.999316	9.999897	10.000336	kOhm	9.4	14	
100.00000 kOhm	100.000560	99.99546	100.00140	100.00566	kOhm	8.2	17	
1.0000000 MOhm	0.99995920	0.9998572	0.9999694	1.0000612	MOhm	9.3	10	
10.000000 MOhm	9.9982190	9.996119	9.998373	10.000319	MOhm	7.2	7	
100.00000 MOhm	100.006930	99.95593	100.00600	100.05793	MOhm	6.0	2	
1.00192000 GOhm		0.9818716	0.9996921	1.0219684	GOhm	>10	11	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9427	100.1700	µA	7.4	34	
100.0000 µA @ 45 Hz		99.8300	99.9874	100.1700	µA	10.0	7	
100.0000 µA @ 1 kHz		99.8300	99.9872	100.1700	µA	10.0	8	
1.000000 mA @ 20 Hz		0.998300	0.999523	1.001700	mA	10.0	28	
1.000000 mA @ 45 Hz		0.998300	0.999984	1.001700	mA	>10	1	
1.000000 mA @ 5 kHz		0.998300	1.000265	1.001700	mA	6.3	16	
1.000000 mA @ 10 kHz		0.995013	1.000560	1.004987	mA	3.47#	11	
10.00000 mA @ 20 Hz		9.98300	9.99528	10.01700	mA	10.0	28	
10.00000 mA @ 45 Hz		9.98300	9.99990	10.01700	mA	>10	1	
10.00000 mA @ 5 kHz		9.98300	10.00167	10.01700	mA	7.7	10	
10.00000 mA @ 10 kHz		9.94970	10.00290	10.05030	mA	4.0	6	
100.0000 mA @ 20 Hz		99.8300	99.9567	100.1700	mA	10.0	26	
100.0000 mA @ 45 Hz		99.8300	100.0027	100.1700	mA	>10	2	
100.0000 mA @ 5 kHz		99.8300	100.0353	100.1700	mA	8.5	21	
100.0000 mA @ 10 kHz		99.4800	100.0627	100.5200	mA	5.5	12	
1.000000 A @ 40 Hz		0.998300	0.999954	1.001700	A	6.8	3	
1.000000 A @ 5 kHz		0.998357	1.000907	1.001643	A	3.95#	55	
AC Volts								
10.00000 mV @ 10 Hz	9.997800	9.97760	9.99878	10.01800	mV	7.2	5	
10.00000 mV @ 40 Hz	9.997700	9.99328	9.99833	10.00212	mV	2.94#	14	
10.00000 mV @ 20 kHz	9.998400	9.99398	9.99897	10.00282	mV	2.94#	13	
10.00000 mV @ 50 kHz	9.998800	9.98770	9.99729	10.00990	mV	4.1	14	
10.00000 mV @ 100 kHz	10.001500	9.95039	9.98880	10.05261	mV	>10	25	
10.00000 mV @ 300 kHz	9.999500	9.59752	9.88451	10.40148	mV	>10	29	
100.0000 mV @ 10 Hz	99.99400	99.7920	99.9914	100.1960	mV	>10	1	
100.0000 mV @ 40 Hz	99.99360	99.9466	99.9962	100.0406	mV	>10	6	
100.0000 mV @ 20 kHz	99.99500	99.9480	99.9897	100.0420	mV	>10	11	
100.0000 mV @ 50 kHz	99.99490	99.8929	99.9937	100.0969	mV	>10	1	
100.0000 mV @ 100 kHz	99.99750	99.7955	99.9850	100.1995	mV	>10	6	
100.0000 mV @ 300 kHz	100.00640	98.9963	99.9423	101.0165	mV	>10	6	
1.000000 V @ 10 Hz	1.0000200	0.998000	1.000062	1.002040	V	>10	2	
1.000000 V @ 40 Hz	0.9999989	0.999529	1.000040	1.000469	V	>10	9	
1.000000 V @ 20 kHz	0.9999984	0.999528	0.999971	1.000468	V	>10	6	
1.000000 V @ 50 kHz	1.0000149	0.998995	1.000070	1.001035	V	>10	5	
1.000000 V @ 100 kHz	1.0000389	0.998019	1.000195	1.002059	V	>10	8	
1.000000 V @ 300 kHz	1.0003754	0.990272	1.001898	1.010479	V	>10	15	
10.00000 V @ 10 Hz	10.000108	9.97991	10.00036	10.02031	V	>10	1	
10.00000 V @ 40 Hz	9.999949	9.99525	10.00038	10.00465	V	>10	9	
10.00000 V @ 20 kHz	10.000001	9.99530	9.99975	10.00470	V	>10	5	
10.00000 V @ 50 kHz	10.000091	9.98989	10.00058	10.01028	V	>10	5	

