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2018 Kinemetrics Q330M+ Digitizer Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated two Kinemetrics Q330M+ digitizers. The digitizers are intended to record sensor output for seismic and infrasound monitoring applications. Notable improvements to the Q330M+ include the support for transmission and authentication of CD1.1 data, integration of analog and digital weather stations, support for multiple gain amplification levels, and the use of a webpage for status and configuration of the digitizer. 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 digitizers are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

ACKNOWLEDGEMENTS

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 Kinemetrics for providing the digitizers to evaluate and for their presence and support in conducting the evaluation.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND DEFINITIONS

BB	Broadband
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
CD1.1	Continuous Data format for transmitting IMS data
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
HNM	High Noise Model
IMS	International Monitoring System of the CTBTO
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories
SP	Short-period

1 INTRODUCTION

Sandia National Laboratories has tested and evaluated two Q330M+ digitizers, developed by Kinemetrics.

Figure 1 Kinemetrics Q330M+ Digitizers

The Kinemetrics Q330M+ 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 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 Kinemetrics Q330M+ digitizers, shown in the figure above, with serial numbers 6640 and 6641 was performed to compare their performance to the manufacturer's specifications and CTBTO requirements.

The two digitizers evaluated are the Q330M+ model, indicating that they have been modified to contain a CTBTO Standard Station Interface (SSI) and perform data authentication and CD1.1 data transmission. The digitizers were operating with the firmware revision 2.2 and 2.3 installed. Q330M+ Digitizer #6640 was provided with 3 recording channels and Digitizer #6641 was provided with two sets of 3 channels, organized into ports A and B. The digitizer recording channels were configured to sample at rates of 20 Hz, 40 Hz, and 100 Hz. Also new in the Q330M+ is an expanded set of gain settings that were evaluated at 1x, 2x, 4x, 8x, 16x, and 32x.

The digitizers were configured to stream data over Ethernet to a computer using a CD1.1 data receiver. The digitizers were also configured to time synchronize to their internal GPS module and maintain an active GPS lock continuously.

QUANTERRA

A Division of Kinematics

Q330M+

SPECIFICATIONS

Channels	3, optionally 6, 24-bit main channels; 6 8-bit auxiliary channels
Dynamic Range (0-7Hz bandwidth)	141dB RMS sine wave 144dB zero-to-peak sine wave 150dB peak-to-peak sine wave
Input Impedance	150 kΩ differential for active sensors; 2 MΩ differential at gain ≥8 for passive sensors
Input Range	40Vpp at gain=1
Gain	Selectable per 3-channel group: 1, 2, 4, 8, 16, 32, 64, 128
Digitizer Noise	16dB below NLNM from 0.02 -16Hz used with standard broadband sensors, such as STS-2.5; voltage noise as low as -163dB re $1V^2/Hz$, depending on gain
Filtering	Configurable Linear or Minimum-phase
Sample Rate	1000, 500, 250, 200, 100, 50, 40, 20, 10, 1
Time Accuracy	<1µs when locked to GPS or PTP server
Total Harmonic Distortion	Better than -120dB
Cross-talk	Better than -130dB
Data Storage and Retrieval	PC/MAC/Linux-formatted removable SLC SD card, standard 8GB (up to 32GB possible); optional external USB flash drive for data copying or mirroring, standard 64GB (up to 256GB possible
Sensor Control	Calibrate: step, low-THD sine wave, MLS or random binary; lock/unlock & re-center
Operational Status	Over 50 State-of-Health channels including temperature, voltages, currents, GPS status, Sensor boom position (6 channels)

Network	Ethernet (10/100BT) Full IP Protocol Stack (Linux)
Authentication	Hardware; supported algorithms: DSA 1024 digital signature and key exchange ECDSA Digital Signature Algorithm (in the future)
Protocols	CD1.1, Q330 native, SeedLink
Other Ports	1 x USB2.0 2 X CONSOLE PORTS UP TO 115 kbaud 1 x digital I/O for vault intrusion switch
Power	12VDC nominal (9-36VDC operational) Consumption depending on configuration
Physical	Sealed, Aluminum, 18 x 4 x 6 in., 10 lbs., rubber endcaps, externally visible status and fault indicators; rated IP68 (24 hours immersion at 1m depth)
Temperature	Fully specified -20 to +60° C Guaranteed operative -40 to +70°C

Specifications subject to change without notice

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11-20-17

Figure 2 Kinemetrics Q330M+ 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.

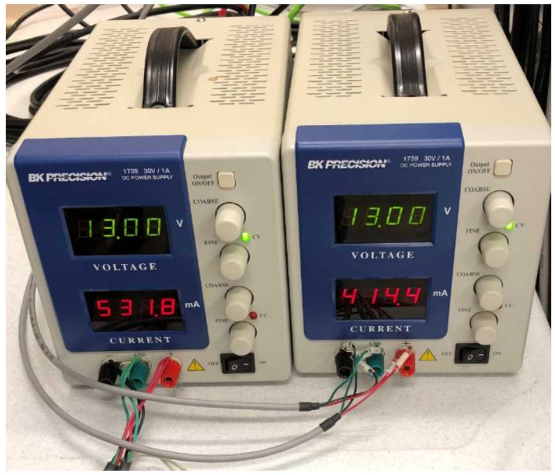


Figure 4 Power Supplies and Temperature Controller

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.

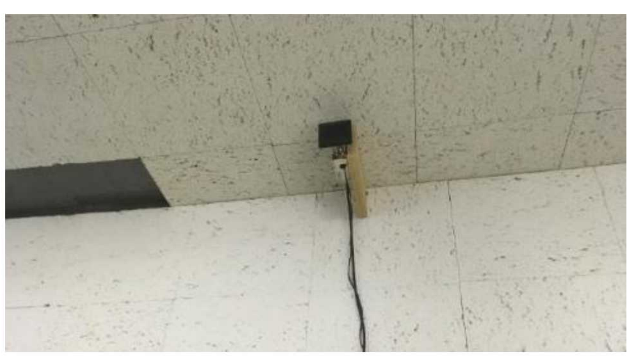


Figure 6 GPS Re-broadcaster

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
CD1.1 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 re-testing had to be performed later in 2018 and early 2019 using updated firmware revisions to address identified issues.

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 active 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 the 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.

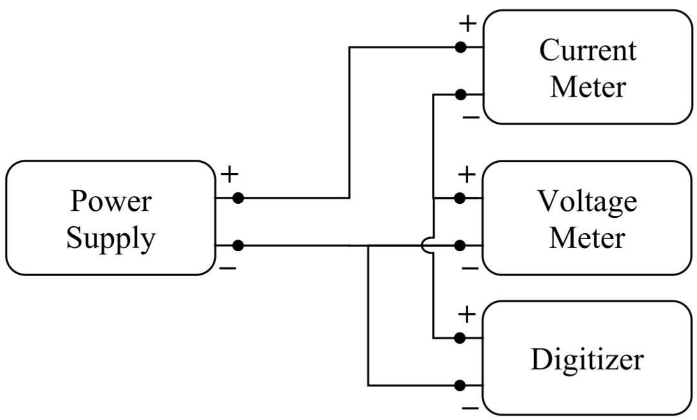


Figure 7 Power Consumption Configuration Diagram

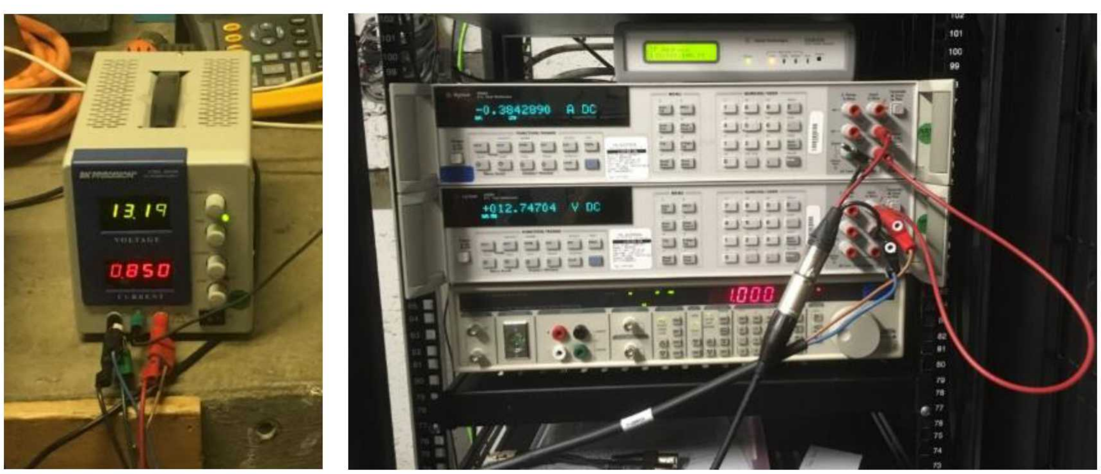


Figure 8 Power Consumption Configuration Picture

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 figures below show 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.

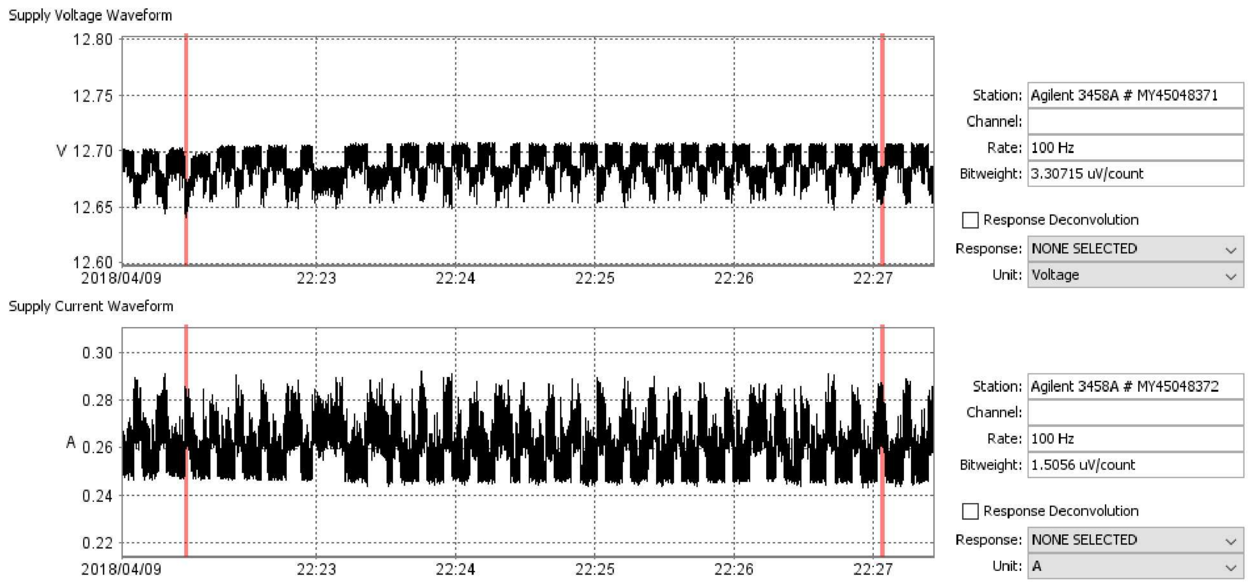


Figure 9 Power Consumption Voltage and Current Time Series, #6640, gain 1x

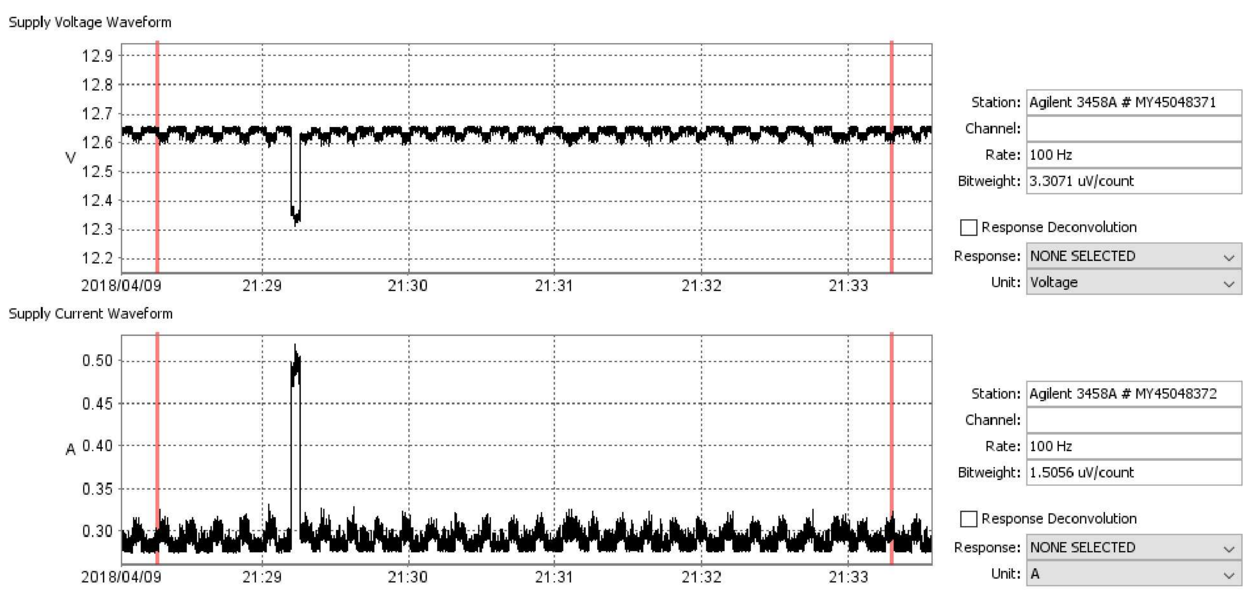


Figure 10 Power Consumption Voltage and Current Time Series, #6641, gain 8H

The resulting mean and standard deviation for each of the voltage, current, and power consumption levels are shown in the tables below.

Table 4 Power Consumption Results: Q330M+ 6640, 3 channels

	Supply Voltage		Supply Current		Power Consumption	
	Mean	SD	Mean	SD	Mean	SD
Gain 1	12.69 V	12.92 mV	0.2578 A	9.876 mA	3.271 W	0.1288 W
Gain 2	12.66 V	14.96 mV	0.2584 A	9.906 mA	3.270 W	0.1294 W
Gain 4	12.67 V	13.69 mV	0.2573 A	9.976 mA	3.260 W	0.1300 W
Gain 8H	12.67 V	34.76 mV	0.2601 A	24.38 mA	3.294 W	0.3188 W
Gain 8L	12.67 V	13.89 mV	0.2583 A	9.990 mA	3.272 W	0.1303 W
Gain 16	12.67 V	13.70 mV	0.2590 A	9.777 mA	3.281 W	0.1275 W
Gain 32	12.66 V	38.89 mV	0.2612 A	25.10 mA	3.306 W	0.3288 W

Table 5 Power Consumption Results: Q330M+ 6641, 6 channels

	Supply Voltage		Supply Current		Power Consumption	
	Mean	SD	Mean	SD	Mean	SD
Gain 1	12.64 V	16.43 mV	0.2853 A	9.855 mA	3.607 W	0.1294 W
Gain 2	12.64 V	19.12 mV	0.2883 A	9.861 mA	3.644 W	0.1303 W
Gain 4	12.64 V	13.58 mV	0.2876 A	9.980 mA	3.635 W	0.1302 W
Gain 8H	12.63 V	34.96 mV	0.2904 A	24.76 mA	3.669 W	0.3239 W
Gain 8L	12.64 V	13.70 mV	0.2885 A	9.957 mA	3.645 W	0.1299 W
Gain 16	12.63 V	13.84 mV	0.2883 A	9.913 mA	3.642 W	0.1294 W
Gain 32	12.63 V	13.98 mV	0.2882 A	9.993 mA	3.640 W	0.1304 W

The Q330M+ digitizers were observed to consume between 3.27 and 3.31 W for a 3-channel configuration and between 3.61 and 3.67 W for a 6-channel configuration. There does not appear to be any increase in power consumption with gain level.

The measurements of power consumption were made while the Q330M+ was configured to record simultaneously at sample rates of 20 Hz, 40 Hz, and 100 Hz. Time series data was recording internally and streamed over a 100 Base-T Ethernet connection. The digitizers were equipped with an authentication card and GPS was configured to be on continuously.

No specification for power consumption was provided in the datasheet to compare this result against.

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.

3.2.2 Configuration

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

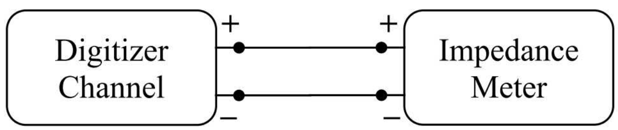


Figure 11 Input Impedance Configuration Diagram

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 taken from the meter, preferably 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 of 150 kohm for the gains of 1x, 2x, 4x, and 8xH and 2 Mohm for the gains of 8xL, 16x, and 32x are shown in the tables below.