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 100 kHz	10.000453	9.98025	9.99993	10.02065	V	>10	3	
10.00000 V @ 300 kHz	10.004297	9.90325	10.00300	10.10534	V	>10	1	
100.0000 V @ 10 Hz	100.00065	99.7986	100.0055	100.2027	V	>10	2	
100.0000 V @ 40 Hz	99.99960	99.9526	100.0038	100.0466	V	>10	9	
100.0000 V @ 20 kHz	100.00240	99.9554	100.0023	100.0494	V	>10	0	
100.0000 V @ 50 kHz	100.00624	99.9042	100.0144	100.1082	V	>10	8	
100.0000 V @ 100 kHz	100.01079	99.8089	100.0147	100.2128	V	>10	2	
100.0000 V @ 200 kHz	100.06064	99.0500	100.0514	101.0712	V	>10	1	
700.0000 V @ 40 Hz	700.01210	699.4321	700.0015	700.5921	V	>10	2	
700.0000 V @ 20 kHz	700.00580	699.4258	699.7836	700.5858	V	>10	38	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000139	10.005000	Hz	>10	3	
40.00000 Hz @ 1 V		39.996000	40.000503	40.004000	Hz	>10	13	
100.00000 Hz @ 1 V		99.990000	100.001152	100.010000	Hz	>10	12	
1000.0000 Hz @ 1 V		999.90000	1000.00887	1000.10000	Hz	>10	9	
10000.0000 Hz @ 1 V		9999.00000	10000.08774	10001.00000	Hz	>10	9	
20000.0000 Hz @ 1 V		19998.00000	20000.17738	20002.00000	Hz	>10	9	
50000.0000 Hz @ 1 V		49995.00000	50000.43868	50005.00000	Hz	>10	9	
100.00000 kHz @ 1 V		99.990000	100.000877	100.010000	kHz	>10	9	
500.00000 kHz @ 1 V		499.950000	500.004435	500.050000	kHz	>10	9	
1.000000 MHz @ 1 V		0.9999000	1.0000088	1.0001000	MHz	>10	9	
2.000000 MHz @ 1 V		1.9998000	2.0000177	2.0002000	MHz	>10	9	
4.000000 MHz @ 1 V		3.9996000	4.0000355	4.0004000	MHz	>10	9	
6.000000 MHz @ 1 V		5.9994000	6.0000532	6.0006000	MHz	>10	9	
8.000000 MHz @ 1 V		7.9992000	8.0000702	8.0008000	MHz	>10	9	
10.000000 MHz @ 1 V		9.9990000	10.0000877	10.0010000	MHz	>10	9	

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

PRIMARY STANDARDS
LABORATORY
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Limitations

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

Equipment (Standard) Used

Asset #	Description	Model #	Expires
6664631	Calibrator,Multifunction	5730A	April 25, 2018
6651332	Generator,Function	33250A	February 16, 2018
20563	Standard,Measurement,AC	5790A	October 10, 2018
20174	Amplifier	5725A	August 11, 2018
11123	Resistor,Standard	5155-9	May 10, 2018

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Traceability

Values and the associated uncertainties reported are traceable to the SI through one of more of the following:

1. Reference standards whose values are disseminated by the PSL and are traceable to National Institute of Standards and Technology (NIST) 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 in special cases and where warranted, such as consensus standards where no national or international standards exist.

NOTE 1: This certificate or report shall not be reproduced except in full, without the advance written approval of the laboratory.

NOTE 2: The as received condition of the standard, set of standards, or measurement equipment described herein was as expected, unless otherwise noted in the body of the certificate or report.

NOTE 3: 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:
Chance, Jason Metrologist	Johnson, Raegan Lynn QA Representative

End-of-Document

Agilent 3458A # MY45048372

PRIMARY STANDARDS
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Limited Calibration Certificate

Document #: 6652539_11715460

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 06752
Custodian	Merchant, Bion J.
Location	SNLNM/TA1/758/1042
Date of Receipt	June 20, 2017
Dates Tested (Start – End)	June 27, 2017 - June 27, 2017
Date Approved	June 29, 2017
Calibration Expiration Date	June 29, 2018

Calibration Description

Calibration Lab	PSL-ELECTRICAL
Calibration Procedure, rev.	HP 3458A, 4.2
Temperature	23 ± 2 deg C
Humidity	40 ± 20 %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**
6652539_11715460

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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