Table 7 Input Impedance Results: Q330M+ 6640

	Channel 1 (Z)		Channel 2 (N)		Channel 3 (E)	
Gain 1	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 2	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 4	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 8H	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 8L	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%
Gain 16	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%
Gain 32	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%

Table 8 Input Impedance Results: Q330M+ 6641, Port A

	Channel 1 (Z)		Channel 2 (N)		Channel 3 (E)	
Gain 1	0.15694 Mohm	4.63%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 2	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 4	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 8H	0.15690 Mohm	4.60%	0.15700 Mohm	4.67%	0.15690 Mohm	4.60%
Gain 8L	1.9980 Mohm	-0.10%	1.9970 Mohm	-0.15%	1.9980 Mohm	-0.10%
Gain 16	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%
Gain 32	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%

Table 9 Input Impedance Results: Q330M+ 6641, Port B

	Channel 1 (Z)		Channel 2 (N)		Channel 3 (E)	
Gain 1	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 2	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 4	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 8H	0.15700 Mohm	4.67%	0.15690 Mohm	4.60%	0.15690 Mohm	4.60%
Gain 8L	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%
Gain 16	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%
Gain 32	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%	1.9980 Mohm	-0.10%

The channels with 150 kohm nominal impedance were all consistently within 4.6% of the nominal value and the channels with 2 Mohm nominal impedance were all consistently within 0.1% of the nominal value.

3.3 DC Accuracy

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

3.3.1 Measurand

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

3.3.2 Configuration

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

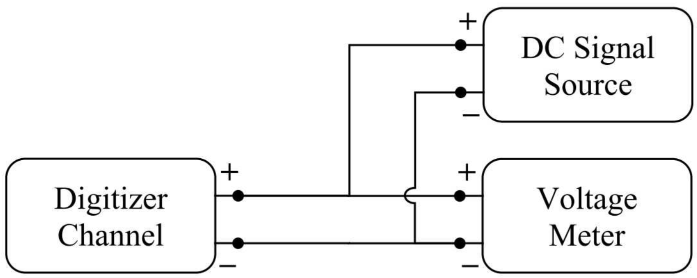


Figure 12 DC Accuracy Configuration Diagram

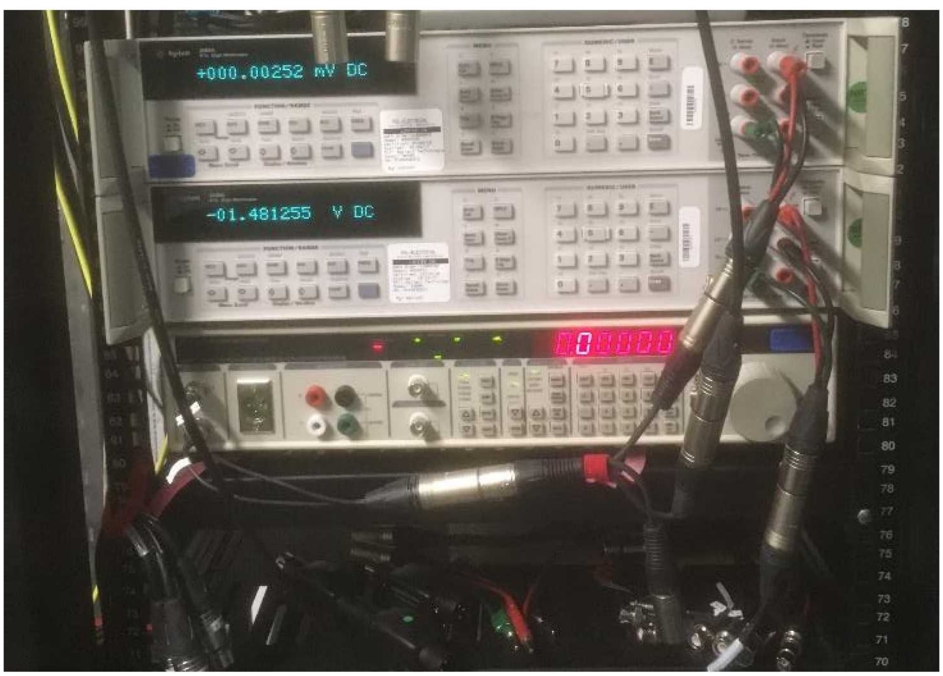


Figure 13 DC Accuracy Configuration Picture

Table 10 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} *and* V_{neg}

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

C_{pos} *and* C_{neg}

The digitizer bit-weight in Volts / count is computed:

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

3.3.4 Result

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

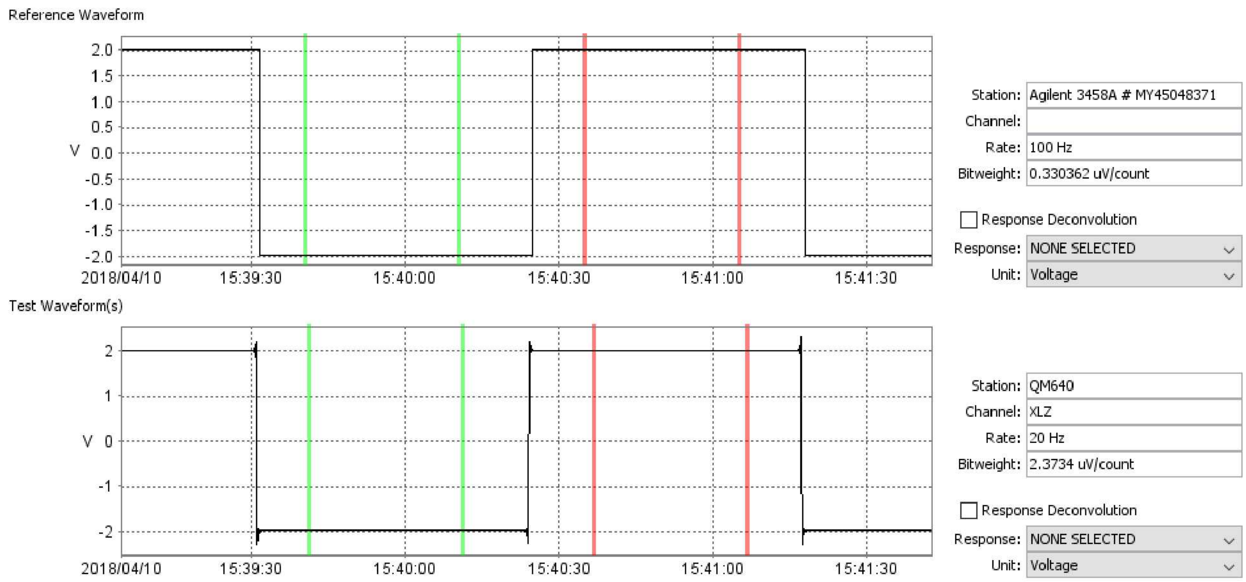


Figure 14 DC Accuracy Time Series

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

Table 11 DC Accuracy Bit-weight: Q330M+ 6640

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Voltage	100 Hz	1.9973 V	0.99733 V	0.49872 V	0.24960 V	0.25025 V	0.12498 V	62.525 mV
Channel 1 (Z)	20 Hz	2.3810 uV/cnt	1.1906 uV/cnt	0.59535 uV/cnt	0.29772 uV/cnt	0.29808 uV/cnt	0.14906 uV/cnt	74.530 nV/cnt
	40 Hz	2.3810 uV/cnt	1.1906 uV/cnt	0.59535 uV/cnt	0.29772 uV/cnt	0.29808 uV/cnt	0.14906 uV/cnt	74.530 nV/cnt
	100 Hz	2.3810 uV/cnt	1.1906 uV/cnt	0.59535 uV/cnt	0.29772 uV/cnt	0.29808 uV/cnt	0.14906 uV/cnt	74.530 nV/cnt
Channel 2 (N)	20 Hz	2.3815 uV/cnt	1.1910 uV/cnt	0.59598 uV/cnt	0.29783 uV/cnt	0.29813 uV/cnt	0.14910 uV/cnt	74.606 nV/cnt
	40 Hz	2.3815 uV/cnt	1.1910 uV/cnt	0.59598 uV/cnt	0.29783 uV/cnt	0.29813 uV/cnt	0.14910 uV/cnt	74.606 nV/cnt
	100 Hz	2.3815 uV/cnt	1.1910 uV/cnt	0.59598 uV/cnt	0.29783 uV/cnt	0.29813 uV/cnt	0.14910 uV/cnt	74.606 nV/cnt
Channel 3 (E)	20 Hz	2.3813 uV/cnt	1.1908 uV/cnt	0.59557 uV/cnt	0.29816 uV/cnt	0.29813 uV/cnt	0.14908 uV/cnt	74.560 nV/cnt
	40 Hz	2.3813 uV/cnt	1.1908 uV/cnt	0.59557 uV/cnt	0.29816 uV/cnt	0.29812 uV/cnt	0.14908 uV/cnt	74.560 nV/cnt
	100 Hz	2.3813 uV/cnt	1.1908 uV/cnt	0.59557 uV/cnt	0.29816 uV/cnt	0.29813 uV/cnt	0.14908 uV/cnt	74.560 nV/cnt
Nominal Bitweight		2.3840 uV/cnt	1.1920 uV/cnt	0.59600 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14900 uV/cnt	74.500 nV/cnt
Maximum Difference		0.13%	0.11%	0.11%	0.09%	0.04%	0.07%	0.14%

Table 12 DC Accuracy Bit-weight: Q330M+ 6641, Port A

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Voltage	100 Hz	1.9973 V	0.99732 V	0.49872 V	0.24960 V	0.25025 V	0.12498 V	62.525 mV
Channel 1 (Z)	20 Hz	2.3803 uV/cnt	1.1907 uV/cnt	0.59582 uV/cnt	0.29822 uV/cnt	0.29799 uV/cnt	0.29799 uV/cnt	0.14906 uV/cnt
	40 Hz	2.3803 uV/cnt	1.1907 uV/cnt	0.59582 uV/cnt	0.29822 uV/cnt	0.29799 uV/cnt	0.29799 uV/cnt	0.14906 uV/cnt
	100 Hz	2.3803 uV/cnt	1.1907 uV/cnt	0.59582 uV/cnt	0.29822 uV/cnt	0.29799 uV/cnt	0.29799 uV/cnt	0.14906 uV/cnt
Channel 2 (N)	20 Hz	2.3805 uV/cnt	1.1908 uV/cnt	0.59575 uV/cnt	0.29747 uV/cnt	0.29794 uV/cnt	0.29794 uV/cnt	0.14904 uV/cnt
	40 Hz	2.3805 uV/cnt	1.1908 uV/cnt	0.59575 uV/cnt	0.29747 uV/cnt	0.29794 uV/cnt	0.29794 uV/cnt	0.14904 uV/cnt
	100 Hz	2.3805 uV/cnt	1.1908 uV/cnt	0.59575 uV/cnt	0.29747 uV/cnt	0.29794 uV/cnt	0.29794 uV/cnt	0.14904 uV/cnt
Channel 3 (E)	20 Hz	2.3802 uV/cnt	1.1906 uV/cnt	0.59546 uV/cnt	0.29730 uV/cnt	0.29798 uV/cnt	0.29798 uV/cnt	0.14906 uV/cnt
	40 Hz	2.3802 uV/cnt	1.1906 uV/cnt	0.59546 uV/cnt	0.29730 uV/cnt	0.29798 uV/cnt	0.29798 uV/cnt	0.14906 uV/cnt
	100 Hz	2.3802 uV/cnt	1.1906 uV/cnt	0.59546 uV/cnt	0.29730 uV/cnt	0.29798 uV/cnt	0.29798 uV/cnt	0.14906 uV/cnt
Nominal Bitweight		2.3840 uV/cnt	1.1920 uV/cnt	0.59600 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14900 uV/cnt	74.500 nV/cnt
Maximum Difference		0.16%	0.11%	0.09%	0.23%	0.02%	0.04%	0.12%

Table 13 DC Accuracy Bit-weight: Q330M+ 6641, Port B

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Voltage	100 Hz	1.9973 V	0.99732 V	0.49872 V	0.24960 V	0.25025 V	0.12498 V	62.525 mV
Channel 1 (Z)	20 Hz	2.3818 uV/cnt	1.1913 uV/cnt	0.59603 uV/cnt	0.29839 uV/cnt	0.29809 uV/cnt	0.29809 uV/cnt	0.14909 uV/cnt
	40 Hz	2.3818 uV/cnt	1.1913 uV/cnt	0.59603 uV/cnt	0.29839 uV/cnt	0.29809 uV/cnt	0.29809 uV/cnt	0.14909 uV/cnt
	100 Hz	2.3818 uV/cnt	1.1913 uV/cnt	0.59603 uV/cnt	0.29839 uV/cnt	0.29809 uV/cnt	0.29809 uV/cnt	0.14909 uV/cnt
Channel 2 (N)	20 Hz	2.3811 uV/cnt	1.1910 uV/cnt	0.59584 uV/cnt	0.29784 uV/cnt	0.29805 uV/cnt	0.29805 uV/cnt	0.14909 uV/cnt
	40 Hz	2.3811 uV/cnt	1.1910 uV/cnt	0.59584 uV/cnt	0.29784 uV/cnt	0.29805 uV/cnt	0.29805 uV/cnt	0.14909 uV/cnt
	100 Hz	2.3811 uV/cnt	1.1910 uV/cnt	0.59584 uV/cnt	0.29784 uV/cnt	0.29805 uV/cnt	0.29805 uV/cnt	0.14909 uV/cnt
Channel 3 (E)	20 Hz	2.3804 uV/cnt	1.1906 uV/cnt	0.59571 uV/cnt	0.29790 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14905 uV/cnt
	40 Hz	2.3804 uV/cnt	1.1906 uV/cnt	0.59571 uV/cnt	0.29790 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14905 uV/cnt
	100 Hz	2.3804 uV/cnt	1.1906 uV/cnt	0.59571 uV/cnt	0.29790 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14905 uV/cnt
Nominal Bitweight		2.3840 uV/cnt	1.1920 uV/cnt	0.59600 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14900 uV/cnt	74.500 nV/cnt
Maximum Difference		0.15%	0.11%	0.05%	0.13%	0.03%	0.06%	0.12%

The nominal bit-weights provided by Kinemetrics were specified to be 2.384 uV/count, 1.192 uV/count, 0.596 uV/count, 0.298 uV/count, 0.149 uV/count, and 74.5 nV/count for gains of 1, 2, 4, 8x, 16x, and 32x, respectively. The measured DC bit-weights were found to be consistent with the nominal values to within better than 0.23%.

As expected, the bit-weight for each channel did not change with respect to the sample rate.

3.4 AC Accuracy

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

3.4.1 Measurand

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

3.4.2 Configuration

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

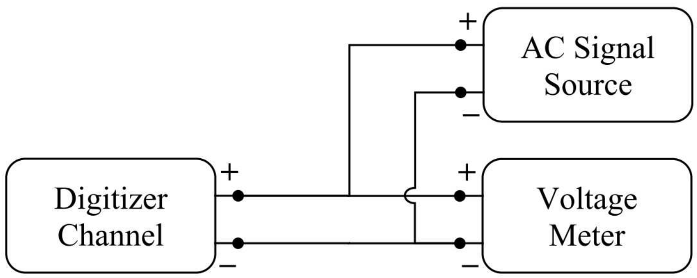


Figure 15 AC Accuracy Configuration Diagram

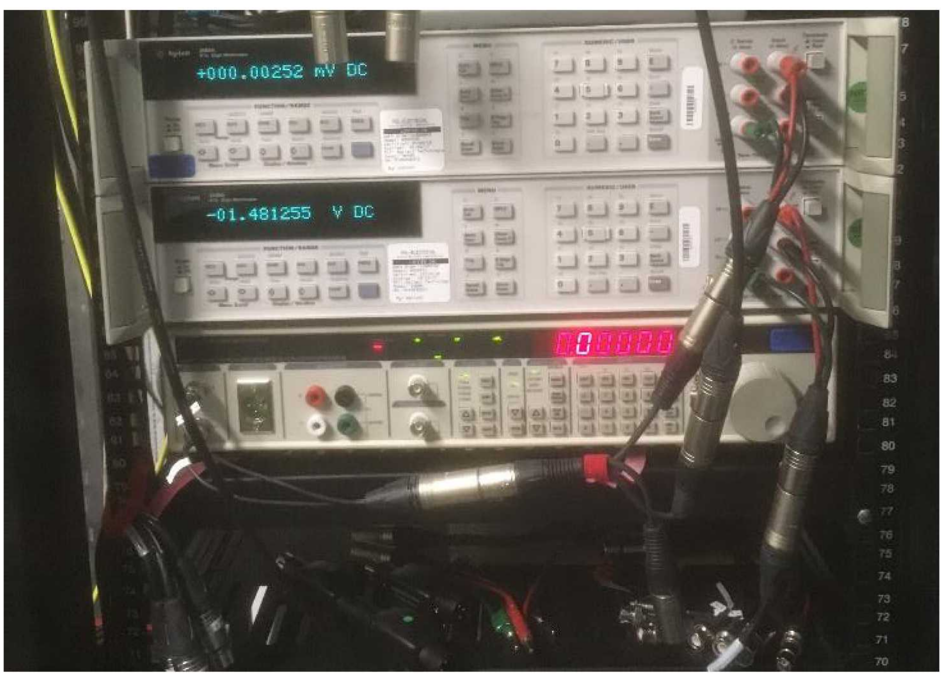


Figure 16 AC Accuracy Configuration Picture

Table 14 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:

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

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

The digitizer bit-weight in Volts / count is computed:

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

3.4.4 Result

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

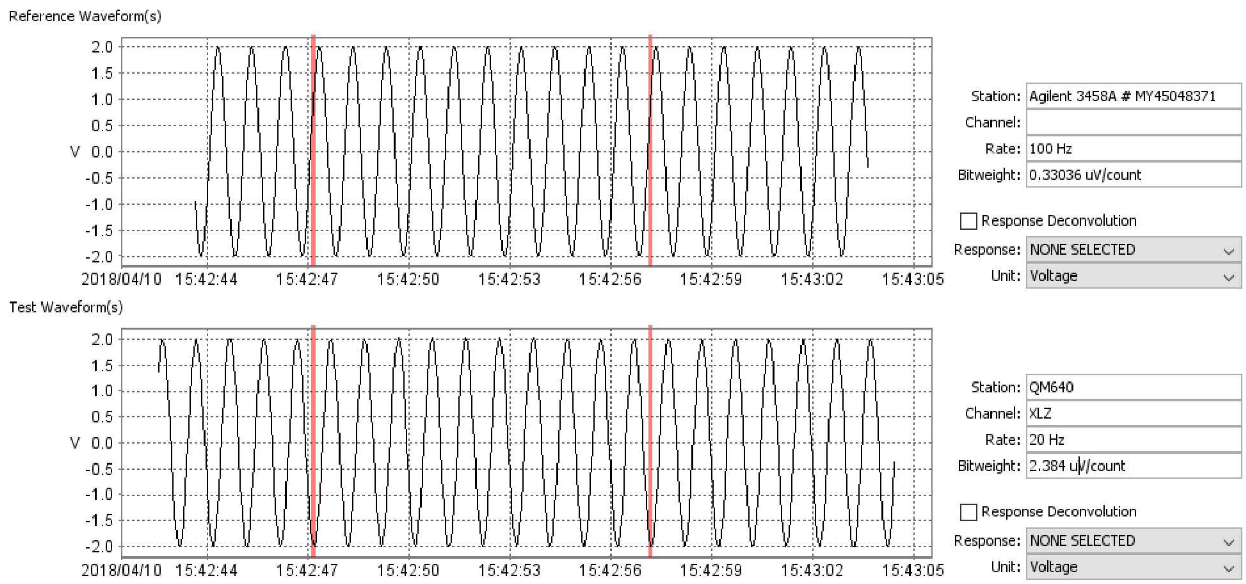


Figure 17 AC Accuracy Time Series

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

Table 15 AC Accuracy Bit-weight: Q330M+ 6640

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Voltage	100 Hz	1.9959 V	0.99692 V	0.49846 V	0.24936 V	0.25003 V	0.12492 V	62.483 mV
Channel 1 (Z)	20 Hz	2.3664 uV/cnt	1.1834 uV/cnt	0.59171 uV/cnt	0.29590 uV/cnt	0.29626 uV/cnt	0.14815 uV/cnt	74.074 nV/cnt
	40 Hz	2.3664 uV/cnt	1.1834 uV/cnt	0.59171 uV/cnt	0.29590 uV/cnt	0.29626 uV/cnt	0.14815 uV/cnt	74.075 nV/cnt
	100 Hz	2.3792 uV/cnt	1.1898 uV/cnt	0.59490 uV/cnt	0.29749 uV/cnt	0.29786 uV/cnt	0.14895 uV/cnt	74.474 nV/cnt
Channel 2 (N)	20 Hz	2.3669 uV/cnt	1.1838 uV/cnt	0.59234 uV/cnt	0.29601 uV/cnt	0.29630 uV/cnt	0.14819 uV/cnt	74.149 nV/cnt
	40 Hz	2.3669 uV/cnt	1.1838 uV/cnt	0.59234 uV/cnt	0.29602 uV/cnt	0.29631 uV/cnt	0.14819 uV/cnt	74.150 nV/cnt
	100 Hz	2.3797 uV/cnt	1.1901 uV/cnt	0.59553 uV/cnt	0.29761 uV/cnt	0.29790 uV/cnt	0.14899 uV/cnt	74.549 nV/cnt
Channel 3 (E)	20 Hz	2.3667 uV/cnt	1.1836 uV/cnt	0.59193 uV/cnt	0.29634 uV/cnt	0.29630 uV/cnt	0.14817 uV/cnt	74.103 nV/cnt
	40 Hz	2.3667 uV/cnt	1.1836 uV/cnt	0.59194 uV/cnt	0.29634 uV/cnt	0.29630 uV/cnt	0.14817 uV/cnt	74.104 nV/cnt
	100 Hz	2.3795 uV/cnt	1.1899 uV/cnt	0.59513 uV/cnt	0.29794 uV/cnt	0.29790 uV/cnt	0.14897 uV/cnt	74.503 nV/cnt
Nominal Bitweight		2.3840 uV/cnt	1.1920 uV/cnt	0.59600 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14900 uV/cnt	74.500 nV/cnt
Maximum Difference		0.74%	0.72%	0.72%	0.71%	0.58%	0.57%	0.57%

Table 16 AC Accuracy Bit-weight: Q330M+ 6641, Port A

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Voltage	100 Hz	1.9959 V	0.99692 V	0.49846 V	0.24936 V	0.25003 V	0.12492 V	62.483 mV
Channel 1 (Z)	20 Hz	2.3657 uV/cnt	1.1834 uV/cnt	0.59217 uV/cnt	0.29640 uV/cnt	0.29617 uV/cnt	0.14815 uV/cnt	74.131 nV/cnt
	40 Hz	2.3657 uV/cnt	1.1834 uV/cnt	0.59218 uV/cnt	0.29640 uV/cnt	0.29617 uV/cnt	0.14815 uV/cnt	74.132 nV/cnt
	100 Hz	2.3785 uV/cnt	1.1898 uV/cnt	0.59537 uV/cnt	0.29800 uV/cnt	0.29776 uV/cnt	0.14895 uV/cnt	74.531 nV/cnt
Channel 2 (N)	20 Hz	2.3660 uV/cnt	1.1835 uV/cnt	0.59211 uV/cnt	0.29566 uV/cnt	0.29612 uV/cnt	0.14812 uV/cnt	74.103 nV/cnt
	40 Hz	2.3660 uV/cnt	1.1835 uV/cnt	0.59211 uV/cnt	0.29566 uV/cnt	0.29612 uV/cnt	0.14813 uV/cnt	74.103 nV/cnt
	100 Hz	2.3787 uV/cnt	1.1899 uV/cnt	0.59530 uV/cnt	0.29725 uV/cnt	0.29772 uV/cnt	0.14892 uV/cnt	74.502 nV/cnt
Channel 3 (E)	20 Hz	2.3657 uV/cnt	1.1834 uV/cnt	0.59182 uV/cnt	0.29548 uV/cnt	0.29616 uV/cnt	0.14814 uV/cnt	74.087 nV/cnt
	40 Hz	2.3784 uV/cnt	1.1898 uV/cnt	0.59502 uV/cnt	0.29708 uV/cnt	0.29776 uV/cnt	0.14894 uV/cnt	74.487 nV/cnt
	100 Hz	2.3657 uV/cnt	1.1834 uV/cnt	0.59183 uV/cnt	0.29549 uV/cnt	0.29616 uV/cnt	0.14815 uV/cnt	74.088 nV/cnt
Nominal Bitweight		2.3840 uV/cnt	1.1920 uV/cnt	0.59600 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14900 uV/cnt	74.500 nV/cnt
Maximum Difference		0.77%	0.72%	0.70%	0.84%	0.63%	0.59%	0.57%

Table 17 AC Accuracy Bit-weight: Q330M+ 6641, Port B

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Voltage	100 Hz	1.9959 V	0.99692 V	0.49846 V	0.24936 V	0.25003 V	0.12492 V	62.483 mV
Channel 1 (Z)	20 Hz	2.3672 uV/cnt	1.1840 uV/cnt	0.59239 uV/cnt	0.29656 uV/cnt	0.29627 uV/cnt	0.14818 uV/cnt	74.136 nV/cnt
	40 Hz	2.3672 uV/cnt	1.1840 uV/cnt	0.59239 uV/cnt	0.29656 uV/cnt	0.29627 uV/cnt	0.14818 uV/cnt	74.136 nV/cnt
	100 Hz	2.3800 uV/cnt	1.1904 uV/cnt	0.59559 uV/cnt	0.29816 uV/cnt	0.29786 uV/cnt	0.14898 uV/cnt	74.536 nV/cnt
Channel 2 (N)	20 Hz	2.3665 uV/cnt	1.1838 uV/cnt	0.59220 uV/cnt	0.29602 uV/cnt	0.29623 uV/cnt	0.14818 uV/cnt	74.124 nV/cnt
	40 Hz	2.3665 uV/cnt	1.1838 uV/cnt	0.59220 uV/cnt	0.29602 uV/cnt	0.29623 uV/cnt	0.14818 uV/cnt	74.125 nV/cnt
	100 Hz	2.3793 uV/cnt	1.1902 uV/cnt	0.59539 uV/cnt	0.29762 uV/cnt	0.29783 uV/cnt	0.14897 uV/cnt	74.524 nV/cnt
Channel 3 (E)	20 Hz	2.3658 uV/cnt	1.1834 uV/cnt	0.59207 uV/cnt	0.29607 uV/cnt	0.29617 uV/cnt	0.14814 uV/cnt	74.117 nV/cnt
	40 Hz	2.3658 uV/cnt	1.1834 uV/cnt	0.59208 uV/cnt	0.29608 uV/cnt	0.29618 uV/cnt	0.14814 uV/cnt	74.118 nV/cnt
	100 Hz	2.3786 uV/cnt	1.1898 uV/cnt	0.59527 uV/cnt	0.29767 uV/cnt	0.29777 uV/cnt	0.14894 uV/cnt	74.517 nV/cnt
Nominal Bitweight		2.3840 uV/cnt	1.1920 uV/cnt	0.59600 uV/cnt	0.29800 uV/cnt	0.29800 uV/cnt	0.14900 uV/cnt	74.500 nV/cnt
Maximum Difference		0.76%	0.72%	0.66%	0.66%	0.61%	0.58%	0.57%

The nominal bit-weights provided by Kinemetrics were specified to be 2.384 uV/count, 1.192 uV/count, 0.596 uV/count, 0.298 uV/count, 0.149 uV/count, and 74.5 nV/count for gains of 1, 2, 4, 8x, 16x, and 32x, respectively. The measured AC bit-weights were found to be consistent with the nominal values to within better than 0.84%.

3.5 AC Full Scale

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

3.5.1 Measurand

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

3.5.2 Configuration

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

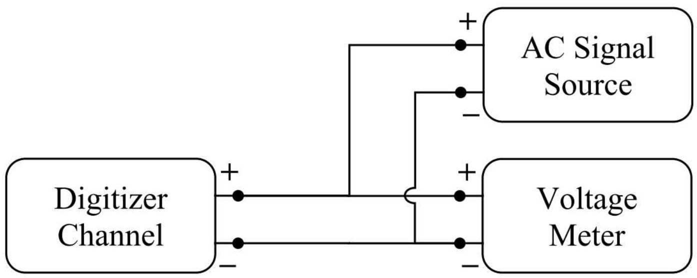


Figure 18 AC Full Scale Configuration Diagram

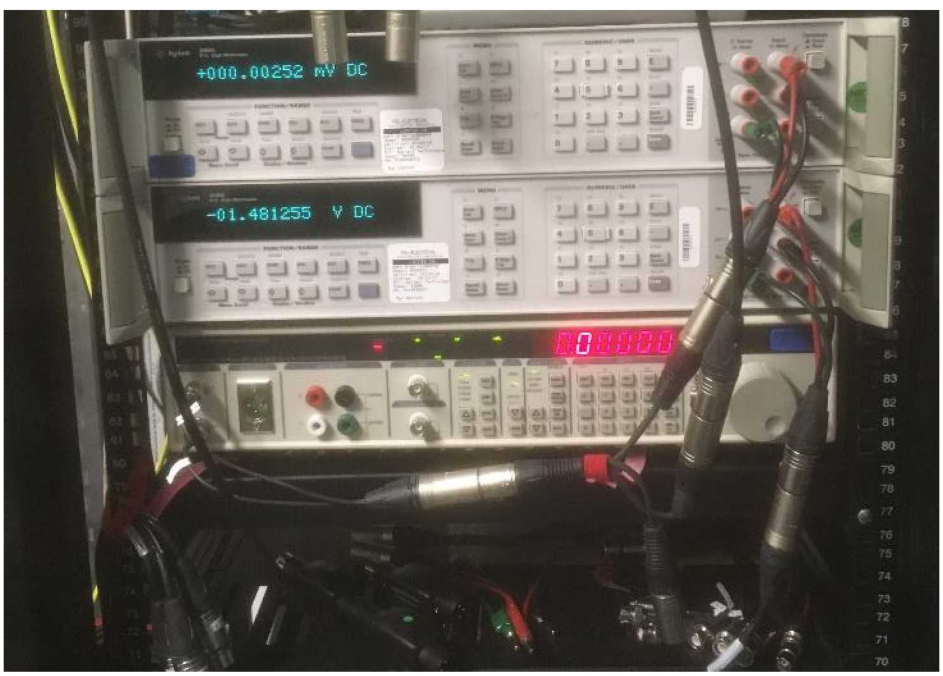


Figure 19 AC Full Scale Configuration Picture

Table 18 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 100% FS
Voltage Meter	Agilent 3458A	MY45048371	1 V full scale