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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: 6/27/2017
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	2/15/2018
6664631	Fluke 5730A Multifunction Calibrator	9/8/2017
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 35.4 deg.C
DC Volts
```

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99812	99.99985	100.00188	mV	2.26#	8	
-100.00000 mV		-100.00188	-99.99981	-99.99812	mV	2.26#	10	
1.00000000 V		0.99998965	1.00000028	1.00001035	V	2.97#	3	
-1.00000000 V		-1.00001035	-1.00000058	-0.99998965	V	2.97#	6	
-10.0000000 V		-10.0000987	-10.0000089	-9.9999013	V	3.92#	9	
-5.0000000 V		-5.0000501	-5.0000048	-4.9999499	V	3.71#	10	
-2.0000000 V		-2.0000209	-2.0000006	-1.9999791	V	3.24#	3	
2.0000000 V		1.9999791	2.0000011	2.0000209	V	3.24#	5	

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		4.9999499	5.0000048	5.0000501	V	3.71#	10	
10.0000000 V		9.9999013	10.0000079	10.0000987	V	3.92#	8	
100.000000 V		99.998821	100.000319	100.001179	V	3.51#	27	
1000.00000 V		999.98900	1000.00336	1000.01100	V	2.42#	31	
DC Current								
100.000 nA		91.597	99.923	108.403	nA	1.85#	1	
1.000000 µA		0.969900	0.999917	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999806	10.030100	µA	5.2	1	
100.00000 µA		99.95000	99.99894	100.05000	µA	5.7	2	
1.0000000 mA		0.9997500	0.9999959	1.0002500	mA	7.6	2	
10.000000 mA		9.997500	9.999998	10.002500	mA	8.1	0	
100.00000 mA		99.97500	100.00088	100.02500	mA	6.1	4	
1.0000000 A		0.9995000	1.0000031	1.0005000	A	7.6	1	
Resistance								
10.00000 Ohm	10.000270	9.99917	10.00025	10.00137	Ohm	5.8	2	
100.00000 Ohm	100.003620	99.99812	100.00375	100.00912	Ohm	6.5	2	
1.0000000 kOhm	0.99998460	0.9999336	0.9999835	1.0000356	kOhm	9.1	2	
10.000000 kOhm	9.9998320	9.999322	9.999839	10.000342	kOhm	9.4	1	
100.00000 kOhm	100.000630	99.99553	100.00083	100.00573	kOhm	8.2	4	
1.0000000 MOhm	0.99996060	0.9998586	0.9999657	1.0000626	MOhm	9.3	5	
10.000000 MOhm	9.9982380	9.996138	9.998409	10.000338	MOhm	7.2	8	
100.00000 MOhm	100.008520	99.95752	100.02156	100.05952	MOhm	6.0	26	
1.00192000 GOhm		0.9818716	1.0013050	1.0219684	GOhm	>10	3	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9380	100.1700	µA	7.4	37	
100.0000 µA @ 45 Hz		99.8300	99.9850	100.1700	µA	10.0	9	
100.0000 µA @ 1 kHz		99.8300	99.9838	100.1700	µA	10.0	10	
1.000000 mA @ 20 Hz		0.998300	0.999483	1.001700	mA	10.0	30	
1.000000 mA @ 45 Hz		0.998300	0.999956	1.001700	mA	>10	3	
1.000000 mA @ 5 kHz		0.998300	1.000252	1.001700	mA	6.3	15	
1.000000 mA @ 10 kHz		0.995013	1.000531	1.004987	mA	3.47#	11	
10.00000 mA @ 20 Hz		9.98300	9.99485	10.01700	mA	10.0	30	
10.00000 mA @ 45 Hz		9.98300	9.99963	10.01700	mA	>10	2	
10.00000 mA @ 5 kHz		9.98300	10.00159	10.01700	mA	7.7	9	
10.00000 mA @ 10 kHz		9.94970	10.00284	10.05030	mA	4.0	6	
100.0000 mA @ 20 Hz		99.8300	99.9512	100.1700	mA	10.0	29	
100.0000 mA @ 45 Hz		99.8300	100.0005	100.1700	mA	>10	0	
100.0000 mA @ 5 kHz		99.8300	100.0334	100.1700	mA	8.5	20	
100.0000 mA @ 10 kHz		99.4800	100.0615	100.5200	mA	5.5	12	
1.000000 A @ 40 Hz		0.998300	0.999871	1.001700	A	6.8	8	
1.000000 A @ 5 kHz		0.998357	1.000928	1.001643	A	3.95#	57	
AC Volts								
10.00000 mV @ 10 Hz	9.997500	9.97730	9.99829	10.01769	mV	7.2	4	
10.00000 mV @ 40 Hz	9.997600	9.99318	9.99808	10.00202	mV	2.94#	11	