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

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

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

3.5.3 Analysis

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

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

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

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

3.5.4 Result

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

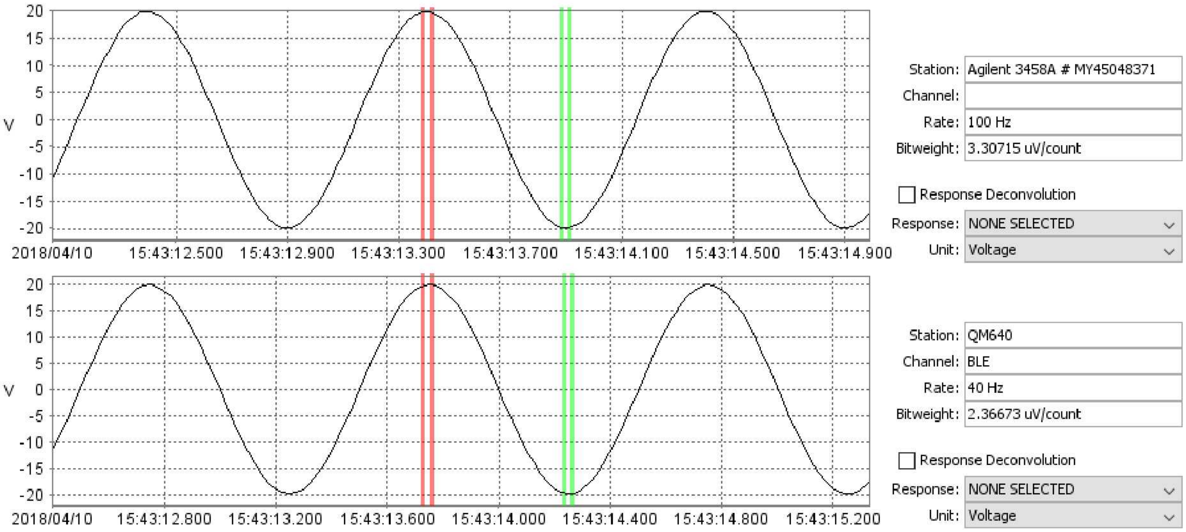


Figure 20 AC Full Scale Time Series

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

Table 19 AC Full Scale: Q330M+ 6640

	Sample Rate		Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Reference Voltage	100 Hz	Max	19.903 V	9.9543 V	4.9770 V	2.4905 V	2.4940 V	1.2473 V	0.62386 V
		Min	-19.956 V	-9.9772 V	-4.9906 V	-2.4972 V	-2.5038 V	-1.2503 V	-0.62547 V
Channel 1 (Z)	20 Hz	Max	19.911 V	9.9504 V	4.9785 V	2.4781 V	2.4922 V	1.2462 V	0.62123 V
		Min	-19.959 V	-9.9722 V	-4.9914 V	-2.4867 V	-2.4978 V	-1.2485 V	-0.62447 V
	40 Hz	Max	19.911 V	9.9504 V	4.9784 V	2.4866 V	2.4868 V	1.2462 V	0.62123 V
		Min	-19.958 V	-9.9721 V	-4.9913 V	-2.4923 V	-2.4952 V	-1.2485 V	-0.62242 V
	100 Hz	Max	19.911 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.959 V	-9.9797 V	-4.9914 V	-2.4964 V	-2.5037 V	-1.2507 V	-0.62529 V
Channel 2 (N)	20 Hz	Max	19.911 V	9.9504 V	4.9785 V	2.4782 V	2.4923 V	1.2462 V	0.62123 V
		Min	-19.959 V	-9.9722 V	-4.9914 V	-2.4867 V	-2.4978 V	-1.2485 V	-0.62447 V
	40 Hz	Max	19.911 V	9.9504 V	4.9784 V	2.4866 V	2.4868 V	1.2462 V	0.62123 V
		Min	-19.958 V	-9.9721 V	-4.9913 V	-2.4924 V	-2.4952 V	-1.2485 V	-0.62242 V
	100 Hz	Max	19.911 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.959 V	-9.9797 V	-4.9914 V	-2.4964 V	-2.5037 V	-1.2507 V	-0.62529 V
Channel 3 (E)	20 Hz	Max	19.911 V	9.9504 V	4.9785 V	2.4782 V	2.4923 V	1.2462 V	0.62123 V
		Min	-19.959 V	-9.9722 V	-4.9914 V	-2.4867 V	-2.4978 V	-1.2485 V	-0.62447 V
	40 Hz	Max	19.911 V	9.9504 V	4.9784 V	2.4866 V	2.4868 V	1.2462 V	0.62123 V
		Min	-19.958 V	-9.9721 V	-4.9913 V	-2.4923 V	-2.4952 V	-1.2485 V	-0.62242 V
	100 Hz	Max	19.911 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.959 V	-9.9797 V	-4.9914 V	-2.4964 V	-2.5037 V	-1.2507 V	-0.62529 V

Table 20 AC Full Scale: Q330M+ 6641, Port A

	Sample Rate		Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Reference	100 Hz	Max	19.911 V	9.9543 V	4.9770 V	2.4905 V	2.4972 V	1.2473 V	0.62386 V
Voltage		Min	-19.960 V	-9.9772 V	-4.9906 V	-2.4972 V	-2.5038 V	-1.2503 V	-0.62547 V
Channel 1	20 Hz	Max	19.787 V	9.9503 V	4.9784 V	2.4781 V	2.4868 V	1.2462 V	0.62121 V
(Z)		Min	-19.841 V	-9.9720 V	-4.9913 V	-2.4867 V	-2.4953 V	-1.2485 V	-0.62240 V
	40 Hz	Max	19.745 V	9.9503 V	4.9785 V	2.4867 V	2.4869 V	1.2462 V	0.62256 V
		Min	-19.798 V	-9.9721 V	-4.9914 V	-2.4924 V	-2.4978 V	-1.2485 V	-0.62448 V
	100 Hz	Max	19.801 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.848 V	-9.9797 V	-4.9914 V	-2.4963 V	-2.5037 V	-1.2507 V	-0.62529 V
Channel 2	20 Hz	Max	19.787 V	9.9503 V	4.9784 V	2.4781 V	2.4868 V	1.2462 V	0.62121 V
(N)		Min	-19.840 V	-9.9720 V	-4.9913 V	-2.4867 V	-2.4953 V	-1.2485 V	-0.62241 V
	40 Hz	Max	19.744 V	9.9503 V	4.9785 V	2.4867 V	2.4869 V	1.2462 V	0.62256 V
		Min	-19.798 V	-9.9721 V	-4.9914 V	-2.4924 V	-2.4953 V	-1.2485 V	-0.62448 V
	100 Hz	Max	19.801 V	9.9532 V	4.9785 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.849 V	-9.9797 V	-4.9914 V	-2.4964 V	-2.5037 V	-1.2507 V	-0.62529 V
Channel 3	20 Hz	Max	19.787 V	9.9503 V	4.9784 V	2.4781 V	2.4868 V	1.2462 V	0.62121 V
(E)		Min	-19.840 V	-9.9720 V	-4.9913 V	-2.4867 V	-2.4953 V	-1.2485 V	-0.62241 V
	40 Hz	Max	19.744 V	9.9503 V	4.9785 V	2.4867 V	2.4868 V	1.2462 V	0.62256 V
		Min	-19.798 V	-9.9721 V	-4.9914 V	-2.4924 V	-2.4953 V	-1.2485 V	-0.62448 V
	100 Hz	Max	19.801 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.849 V	-9.9797 V	-4.9914 V	-2.4963 V	-2.5037 V	-1.2507 V	-0.62529 V

Table 21 AC Full Scale: Q330M+ 6641, Port B

	Sample Rate		Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Reference	100 Hz	Max	19.911 V	9.9543 V	4.9770 V	2.4905 V	2.4972 V	1.2473 V	0.62386 V
Voltage		Min	-19.960 V	-9.9772 V	-4.9906 V	-2.4972 V	-2.5038 V	-1.2503 V	-0.62547 V
Channel 1	20 Hz	Max	19.787 V	9.9503 V	4.9784 V	2.4781 V	2.4868 V	1.2462 V	0.62121 V
(Z)		Min	-19.841 V	-9.9720 V	-4.9913 V	-2.4867 V	-2.4953 V	-1.2485 V	-0.62241 V
	40 Hz	Max	19.745 V	9.9504 V	4.9785 V	2.4867 V	2.4869 V	1.2462 V	0.62257 V
		Min	-19.798 V	-9.9721 V	-4.9914 V	-2.4924 V	-2.4978 V	-1.2485 V	-0.62448 V
	100 Hz	Max	19.800 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.848 V	-9.9797 V	-4.9914 V	-2.4963 V	-2.5037 V	-1.2507 V	-0.62529 V
Channel 2	20 Hz	Max	19.787 V	9.9503 V	4.9784 V	2.4781 V	2.4868 V	1.2462 V	0.62121 V
(N)		Min	-19.841 V	-9.9720 V	-4.9913 V	-2.4867 V	-2.4953 V	-1.2485 V	-0.62241 V
	40 Hz	Max	19.745 V	9.9503 V	4.9785 V	2.4867 V	2.4869 V	1.2462 V	0.62256 V
		Min	-19.798 V	-9.9721 V	-4.9914 V	-2.4924 V	-2.4953 V	-1.2485 V	-0.62448 V
	100 Hz	Max	19.800 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.848 V	-9.9797 V	-4.9914 V	-2.4963 V	-2.5037 V	-1.2507 V	-0.62529 V
Channel 3	20 Hz	Max	19.787 V	9.9503 V	4.9784 V	2.4781 V	2.4868 V	1.2462 V	0.62121 V
(E)		Min	-19.841 V	-9.9720 V	-4.9913 V	-2.4867 V	-2.4953 V	-1.2485 V	-0.62241 V
	40 Hz	Max	19.745 V	9.9503 V	4.9785 V	2.4867 V	2.4869 V	1.2462 V	0.62256 V
		Min	-19.798 V	-9.9721 V	-4.9914 V	-2.4924 V	-2.4978 V	-1.2485 V	-0.62448 V
	100 Hz	Max	19.801 V	9.9532 V	4.9784 V	2.4898 V	2.4963 V	1.2478 V	0.62359 V
		Min	-19.848 V	-9.9797 V	-4.9914 V	-2.4963 V	-2.5037 V	-1.2507 V	-0.62529 V

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

3.6 AC Over Scale

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

3.6.1 Measurand

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

3.6.2 Configuration

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

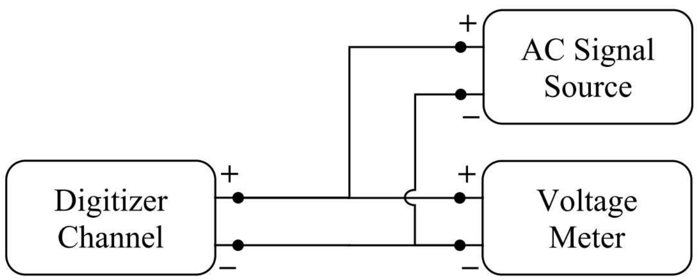


Figure 21 AC Over Scale Configuration Diagram

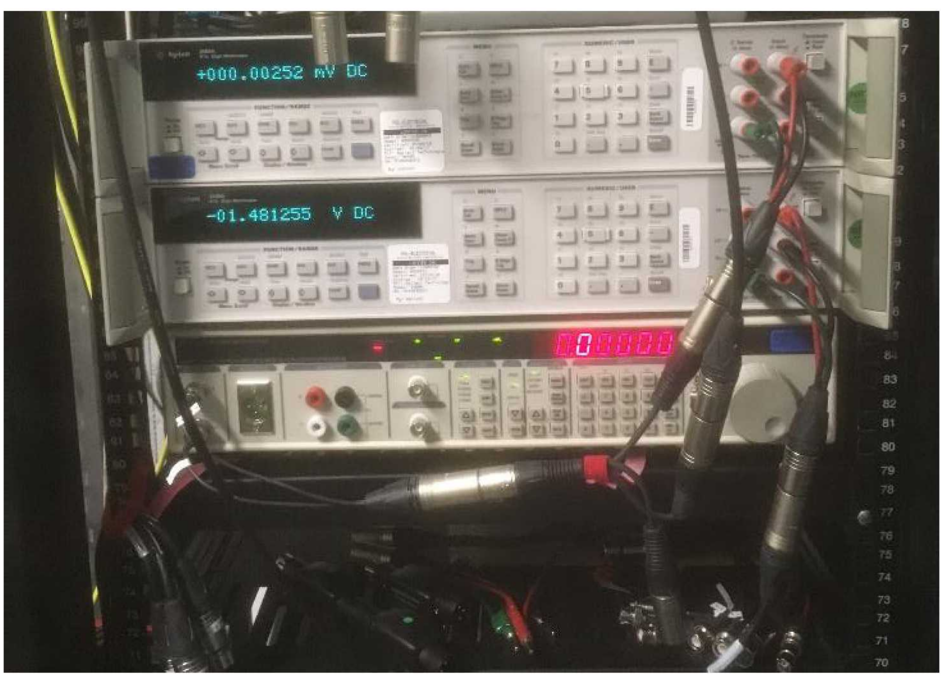


Figure 22 AC Over Scale Configuration Picture

Table 22 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:

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

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

The time series data is compared against the reference to verify that there is visible limiting of the values near the full scale.

3.6.4 Result

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

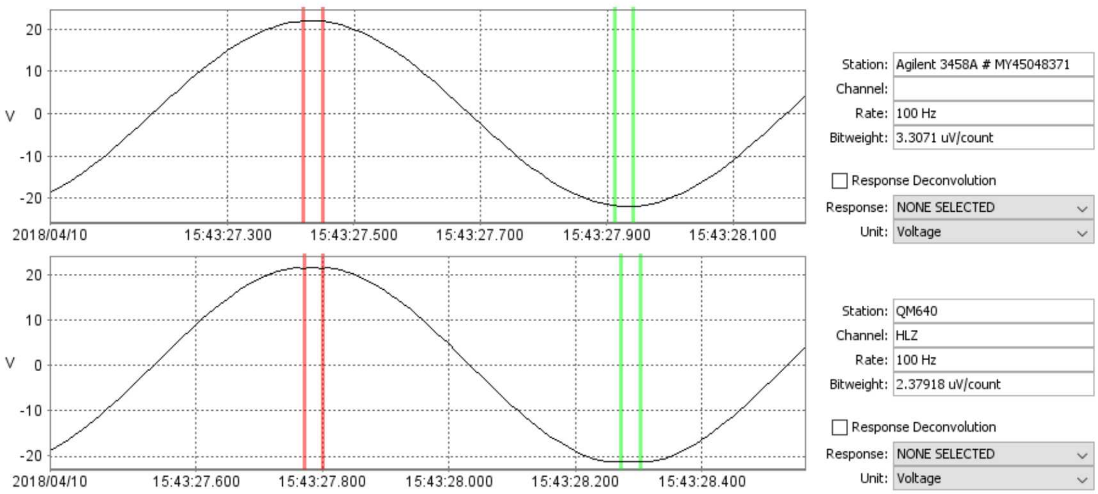


Figure 23 AC Over Scale Time Series

Note that in the figure above, signs of flattening in the time series are visible at each of the positive and negative peaks. The following tables contain the computed positive and negative peak voltages for each of the channels, sample rates, and gain levels.

Table 23 AC Over Scale: Q330M+ 6640

	Rate		Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Reference Voltage	100 Hz	Max	21.903 V	10.949 V	5.4751 V	2.7408 V	2.7471 V	1.3747 V	0.68630 V
		Min	-21.952 V	-10.975 V	-5.4903 V	-2.7483 V	-2.7553 V	-1.3790 V	-0.68790 V
Channel 1 (Z)	20 Hz	Max	21.404 V	10.701 V	5.3544 V	2.6804 V	2.5145 V	1.2576 V	0.62996 V
		Min	-21.400 V	-10.702 V	-5.3558 V	-2.6754 V	-2.5152 V	-1.2574 V	-0.63005 V
	40 Hz	Max	21.474 V	10.758 V	5.3561 V	2.6977 V	2.5224 V	1.2613 V	0.62977 V
		Min	-21.489 V	-10.762 V	-5.3618 V	-2.6974 V	-2.5155 V	-1.2617 V	-0.62986 V
	100 Hz	Max	21.384 V	10.698 V	5.3505 V	2.6776 V	2.5137 V	1.2570 V	0.62870 V
		Min	-21.383 V	-10.699 V	-5.3508 V	-2.6779 V	-2.5135 V	-1.2569 V	-0.62869 V
Channel 2 (N)	20 Hz	Max	21.405 V	10.703 V	5.3576 V	2.6779 V	2.5145 V	1.2577 V	0.63035 V
		Min	-21.402 V	-10.704 V	-5.3591 V	-2.6722 V	-2.5152 V	-1.2575 V	-0.63044 V
	40 Hz	Max	21.476 V	10.759 V	5.3590 V	2.6949 V	2.5224 V	1.2614 V	0.63007 V
		Min	-21.490 V	-10.764 V	-5.3649 V	-2.6945 V	-2.5155 V	-1.2618 V	-0.63016 V
	100 Hz	Max	21.386 V	10.700 V	5.3539 V	2.6757 V	2.5137 V	1.2571 V	0.62909 V
		Min	-21.385 V	-10.701 V	-5.3543 V	-2.6745 V	-2.5135 V	-1.2570 V	-0.62908 V
Channel 3 (E)	20 Hz	Max	21.401 V	10.699 V	5.3527 V	2.6717 V	2.5141 V	1.2573 V	0.62971 V
		Min	-21.397 V	-10.700 V	-5.3539 V	-2.6710 V	-2.5149 V	-1.2572 V	-0.62980 V
	40 Hz	Max	21.472 V	10.756 V	5.3544 V	2.6939 V	2.5220 V	1.2611 V	0.62958 V
		Min	-21.486 V	-10.760 V	-5.3601 V	-2.6934 V	-2.5222 V	-1.2615 V	-0.62967 V
	100 Hz	Max	21.381 V	10.697 V	5.3486 V	2.6735 V	2.5133 V	1.2568 V	0.62845 V
		Min	-21.381 V	-10.697 V	-5.3489 V	-2.6734 V	-2.5131 V	-1.2566 V	-0.62844 V

Table 24 AC Over Scale: Q330M+ 6641, Port A

	Rate		Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Reference Voltage	100 Hz	Max	21.897 V	10.949 V	5.4751 V	2.7404 V	2.7471 V	1.3748 V	0.68630 V
		Min	-21.945 V	-10.975 V	-5.4903 V	-2.7483 V	-2.7553 V	-1.3793 V	-0.68790 V
Channel 1 (Z)	20 Hz	Max	21.487 V	10.756 V	5.3579 V	2.6974 V	2.5213 V	1.2613 V	0.62995 V
		Min	-21.498 V	-10.761 V	-5.3638 V	-2.6979 V	-2.5214 V	-1.2616 V	-0.63003 V
	40 Hz	Max	21.388 V	10.699 V	5.3563 V	2.6773 V	2.5134 V	1.2567 V	0.63020 V
		Min	-21.382 V	-10.700 V	-5.3578 V	-2.6760 V	-2.5141 V	-1.2566 V	-0.63029 V
	100 Hz	Max	21.375 V	10.697 V	5.3525 V	2.6781 V	2.5125 V	1.2569 V	0.62908 V
		Min	-21.376 V	-10.697 V	-5.3529 V	-2.6780 V	-2.5123 V	-1.2569 V	-0.62893 V
Channel 2 (N)	20 Hz	Max	21.489 V	10.757 V	5.3574 V	2.6911 V	2.5209 V	1.2611 V	0.62976 V
		Min	-21.500 V	-10.762 V	-5.3633 V	-2.6913 V	-2.5210 V	-1.2614 V	-0.62985 V
	40 Hz	Max	21.391 V	10.701 V	5.3558 V	2.6698 V	2.5130 V	1.2565 V	0.62996 V
		Min	-21.385 V	-10.702 V	-5.3572 V	-2.6686 V	-2.5137 V	-1.2564 V	-0.63005 V
	100 Hz	Max	21.377 V	10.698 V	5.3519 V	2.6713 V	2.5121 V	1.2567 V	0.62882 V
		Min	-21.378 V	-10.699 V	-5.3523 V	-2.6712 V	-2.5119 V	-1.2567 V	-0.62869 V
Channel 3 (E)	20 Hz	Max	21.487 V	10.756 V	5.3554 V	2.6896 V	2.5213 V	1.2612 V	0.62966 V
		Min	-21.498 V	-10.761 V	-5.3611 V	-2.6897 V	-2.5214 V	-1.2616 V	-0.62975 V
	40 Hz	Max	21.388 V	10.699 V	5.3536 V	2.6681 V	2.5133 V	1.2567 V	0.62983 V
		Min	-21.382 V	-10.700 V	-5.3548 V	-2.6669 V	-2.5141 V	-1.2565 V	-0.62992 V
	100 Hz	Max	21.374 V	10.697 V	5.3496 V	2.6698 V	2.5125 V	1.2569 V	0.62868 V
		Min	-21.375 V	-10.697 V	-5.3499 V	-2.6697 V	-2.5123 V	-1.2568 V	-0.62856 V

Table 25 AC Over Scale: Q330M+ 6641, Port B

	Rate		Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Reference Voltage	100 Hz	Max	21.897 V	10.949 V	5.4751 V	2.7404 V	2.7471 V	1.3748 V	0.68630 V
		Min	-21.945 V	-10.975 V	-5.4903 V	-2.7483 V	-2.7553 V	-1.3793 V	-0.68790 V
Channel 1 (Z)	20 Hz	Max	21.499 V	10.761 V	5.3595 V	2.6988 V	2.5221 V	1.2615 V	0.62998 V
		Min	-21.511 V	-10.766 V	-5.3654 V	-2.6993 V	-2.5222 V	-1.2618 V	-0.63006 V
	40 Hz	Max	21.396 V	10.705 V	5.3580 V	2.6790 V	2.5142 V	1.2570 V	0.63024 V
		Min	-21.396 V	-10.706 V	-5.3596 V	-2.6777 V	-2.5149 V	-1.2569 V	-0.63033 V
	100 Hz	Max	21.389 V	10.702 V	5.3543 V	2.6796 V	2.5134 V	1.2572 V	0.62912 V
		Min	-21.389 V	-10.703 V	-5.3548 V	-2.6795 V	-2.5132 V	-1.2571 V	-0.62897 V
Channel 2 (N)	20 Hz	Max	21.494 V	10.759 V	5.3581 V	2.6942 V	2.5218 V	1.2615 V	0.62990 V
		Min	-21.505 V	-10.764 V	-5.3639 V	-2.6945 V	-2.5219 V	-1.2618 V	-0.62999 V
	40 Hz	Max	21.389 V	10.703 V	5.3565 V	2.6735 V	2.5139 V	1.2570 V	0.63014 V
		Min	-21.390 V	-10.704 V	-5.3579 V	-2.6722 V	-2.5146 V	-1.2568 V	-0.63024 V
	100 Hz	Max	21.383 V	10.700 V	5.3527 V	2.6746 V	2.5131 V	1.2571 V	0.62902 V
		Min	-21.383 V	-10.701 V	-5.3531 V	-2.6745 V	-2.5129 V	-1.2571 V	-0.62887 V
Channel 3 (E)	20 Hz	Max	21.488 V	10.756 V	5.3572 V	2.6947 V	2.5214 V	1.2612 V	0.62986 V
		Min	-21.499 V	-10.761 V	-5.3630 V	-2.6950 V	-2.5215 V	-1.2616 V	-0.62994 V
	40 Hz	Max	21.389 V	10.699 V	5.3555 V	2.6740 V	2.5134 V	1.2567 V	0.63008 V
		Min	-21.383 V	-10.700 V	-5.3569 V	-2.6728 V	-2.5142 V	-1.2565 V	-0.63017 V
	100 Hz	Max	21.376 V	10.697 V	5.3517 V	2.6751 V	2.5126 V	1.2568 V	0.62895 V
		Min	-21.376 V	-10.697 V	-5.3520 V	-2.6750 V	-2.5124 V	-1.2568 V	-0.62881 V

For all sample rates and gain levels, the digitizer channels were determined to have a full-scale amplitude that exceeded the nominally specified full scale value by approximately 7% at gains of 1x, 2x, 4x, and 8xH and approximately 0.5 % at gains of 8xL, 16x, and 32x.

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 shorted. 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

Figure 24 Input Shorted Offset Configuration Diagram

Figure 25 Input Shorted Offset Configuration Picture

Table 26 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 bitweight, from the AC Accuracy at 1 Hz, is applied to the collected data:

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

The mean value, in volts, is evaluated:

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

3.7.4 Result

The figure below shows a representative waveform time series for the recording made on a digitizer channel under test. The window regions bounded by the red lines indicate the segment of data used for analysis. Each window represents 24 hours of data

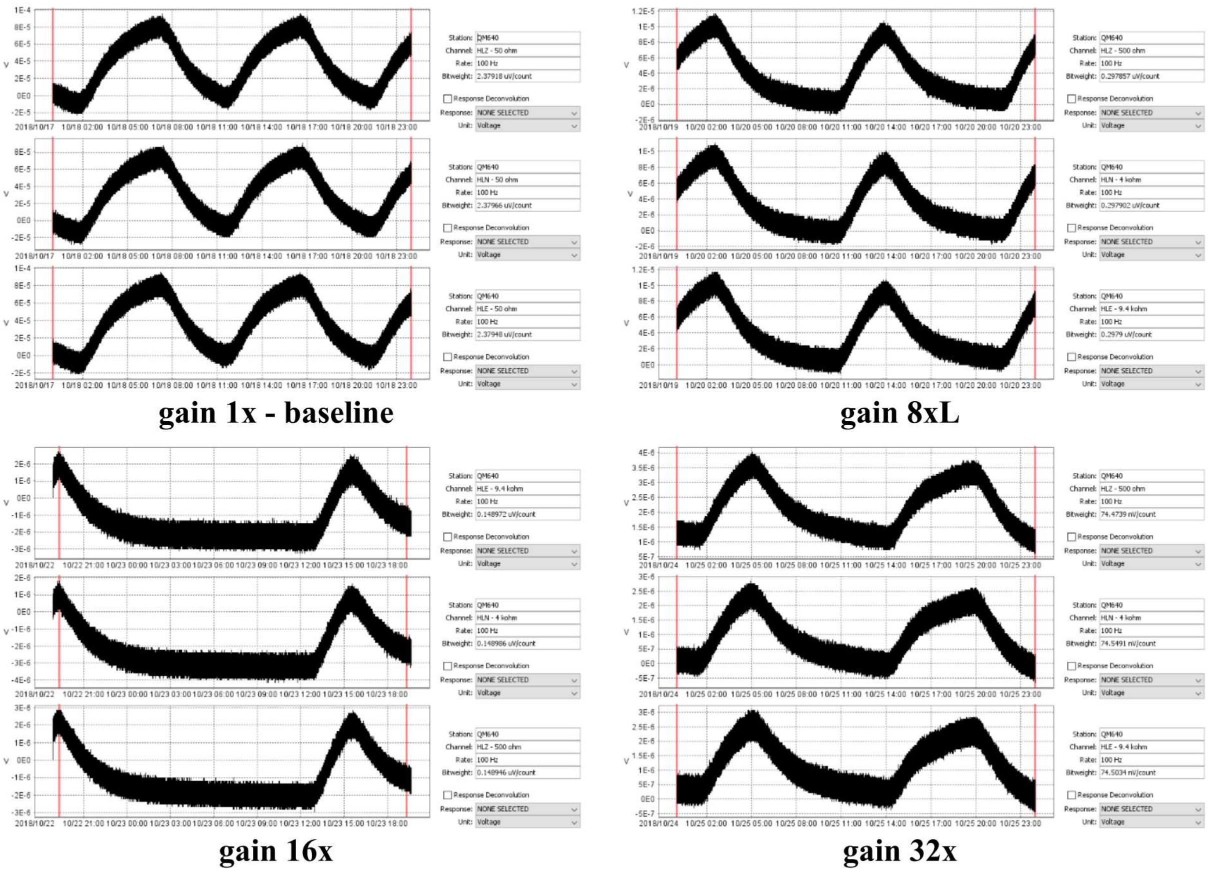
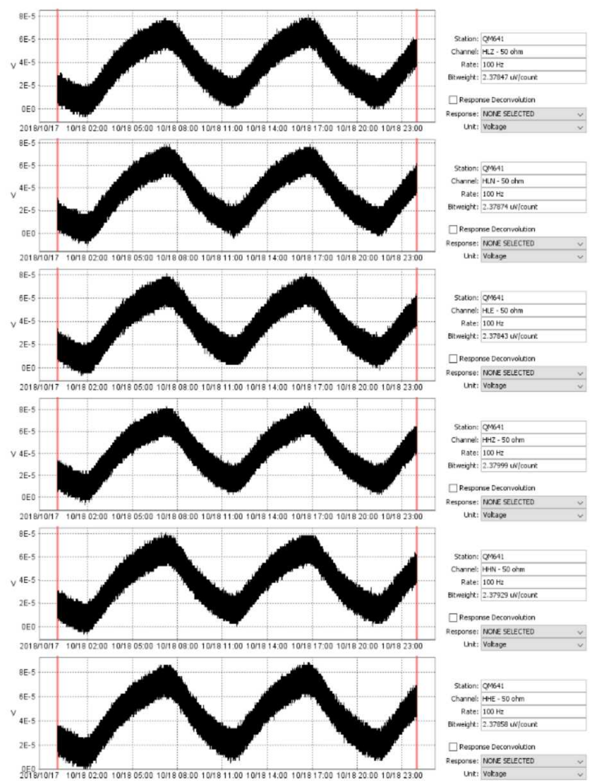
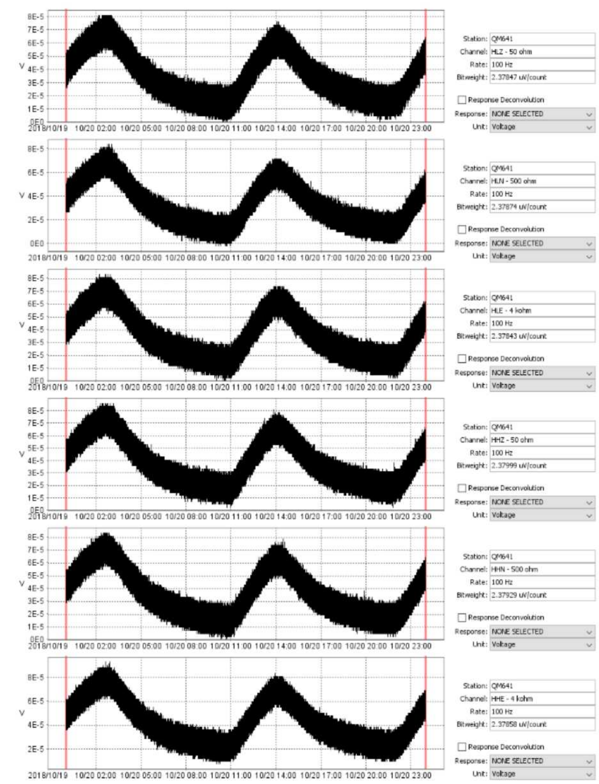


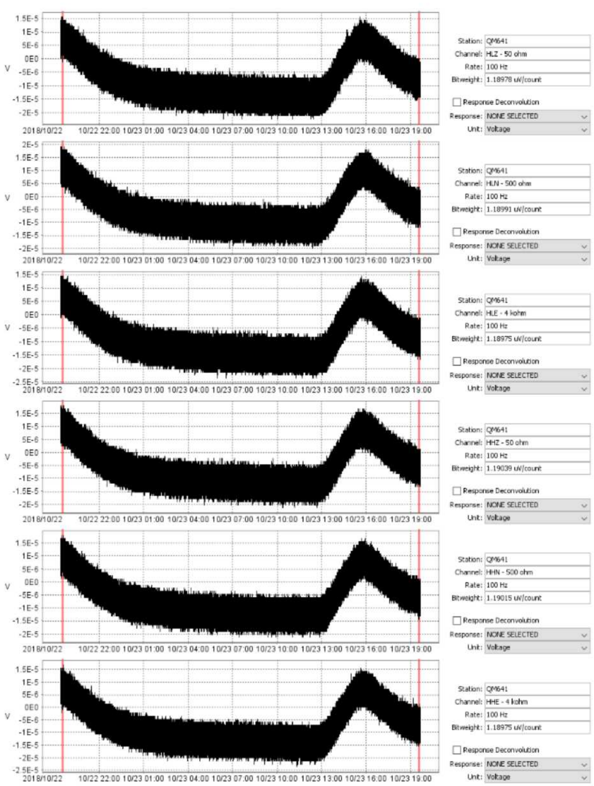
Figure 26 Input Shorted Offset Time Series, #6640



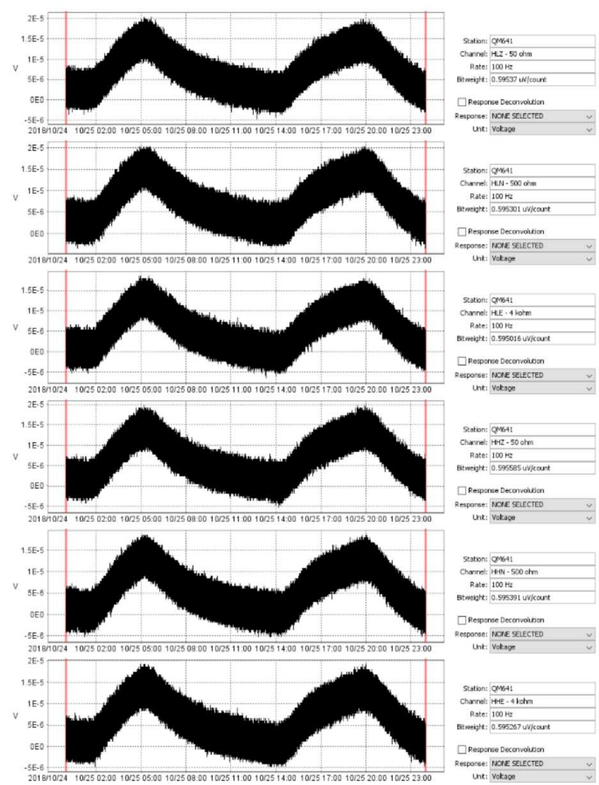
gain 1x - baseline



gain 1x



gain 2x



gain 4x

Figure 27 Input Shorted Offset Time Series, #6641

The variations in DC offset observed above over the 24 hour recording of the time-series are consistent with a 1 to 2 degree Celsius change in environmental temperature, based upon the later Temperature Self-Noise testing and the measured 16 – 17 counts per degree Celsius offset change.