10.00000 mV @ 20 kHz	9.998400	9.99398	9.99939	10.00282	mV	2.94#	22	
10.00000 mV @ 50 kHz	9.998900	9.98780	9.99672	10.01000	mV	4.1	20	
10.00000 mV @ 100 kHz	10.001500	9.95039	9.98671	10.05261	mV	>10	29	
10.00000 mV @ 300 kHz	9.998800	9.59685	9.86304	10.40075	mV	>10	34	
100.0000 mV @ 10 Hz	99.99330	99.7913	100.0001	100.1953	mV	>10	3	
100.0000 mV @ 40 Hz	99.99450	99.9475	100.0002	100.0415	mV	>10	12	
100.0000 mV @ 20 kHz	99.99500	99.9480	99.9922	100.0420	mV	>10	6	
100.0000 mV @ 50 kHz	99.99480	99.8928	99.9944	100.0968	mV	>10	0	
100.0000 mV @ 100 kHz	99.99690	99.7949	99.9824	100.1989	mV	>10	7	
100.0000 mV @ 300 kHz	99.99290	98.9830	99.9141	101.0028	mV	>10	8	
1.000000 V @ 10 Hz	1.0000181	0.997998	1.000063	1.002038	V	>10	2	
1.000000 V @ 40 Hz	1.0000172	0.999547	1.000045	1.000487	V	>10	6	
1.000000 V @ 20 kHz	1.0000173	0.999547	0.999938	1.000497	V	>10	17	
1.000000 V @ 50 kHz	1.0000320	0.999012	1.000005	1.001052	V	>10	3	
1.000000 V @ 100 kHz	1.0000237	0.998004	1.000072	1.002044	V	>10	2	
1.000000 V @ 300 kHz	1.0001382	0.990037	1.001300	1.010240	V	>10	12	
10.00000 V @ 10 Hz	10.000250	9.98005	10.00071	10.02045	V	>10	2	

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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	10.000221	9.99552	10.00050	10.00492	V	>10	6	
10.00000 V @ 20 kHz	10.000154	9.99545	9.99983	10.00485	V	>10	7	
10.00000 V @ 50 kHz	10.000260	9.99006	10.00042	10.01046	V	>10	2	
10.00000 V @ 100 kHz	9.999942	9.97974	9.99865	10.02014	V	>10	6	
10.00000 V @ 300 kHz	10.001953	9.90093	9.99372	10.10297	V	>10	8	
100.0000 V @ 10 Hz	100.00196	99.8000	100.0063	100.2040	V	>10	2	
100.0000 V @ 40 Hz	100.00209	99.9551	100.0053	100.0491	V	>10	7	
100.0000 V @ 20 kHz	100.00333	99.9563	99.9998	100.0503	V	>10	8	
100.0000 V @ 50 kHz	100.00953	99.9075	100.0102	100.1115	V	>10	1	
100.0000 V @ 100 kHz	100.01541	99.8134	100.0069	100.2174	V	>10	4	
100.0000 V @ 200 kHz	100.06695	99.0563	100.0300	101.0776	V	>10	4	
700.0000 V @ 40 Hz	700.02110	699.4411	699.9362	700.6011	V	>10	15	
700.0000 V @ 20 kHz	700.02830	699.4483	699.6416	700.6083	V	>10	67	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000086	10.005000	Hz	>10	2	
40.00000 Hz @ 1 V		39.996000	40.000213	40.004000	Hz	>10	5	
100.00000 Hz @ 1 V		99.990000	100.000457	100.010000	Hz	>10	5	
1000.0000 Hz @ 1 V		999.90000	1000.00305	1000.10000	Hz	>10	3	
10000.0000 Hz @ 1 V		9999.00000	10000.02861	10001.00000	Hz	>10	3	
20000.0000 Hz @ 1 V		19998.00000	20000.05913	20002.00000	Hz	>10	3	
50000.0000 Hz @ 1 V		49995.00000	50000.14782	50005.00000	Hz	>10	3	
100.00000 kHz @ 1 V		99.990000	100.000296	100.010000	kHz	>10	3	
500.00000 kHz @ 1 V		499.950000	500.001478	500.050000	kHz	>10	3	
1.000000 MHz @ 1 V		0.9999000	1.0000029	1.0001000	MHz	>10	3	
2.000000 MHz @ 1 V		1.9998000	2.0000059	2.0002000	MHz	>10	3	
4.000000 MHz @ 1 V		3.9996000	4.0000116	4.0004000	MHz	>10	3	
6.000000 MHz @ 1 V		5.9994000	6.0000174	6.0006000	MHz	>10	3	
8.000000 MHz @ 1 V		7.9992000	8.0000233	8.0008000	MHz	>10	3	
10.000000 MHz @ 1 V		9.9990000	10.0000296	10.0010000	MHz	>10	3	

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

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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 Metrologist	Aragon, Steven J. Metrologist

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