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

Table 27 Input Shorted Offset, #6640

Channel	Gain	Impedance	20 Hz		40 Hz		100 Hz	
			Offset (Volts)	Offset (Counts)	Offset (Volts)	Offset (Counts)	Offset (Volts)	Offset (Counts)
Z	1x	50 ohm	34.82 uV	14.71 cnt	34.89 uV	14.75 cnt	35.08 uV	14.74 cnt
N	1x	50 ohm	29.32 uV	12.39 cnt	29.40 uV	12.42 cnt	29.56 uV	12.42 cnt
E	1x	50 ohm	35.45 uV	14.98 cnt	35.53 uV	15.01 cnt	35.72 uV	15.01 cnt
Z	8xL	500 ohm	3.83 uV	12.93 cnt	3.84 uV	12.96 cnt	3.86 uV	12.96 cnt
N	8xL	4k ohm	3.34 uV	11.26 cnt	3.34 uV	11.29 cnt	3.36 uV	11.29 cnt
E	8xL	9.4k ohm	4.00 uV	13.51 cnt	4.01 uV	13.54 cnt	4.03 uV	13.54 cnt
Z	16x	500 ohm	-1.00 uV	-6.74 cnt	-1.28 uV	-8.66 cnt	-1.29 uV	-8.66 cnt
N	16x	4k ohm	-2.20 uV	-14.84 cnt	-2.19 uV	-14.81 cnt	-2.21 uV	-14.81 cnt
E	16x	9.4k ohm	-1.29 uV	-8.69 cnt	-0.99 uV	-6.70 cnt	-1.00 uV	-6.70 cnt
Z	32x	500 ohm	2.10 uV	28.32 cnt	2.10 uV	28.36 cnt	2.11 uV	28.36 cnt
N	32x	4k ohm	0.92 uV	12.38 cnt	0.92 uV	12.41 cnt	0.92 uV	12.41 cnt
E	32x	9.4k ohm	1.14 uV	15.36 cnt	1.14 uV	15.39 cnt	1.15 uV	15.39 cnt

Table 27 Input Shorted Offset, #6641 Port A

Channel	Gain	Impedance	20 Hz		40 Hz		100 Hz	
			Offset (Volts)	Offset (Counts)	Offset (Volts)	Offset (Counts)	Offset (Volts)	Offset (Counts)
Z	1x	50 ohm	35.82 uV	15.14 cnt	35.89 uV	15.17 cnt	36.09 uV	15.17 cnt
N	1x	50 ohm	33.92 uV	14.34 cnt	34.00 uV	14.37 cnt	34.18 uV	14.37 cnt
E	1x	50 ohm	36.40 uV	15.39 cnt	36.47 uV	15.42 cnt	36.67 uV	15.42 cnt
Z	1x	50 ohm	34.95 uV	14.77 cnt	35.02 uV	14.80 cnt	35.21 uV	14.80 cnt
N	1x	500 ohm	32.78 uV	13.86 cnt	32.86 uV	13.89 cnt	33.03 uV	13.89 cnt
E	1x	4k ohm	35.52 uV	15.01 cnt	35.59 uV	15.05 cnt	35.79 uV	15.05 cnt
Z	2x	50 ohm	-7.59 uV	-6.41 cnt	-7.69 uV	-6.50 cnt	-7.73 uV	-6.50 cnt
N	2x	500 ohm	-4.59 uV	-3.88 cnt	-4.70 uV	-3.97 cnt	-4.72 uV	-3.97 cnt
E	2x	4k ohm	-8.61 uV	-7.28 cnt	-8.72 uV	-7.37 cnt	-8.76 uV	-7.37 cnt
Z	4x	50 ohm	7.35 uV	12.41 cnt	7.37 uV	12.44 cnt	7.41 uV	12.44 cnt
N	4x	500 ohm	7.68 uV	12.96 cnt	7.69 uV	13.00 cnt	7.74 uV	13.00 cnt
E	4x	4k ohm	5.50 uV	9.30 cnt	5.52 uV	9.33 cnt	5.55 uV	9.33 cnt

Table 27 Input Shorted Offset, #6641 Port B

Channel	Gain	Impedance	20 Hz		40 Hz		100 Hz	
			Offset (Volts)	Offset (Counts)	Offset (Volts)	Offset (Counts)	Offset (Volts)	Offset (Counts)
Z	1x	50 ohm	39.19 uV	16.55 cnt	39.26 uV	16.59 cnt	39.48 uV	16.59 cnt
N	1x	50 ohm	36.79 uV	15.54 cnt	36.86 uV	15.58 cnt	37.06 uV	15.58 cnt
E	1x	50 ohm	43.03 uV	18.19 cnt	43.10 uV	18.22 cnt	43.33 uV	18.22 cnt
Z	1x	50 ohm	38.02 uV	16.06 cnt	38.09 uV	16.09 cnt	38.30 uV	16.09 cnt
N	1x	500 ohm	35.61 uV	15.05 cnt	35.69 uV	15.08 cnt	35.88 uV	15.08 cnt
E	1x	4k ohm	41.97 uV	17.74 cnt	42.04 uV	17.77 cnt	42.27 uV	17.77 cnt
Z	2x	50 ohm	-5.70 uV	-4.81 cnt	-5.80 uV	-4.90 cnt	-5.83 uV	-4.90 cnt
N	2x	500 ohm	-6.27 uV	-5.29 cnt	-6.37 uV	-5.38 cnt	-6.40 uV	-5.38 cnt
E	2x	4k ohm	-7.57 uV	-6.40 cnt	-7.67 uV	-6.48 cnt	-7.71 uV	-6.48 cnt
Z	4x	50 ohm	6.66 uV	11.25 cnt	6.68 uV	11.28 cnt	6.72 uV	11.28 cnt
N	4x	500 ohm	5.77 uV	9.74 cnt	5.79 uV	9.77 cnt	5.82 uV	9.77 cnt
E	4x	4k ohm	6.18 uV	10.44 cnt	6.20 uV	10.47 cnt	6.23 uV	10.47 cnt

There does not appear to be any impact of sample rate or termination impedance on the level of the DC offset. The offset measured in volts does appear to vary fairly linearly with gain, however the underlying offset in counts does not appear to vary with gain level. The most significant impact on the DC offset on the Q330M+ appears to be due to ambient temperature, which will be confirmed further in later testing on the Temperature Self-Noise.

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 sensor.

3.8.1 Measurand

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

3.8.2 Configuration

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

Figure 28 Self Noise Configuration Diagram

Figure 29 Self Noise Configuration Picture

Table 28 Self Noise Testbed Equipment

	Impedance
Resistor	50 ohm, 500 ohm, 4 kohm, and 9.4 kohm

The following combinations of gain level and terminator impedance were tested on the specified digitizer channels:

Table 29 Q330M+, 6640 Self-Noise Configurations

Terminator Impedance	Gain	Channel 1 (Z)	Channel 2 (N)	Channel 3 (E)
50 ohm	1x	x	x	x
500 ohm	8x	x		
4 kohm	8x		x	
9.4 kohm	8x			x
500 ohm	16x	x		
4 kohm	16x		x	
9.4 kohm	16x			x
500 ohm	32x	x		
4 kohm	32x		x	
9.4 kohm	32x			x

Table 30 Q330M+, 6641 Self-Noise Configurations

		Port A			Port B		
Terminator Impedance	Gain	Channel 1 (Z)	Channel 2 (N)	Channel 3 (E)	Channel 1 (Z)	Channel 2 (N)	Channel 3 (E)
50 ohm	1x	x	x	x	x	x	x
50 ohm	1x	x			x		
500 ohm	1x		x			x	
4 kohm	1x			x			x
500 ohm	2x	x			x		
4 kohm	2x		x			x	
9.4 kohm	2x			x			x
500 ohm	4x	x			x		
4 kohm	4x		x			x	
9.4 kohm	4x			x			x

A minimum of 24 hours of data is recorded at each configuration.

3.8.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 4k, 8k, or 16k sample Hann window depending on the sample rate. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation pass-band of 0.01 Hz and the 95% confidence interval is less than 0.5 dB. The resulting 95% confidence interval was determined to be less than 0.425 dB.

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

Over frequencies (in Hertz):

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

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

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

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

3.8.4 Result

The individual results for each self-noise configuration are shown in the sections below.

In summary, all the evaluated channels performed similarly to one another when configured at the same sample rate and gain, with the exception of at a gain of 32x where there was as much as 2 dB (rel 1 V^2/Hz) difference between the self-noise PSD levels.

The selection of a terminating resistor from a range of 50 ohm to 9.4 kohm did not appear to have a significant impact on the PSD self-noise levels.

Each channel has the capability to record at multiple sample rate simultaneously. As configured, the channels were sampling at 20 Hz, 40 Hz, and 100 Hz. The self-noise PSD levels were very similar across the sample rates, as shown in the figure below from the test when the Q330M+ 6641 was terminated with 50 ohm resistors on all of its channels.

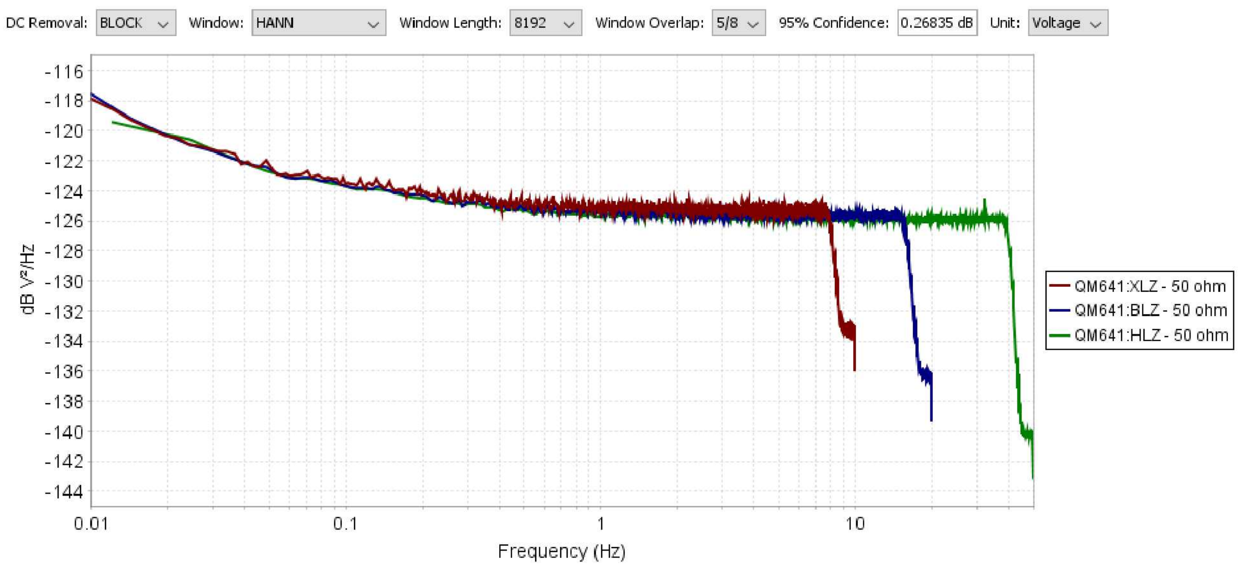


Figure 30 Q330M+ 6641 Self-Noise across 20 Hz, 40 Hz, and 100 Hz

There is a very slight reduction in the PSD levels at higher frequencies as the sample rate increases, which is consistent with the quantization noise being distributed across a wider passband. However, the noise levels are largely unchanged from one sample rate to the next, indicating that the self-noise is dominated by contributions from the analog components prior to quantization.

The self-noise PSD levels were observed to decrease with increasing gain, as shown in the figure below. The Q330M+ differentiates its gain settings between high-amplitude levels at gains of 1x, 2x, 4x, and 8xH and low-amplitude levels at gains of 8xL, 16x, 32x, and 64x. Note that this evaluation did not examine the gain settings of 8xH and 64x.

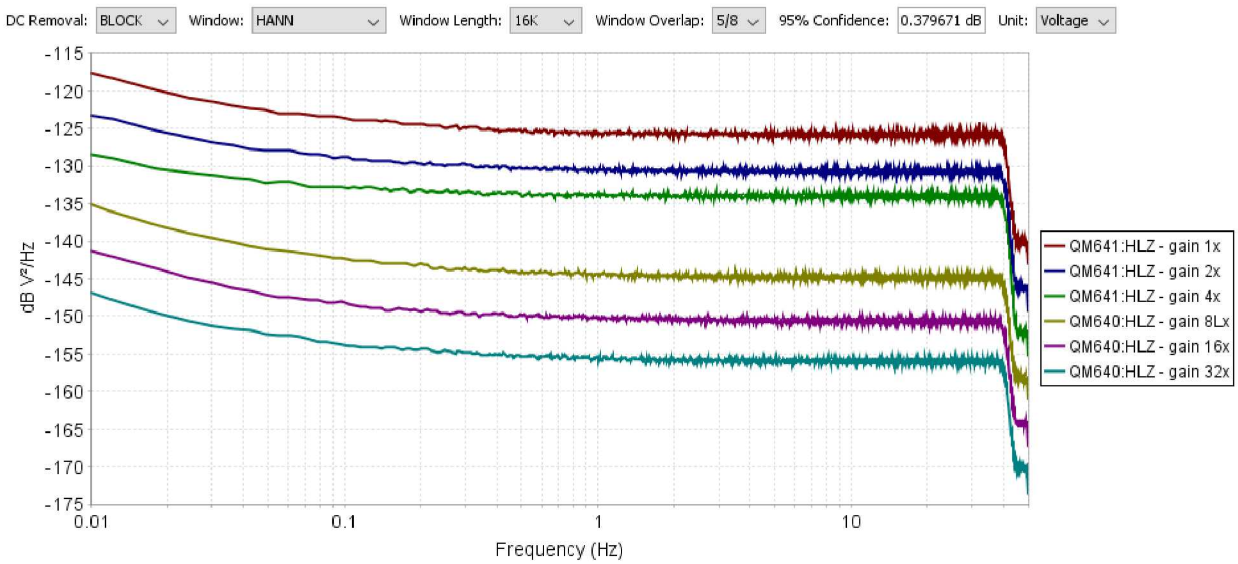


Figure 31 Q330M+ Self-Noise across gains from 1x – 32 x

We observe that the self-noise PSD levels exhibit incremental improvements when the gains setting was change from 1x to 2x and 4x. However, there are diminishing returns to using a gain setting of 4x.

Utilizing the low-amplitude gain settings of 8xL, 16x, and 32x, the Q330M+ exhibited low self-noise levels that were equivalent to the theoretical maximum reduction in noise of 6.02 dB per doubling of the gain level.

Table 31 Q330M+ 6640 Self-Noise PSD reduction versus gain

Gain Level	PSD Noise Reduction from 1x	Theoretical (6.02 dB per 2x gain)
2x	-4.92 dB	-6.02 dB
4x	-8.22 dB	-12.04 dB
8xL	-18.78 dB	-18.06 dB
16x	-23.81 dB	-24.08 dB
32x	-29.94 dB	-30.10 dB

3.8.4.1 Baseline: gain 1x and 50 ohm

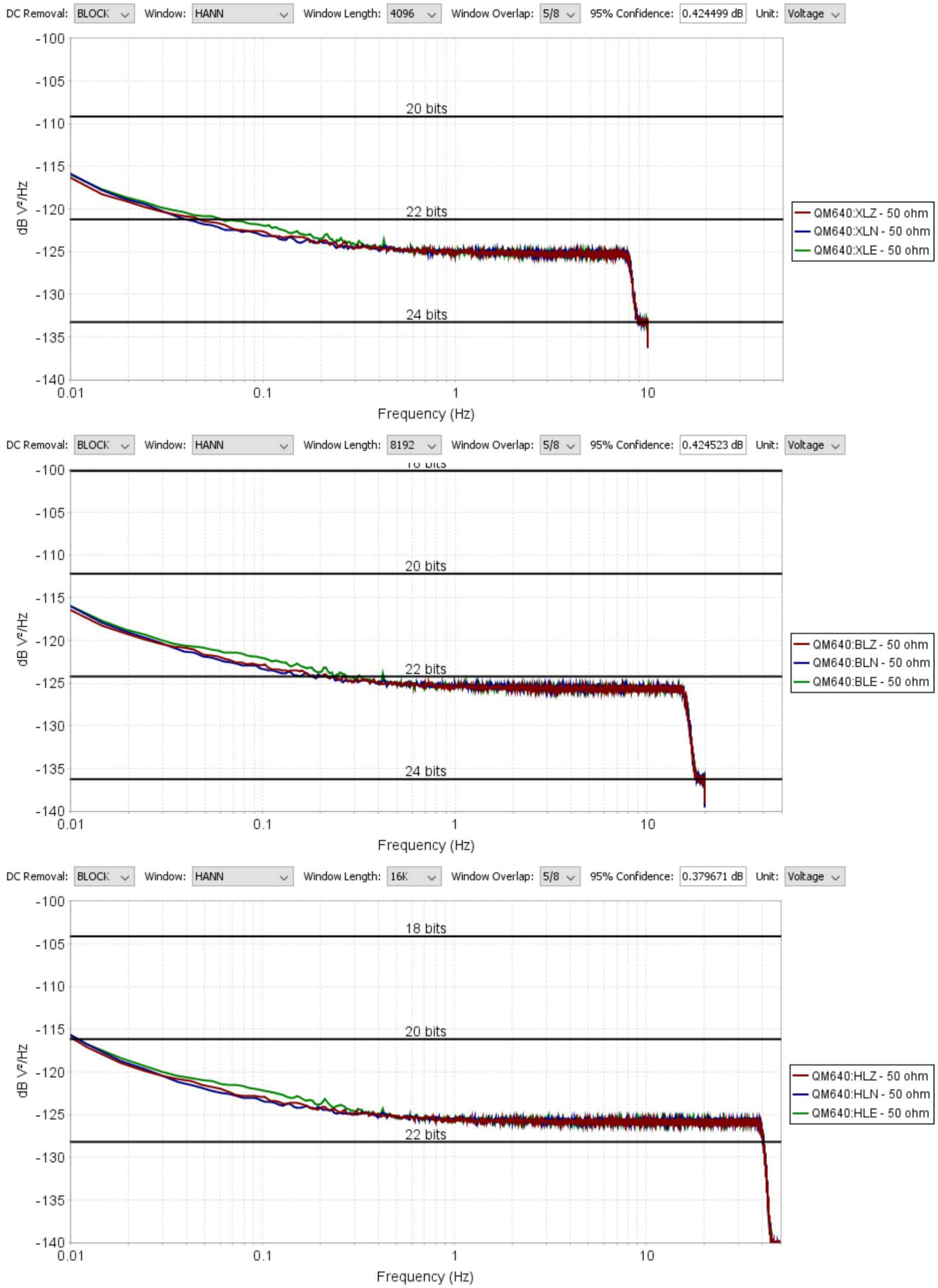


Figure 32 Q330M+ 6640 Self-Noise, gain 1x, 50 ohm baseline comparison at 20 Hz, 40 Hz, and 100 Hz

Table 32 Q330M+ 6640 Self-Noise Power Spectra, gain 1x, 50 ohm

Frequency	Channel 1 (Z)	Channel 2 (N)	Channel 2 (E)
0.0100 Hz	-117.23 dB	-117.00 dB	-116.98 dB
0.0125 Hz	-117.81 dB	-117.80 dB	-117.36 dB
0.0160 Hz	-118.64 dB	-118.29 dB	-118.07 dB
0.0200 Hz	-119.37 dB	-118.98 dB	-118.76 dB
0.0250 Hz	-120.10 dB	-119.88 dB	-119.39 dB
0.0315 Hz	-120.60 dB	-120.81 dB	-120.13 dB
0.040 Hz	-121.03 dB	-121.37 dB	-120.70 dB
0.050 Hz	-121.63 dB	-121.99 dB	-121.05 dB
0.063 Hz	-122.13 dB	-122.61 dB	-121.38 dB
0.080 Hz	-122.77 dB	-122.93 dB	-121.68 dB
0.100 Hz	-123.11 dB	-123.52 dB	-122.22 dB
0.125 Hz	-123.59 dB	-123.75 dB	-122.70 dB
0.160 Hz	-123.93 dB	-124.17 dB	-123.25 dB
0.200 Hz	-124.31 dB	-124.38 dB	-123.68 dB
0.250 Hz	-124.66 dB	-124.79 dB	-124.12 dB
0.315 Hz	-124.91 dB	-124.92 dB	-124.58 dB
0.40 Hz	-125.03 dB	-125.04 dB	-124.96 dB
0.50 Hz	-125.24 dB	-125.28 dB	-125.24 dB
0.63 Hz	-125.39 dB	-125.47 dB	-125.45 dB
0.80 Hz	-125.57 dB	-125.55 dB	-125.55 dB
1.00 Hz	-125.67 dB	-125.58 dB	-125.62 dB
1.25 Hz	-125.74 dB	-125.65 dB	-125.68 dB
1.60 Hz	-125.80 dB	-125.72 dB	-125.72 dB
2.00 Hz	-125.80 dB	-125.74 dB	-125.73 dB
2.50 Hz	-125.82 dB	-125.78 dB	-125.77 dB
3.15 Hz	-125.90 dB	-125.79 dB	-125.82 dB
4.0 Hz	-125.94 dB	-125.82 dB	-125.87 dB
5.0 Hz	-125.95 dB	-125.87 dB	-125.87 dB
6.3 Hz	-125.96 dB	-125.85 dB	-125.87 dB
8.0 Hz	-125.95 dB	-125.85 dB	-125.87 dB
10.0 Hz	-125.96 dB	-125.85 dB	-125.87 dB
12.5 Hz	-125.96 dB	-125.87 dB	-125.88 dB
16.0 Hz	-125.98 dB	-125.89 dB	-125.90 dB
20.0 Hz	-125.99 dB	-125.90 dB	-125.90 dB
25.0 Hz	-125.99 dB	-125.89 dB	-125.91 dB
31.5 Hz	-125.99 dB	-125.88 dB	-125.92 dB
40.0 Hz	-127.02 dB	-126.87 dB	-126.94 dB

Table 33 Q330M+ 6640 Self-Noise, gain 1x, 50 ohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	1.625 uV rms	0.6042 uV rms	1.121 uV rms	1.605 uV rms	1.539 uV rms
		0.6866 cnt rms	0.2553 cnt rms	0.4739 cnt rms	0.6782 cnt rms	0.6505 cnt rms
	40 Hz	2.146 uV rms	0.5845 uV rms	1.078 uV rms	2.081 uV rms	2.034 uV rms
		0.9067 cnt rms	0.2470 cnt rms	0.4554 cnt rms	0.8794 cnt rms	0.8594 cnt rms
	100 Hz	3.263 uV rms	0.5758 uV rms	1.056 uV rms	2.040 uV rms	1.992 uV rms
		1.372 cnt rms	0.2420 cnt rms	0.4437 cnt rms	0.8573 cnt rms	0.8375 cnt rms
Channel 2 (N) 50 ohm	20 Hz	1.639 uV rms	0.6008 uV rms	1.127 uV rms	1.617 uV rms	1.554 uV rms
		0.6923 cnt rms	0.2538 cnt rms	0.4761 cnt rms	0.6833 cnt rms	0.6565 cnt rms
	40 Hz	2.167 uV rms	0.5809 uV rms	1.084 uV rms	2.101 uV rms	2.056 uV rms
		0.9154 cnt rms	0.2454 cnt rms	0.4580 cnt rms	0.8878 cnt rms	0.8686 cnt rms
	100 Hz	3.300 uV rms	0.5717 uV rms	1.061 uV rms	2.060 uV rms	2.015 uV rms
		1.387 cnt rms	0.2402 cnt rms	0.4460 cnt rms	0.8658 cnt rms	0.8467 cnt rms
Channel 3 (E) 50 ohm	20 Hz	1.645 uV rms	0.6247 uV rms	1.140 uV rms	1.624 uV rms	1.551 uV rms
		0.6950 cnt rms	0.2640 cnt rms	0.4816 cnt rms	0.6862 cnt rms	0.6555 cnt rms
	40 Hz	2.170 uV rms	0.6061 uV rms	1.097 uV rms	2.105 uV rms	2.052 uV rms
		0.9170 cnt rms	0.2561 cnt rms	0.4633 cnt rms	0.8894 cnt rms	0.8672 cnt rms
	100 Hz	3.297 uV rms	0.5979 uV rms	1.074 uV rms	2.064 uV rms	2.011 uV rms
		1.386 cnt rms	0.2513 cnt rms	0.4514 cnt rms	0.8673 cnt rms	0.8452 cnt rms

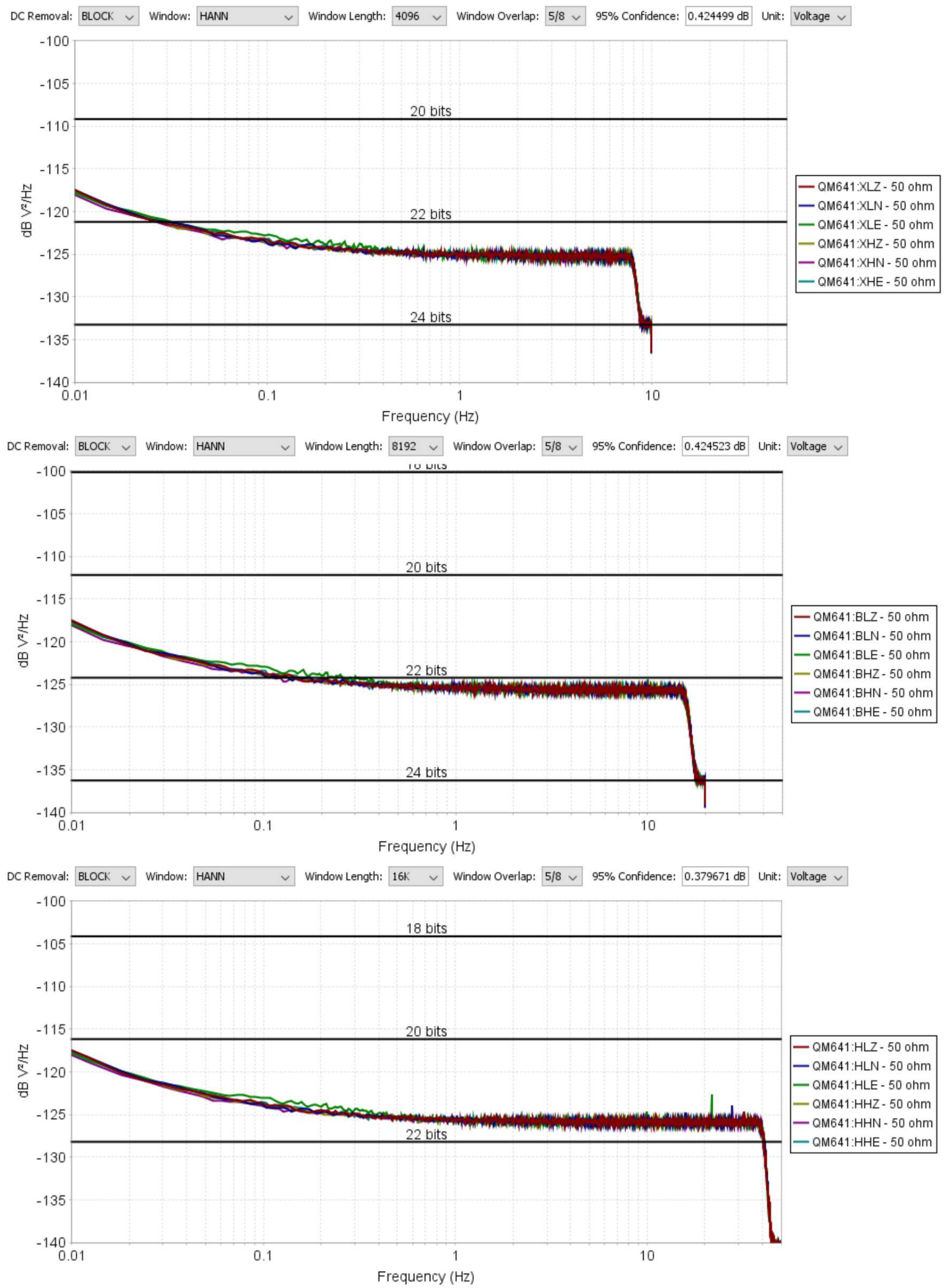


Figure 33 Q330M+ 6641 Self-Noise, gain 1x, 50 ohm baseline comparison at 20 Hz, 40 Hz, and 100 Hz

Table 34 Q330M+ 6641 Port A Self-Noise Power Spectra, gain 1x, 50 ohm

Frequency	Port A			Port B		
	Channel 1 (Z)	Channel 2 (N)	Channel 2 (E)	Channel 1 (Z)	Channel 2 (N)	Channel 2 (E)
0.0100 Hz	-118.43 dB	-118.42 dB	-118.81 dB	-118.44 dB	-118.92 dB	-118.37 dB
0.0125 Hz	-118.58 dB	-118.88 dB	-119.26 dB	-119.08 dB	-119.12 dB	-118.96 dB
0.0160 Hz	-119.51 dB	-119.41 dB	-119.79 dB	-119.50 dB	-120.15 dB	-119.89 dB
0.0200 Hz	-120.63 dB	-120.42 dB	-120.09 dB	-120.25 dB	-120.73 dB	-120.35 dB
0.0250 Hz	-121.16 dB	-121.08 dB	-120.99 dB	-120.70 dB	-120.98 dB	-120.96 dB
0.0315 Hz	-121.78 dB	-121.50 dB	-121.36 dB	-122.01 dB	-121.99 dB	-121.56 dB
0.040 Hz	-122.15 dB	-121.87 dB	-122.07 dB	-122.42 dB	-122.48 dB	-121.87 dB
0.050 Hz	-122.78 dB	-122.51 dB	-122.39 dB	-122.90 dB	-123.05 dB	-122.57 dB
0.063 Hz	-123.02 dB	-123.26 dB	-122.65 dB	-123.24 dB	-123.51 dB	-123.12 dB
0.080 Hz	-123.36 dB	-123.56 dB	-122.95 dB	-123.65 dB	-123.72 dB	-123.55 dB
0.100 Hz	-123.70 dB	-124.00 dB	-123.13 dB	-123.87 dB	-124.05 dB	-123.79 dB
0.125 Hz	-124.05 dB	-124.36 dB	-123.51 dB	-124.22 dB	-124.40 dB	-124.04 dB
0.160 Hz	-124.57 dB	-124.51 dB	-123.84 dB	-124.51 dB	-124.65 dB	-124.35 dB
0.200 Hz	-124.68 dB	-124.82 dB	-124.05 dB	-124.90 dB	-124.83 dB	-124.68 dB
0.250 Hz	-124.83 dB	-124.95 dB	-124.39 dB	-125.05 dB	-124.97 dB	-124.80 dB
0.315 Hz	-125.04 dB	-125.16 dB	-124.57 dB	-125.16 dB	-125.18 dB	-125.09 dB
0.40 Hz	-125.32 dB	-125.28 dB	-124.92 dB	-125.33 dB	-125.41 dB	-125.26 dB
0.50 Hz	-125.39 dB	-125.40 dB	-125.18 dB	-125.44 dB	-125.52 dB	-125.36 dB
0.63 Hz	-125.47 dB	-125.58 dB	-125.43 dB	-125.57 dB	-125.67 dB	-125.48 dB
0.80 Hz	-125.58 dB	-125.68 dB	-125.59 dB	-125.62 dB	-125.71 dB	-125.60 dB
1.00 Hz	-125.64 dB	-125.70 dB	-125.66 dB	-125.67 dB	-125.72 dB	-125.66 dB
1.25 Hz	-125.69 dB	-125.73 dB	-125.71 dB	-125.73 dB	-125.77 dB	-125.71 dB
1.60 Hz	-125.72 dB	-125.78 dB	-125.73 dB	-125.81 dB	-125.79 dB	-125.78 dB
2.00 Hz	-125.75 dB	-125.85 dB	-125.78 dB	-125.83 dB	-125.89 dB	-125.80 dB
2.50 Hz	-125.81 dB	-125.86 dB	-125.81 dB	-125.86 dB	-125.90 dB	-125.82 dB
3.15 Hz	-125.86 dB	-125.88 dB	-125.84 dB	-125.87 dB	-125.93 dB	-125.85 dB
4.0 Hz	-125.88 dB	-125.91 dB	-125.88 dB	-125.91 dB	-125.97 dB	-125.88 dB
5.0 Hz	-125.88 dB	-125.93 dB	-125.92 dB	-125.93 dB	-126.00 dB	-125.90 dB
6.3 Hz	-125.91 dB	-125.94 dB	-125.91 dB	-125.95 dB	-126.01 dB	-125.91 dB
8.0 Hz	-125.91 dB	-125.94 dB	-125.91 dB	-125.95 dB	-126.00 dB	-125.93 dB
10.0 Hz	-125.91 dB	-125.95 dB	-125.91 dB	-125.96 dB	-125.99 dB	-125.93 dB
12.5 Hz	-125.91 dB	-125.95 dB	-125.92 dB	-125.95 dB	-125.99 dB	-125.93 dB
16.0 Hz	-125.92 dB	-125.97 dB	-125.95 dB	-125.97 dB	-126.01 dB	-125.94 dB
20.0 Hz	-125.92 dB	-125.98 dB	-125.95 dB	-125.98 dB	-126.00 dB	-125.96 dB
25.0 Hz	-125.92 dB	-125.98 dB	-125.94 dB	-125.97 dB	-125.99 dB	-125.94 dB
31.5 Hz	-125.92 dB	-125.97 dB	-125.94 dB	-125.97 dB	-126.00 dB	-125.94 dB
40.0 Hz	-126.94 dB	-126.96 dB	-126.97 dB	-126.99 dB	-127.01 dB	-126.97 dB

Table 35 Q330M+ 6641 Port A Self-Noise, gain 1x, 50 ohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	1.618 uV rms	0.5881 uV rms	1.116 uV rms	1.605 uV rms	1.546 uV rms
		0.6841 cnt rms	0.2486 cnt rms	0.4718 cnt rms	0.6786 cnt rms	0.6536 cnt rms
	40 Hz	2.148 uV rms	0.5675 uV rms	1.073 uV rms	2.088 uV rms	2.046 uV rms
		0.9079 cnt rms	0.2399 cnt rms	0.4536 cnt rms	0.8827 cnt rms	0.8648 cnt rms
	100 Hz	3.280 uV rms	0.5581 uV rms	1.050 uV rms	2.046 uV rms	2.004 uV rms
		1.379 cnt rms	0.2347 cnt rms	0.4415 cnt rms	0.8602 cnt rms	0.8426 cnt rms
Channel 2 (N) 50 ohm	20 Hz	1.613 uV rms	0.5856 uV rms	1.112 uV rms	1.600 uV rms	1.541 uV rms
		0.6818 cnt rms	0.2475 cnt rms	0.4701 cnt rms	0.6762 cnt rms	0.6513 cnt rms
	40 Hz	2.139 uV rms	0.5651 uV rms	1.069 uV rms	2.079 uV rms	2.037 uV rms
		0.9039 cnt rms	0.2389 cnt rms	0.4518 cnt rms	0.8786 cnt rms	0.8607 cnt rms
	100 Hz	3.263 uV rms	0.5555 uV rms	1.045 uV rms	2.037 uV rms	1.995 uV rms
		1.372 cnt rms	0.2335 cnt rms	0.4394 cnt rms	0.8562 cnt rms	0.8387 cnt rms
Channel 3 (E) 50 ohm	20 Hz	1.623 uV rms	0.6053 uV rms	1.126 uV rms	1.611 uV rms	1.546 uV rms
		0.6862 cnt rms	0.2559 cnt rms	0.4761 cnt rms	0.6810 cnt rms	0.6533 cnt rms
	40 Hz	2.150 uV rms	0.5854 uV rms	1.084 uV rms	2.091 uV rms	2.044 uV rms
		0.9088 cnt rms	0.2475 cnt rms	0.4580 cnt rms	0.8839 cnt rms	0.8640 cnt rms
	100 Hz	3.277 uV rms	0.5764 uV rms	1.060 uV rms	2.049 uV rms	2.003 uV rms
		1.378 cnt rms	0.2424 cnt rms	0.4457 cnt rms	0.8616 cnt rms	0.8419 cnt rms

Table 36 Q330M+ 6641 Port B Self-Noise, gain 1x, 50 ohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	1.612 uV rms	0.5851 uV rms	1.111 uV rms	1.599 uV rms	1.540 uV rms
		0.6808 cnt rms	0.2472 cnt rms	0.4695 cnt rms	0.6753 cnt rms	0.6505 cnt rms
	40 Hz	2.137 uV rms	0.5639 uV rms	1.067 uV rms	2.078 uV rms	2.036 uV rms
		0.9029 cnt rms	0.2382 cnt rms	0.4508 cnt rms	0.8778 cnt rms	0.8601 cnt rms
	100 Hz	3.261 uV rms	0.5543 uV rms	1.044 uV rms	2.036 uV rms	1.994 uV rms
		1.370 cnt rms	0.2329 cnt rms	0.4386 cnt rms	0.8553 cnt rms	0.8379 cnt rms
Channel 2 (N) 50 ohm	20 Hz	1.602 uV rms	0.5793 uV rms	1.105 uV rms	1.590 uV rms	1.532 uV rms
		0.6770 cnt rms	0.2448 cnt rms	0.4668 cnt rms	0.6720 cnt rms	0.6475 cnt rms
	40 Hz	2.127 uV rms	0.5579 uV rms	1.061 uV rms	2.068 uV rms	2.027 uV rms
		0.8986 cnt rms	0.2357 cnt rms	0.4482 cnt rms	0.8739 cnt rms	0.8565 cnt rms
	100 Hz	3.249 uV rms	0.5484 uV rms	1.038 uV rms	2.025 uV rms	1.985 uV rms
		1.366 cnt rms	0.2305 cnt rms	0.4361 cnt rms	0.8513 cnt rms	0.8342 cnt rms
Channel 3 (E) 50 ohm	20 Hz	1.616 uV rms	0.5890 uV rms	1.115 uV rms	1.603 uV rms	1.543 uV rms
		0.6829 cnt rms	0.2490 cnt rms	0.4713 cnt rms	0.6775 cnt rms	0.6523 cnt rms
	40 Hz	2.143 uV rms	0.5679 uV rms	1.071 uV rms	2.083 uV rms	2.041 uV rms
		0.9056 cnt rms	0.2401 cnt rms	0.4529 cnt rms	0.8806 cnt rms	0.8626 cnt rms
	100 Hz	3.272 uV rms	0.5589 uV rms	1.049 uV rms	2.042 uV rms	2.000 uV rms
		1.376 cnt rms	0.2350 cnt rms	0.4409 cnt rms	0.8585 cnt rms	0.8407 cnt rms

3.8.4.2 Gain 1x and 50 ohm, 500 ohm, and 4 kohm Terminators

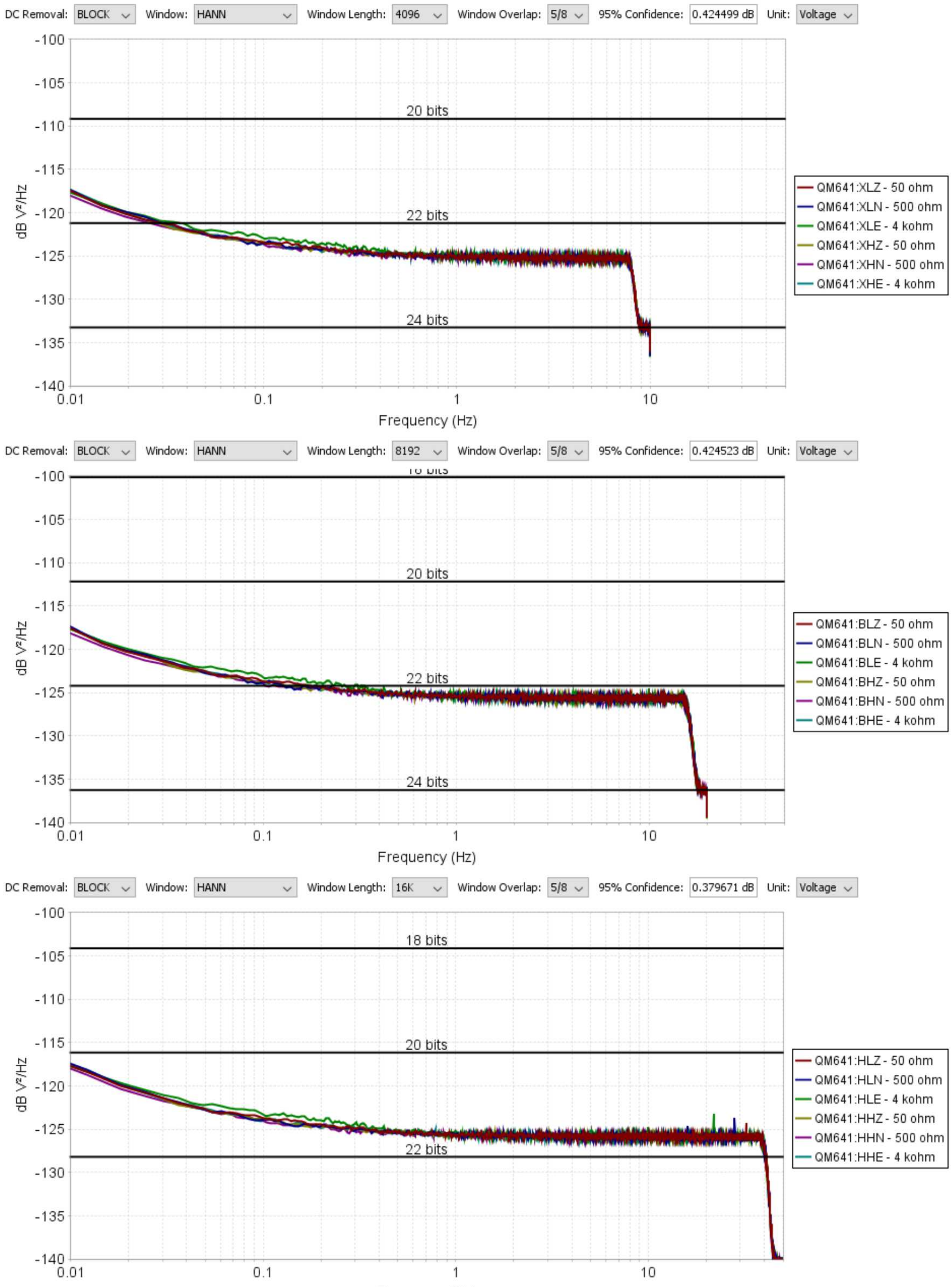


Figure 34 Q330M+ 6641 Self-Noise, gain 1x, 50 ohm, 500 ohm, and 4 kohm at 20 Hz, 40 Hz, and 100 Hz

Table 37 Q330M+ 6641 Self-Noise Power Spectra, gain 1x, 50 ohm, 500 ohm, and 4 kohm

Frequency	Port A			Port B		
	Channel 1 (Z) 50 ohm	Channel 2 (N) 500 ohm	Channel 3 (E) 4 kohm	Channel 1 (Z) 50 ohm	Channel 2 (N) 500 ohm	Channel 3 (E) 4 kohm
0.0100 Hz	-118.26 dB	-118.19 dB	-118.50 dB	-118.26 dB	-119.00 dB	-117.94 dB
0.0125 Hz	-118.75 dB	-118.68 dB	-118.87 dB	-118.86 dB	-119.19 dB	-118.33 dB
0.0160 Hz	-119.65 dB	-119.83 dB	-119.22 dB	-119.43 dB	-120.09 dB	-119.63 dB
0.0200 Hz	-120.45 dB	-120.42 dB	-120.11 dB	-120.35 dB	-120.65 dB	-120.12 dB
0.0250 Hz	-121.13 dB	-120.67 dB	-120.52 dB	-120.87 dB	-121.22 dB	-120.94 dB
0.0315 Hz	-121.64 dB	-121.58 dB	-121.17 dB	-121.74 dB	-122.00 dB	-121.83 dB
0.040 Hz	-122.02 dB	-122.22 dB	-121.71 dB	-122.51 dB	-122.46 dB	-122.25 dB
0.050 Hz	-122.95 dB	-122.90 dB	-122.16 dB	-122.87 dB	-122.71 dB	-122.77 dB
0.063 Hz	-123.19 dB	-123.09 dB	-122.47 dB	-123.22 dB	-123.23 dB	-123.07 dB
0.080 Hz	-123.39 dB	-123.60 dB	-122.80 dB	-123.51 dB	-123.71 dB	-123.51 dB
0.100 Hz	-123.78 dB	-124.00 dB	-123.21 dB	-123.85 dB	-124.23 dB	-123.95 dB
0.125 Hz	-124.02 dB	-124.29 dB	-123.48 dB	-124.20 dB	-124.42 dB	-124.34 dB
0.160 Hz	-124.21 dB	-124.59 dB	-123.69 dB	-124.66 dB	-124.62 dB	-124.54 dB
0.200 Hz	-124.56 dB	-124.67 dB	-123.96 dB	-124.74 dB	-124.75 dB	-124.68 dB
0.250 Hz	-124.83 dB	-124.95 dB	-124.32 dB	-124.92 dB	-125.04 dB	-124.91 dB
0.315 Hz	-124.98 dB	-125.10 dB	-124.63 dB	-125.16 dB	-125.22 dB	-125.04 dB
0.40 Hz	-125.21 dB	-125.24 dB	-124.92 dB	-125.34 dB	-125.38 dB	-125.32 dB
0.50 Hz	-125.41 dB	-125.42 dB	-125.25 dB	-125.46 dB	-125.49 dB	-125.39 dB
0.63 Hz	-125.54 dB	-125.53 dB	-125.39 dB	-125.50 dB	-125.62 dB	-125.46 dB
0.80 Hz	-125.64 dB	-125.60 dB	-125.51 dB	-125.62 dB	-125.67 dB	-125.56 dB
1.00 Hz	-125.70 dB	-125.71 dB	-125.60 dB	-125.69 dB	-125.71 dB	-125.68 dB
1.25 Hz	-125.75 dB	-125.75 dB	-125.69 dB	-125.74 dB	-125.78 dB	-125.72 dB
1.60 Hz	-125.76 dB	-125.77 dB	-125.73 dB	-125.76 dB	-125.79 dB	-125.79 dB
2.00 Hz	-125.78 dB	-125.79 dB	-125.75 dB	-125.83 dB	-125.84 dB	-125.78 dB
2.50 Hz	-125.82 dB	-125.81 dB	-125.83 dB	-125.87 dB	-125.87 dB	-125.79 dB
3.15 Hz	-125.84 dB	-125.85 dB	-125.85 dB	-125.88 dB	-125.87 dB	-125.89 dB
4.0 Hz	-125.88 dB	-125.90 dB	-125.89 dB	-125.92 dB	-125.93 dB	-125.94 dB
5.0 Hz	-125.89 dB	-125.92 dB	-125.91 dB	-125.93 dB	-125.97 dB	-125.94 dB
6.3 Hz	-125.89 dB	-125.94 dB	-125.89 dB	-125.94 dB	-125.99 dB	-125.93 dB
8.0 Hz	-125.90 dB	-125.95 dB	-125.87 dB	-125.96 dB	-125.99 dB	-125.92 dB
10.0 Hz	-125.92 dB	-125.96 dB	-125.88 dB	-125.96 dB	-125.97 dB	-125.93 dB
12.5 Hz	-125.93 dB	-125.95 dB	-125.92 dB	-125.95 dB	-125.97 dB	-125.93 dB
16.0 Hz	-125.94 dB	-125.98 dB	-125.94 dB	-125.96 dB	-125.99 dB	-125.94 dB
20.0 Hz	-125.93 dB	-125.99 dB	-125.94 dB	-125.97 dB	-126.00 dB	-125.94 dB
25.0 Hz	-125.93 dB	-125.98 dB	-125.93 dB	-125.98 dB	-125.99 dB	-125.94 dB
31.5 Hz	-125.94 dB	-125.98 dB	-125.94 dB	-125.97 dB	-126.00 dB	-125.95 dB
40.0 Hz	-126.98 dB	-127.02 dB	-126.95 dB	-127.01 dB	-126.99 dB	-126.95 dB

Table 38 Q330M+ 6641 Port A Self-Noise, gain 1x, 50 ohm, 500 ohm, and 4 kohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	1.617 uV rms	0.5892 uV rms	1.116 uV rms	1.605 uV rms	1.545 uV rms
		0.6837 cnt rms	0.2490 cnt rms	0.4717 cnt rms	0.6786 cnt rms	0.6532 cnt rms
	40 Hz	2.146 uV rms	0.5699 uV rms	1.073 uV rms	2.087 uV rms	2.044 uV rms
		0.9071 cnt rms	0.2409 cnt rms	0.4535 cnt rms	0.8823 cnt rms	0.8641 cnt rms
	100 Hz	3.277 uV rms	0.5598 uV rms	1.050 uV rms	2.045 uV rms	2.002 uV rms
		1.378 cnt rms	0.2354 cnt rms	0.4413 cnt rms	0.8599 cnt rms	0.8419 cnt rms
Channel 2 (N) 500 ohm	20 Hz	1.614 uV rms	0.5855 uV rms	1.114 uV rms	1.601 uV rms	1.542 uV rms
		0.6821 cnt rms	0.2474 cnt rms	0.4709 cnt rms	0.6766 cnt rms	0.6517 cnt rms
	40 Hz	2.139 uV rms	0.5662 uV rms	1.071 uV rms	2.080 uV rms	2.037 uV rms
		0.9041 cnt rms	0.2393 cnt rms	0.4525 cnt rms	0.8790 cnt rms	0.8611 cnt rms
	100 Hz	3.262 uV rms	0.5557 uV rms	1.047 uV rms	2.037 uV rms	1.996 uV rms
		1.371 cnt rms	0.2336 cnt rms	0.4402 cnt rms	0.8565 cnt rms	0.8389 cnt rms
Channel 3 (E) 4 kohm	20 Hz	1.626 uV rms	0.6087 uV rms	1.128 uV rms	1.614 uV rms	1.547 uV rms
		0.6872 cnt rms	0.2573 cnt rms	0.4767 cnt rms	0.6821 cnt rms	0.6541 cnt rms
	40 Hz	2.153 uV rms	0.5887 uV rms	1.084 uV rms	2.094 uV rms	2.046 uV rms
		0.9100 cnt rms	0.2489 cnt rms	0.4582 cnt rms	0.8852 cnt rms	0.8650 cnt rms
	100 Hz	3.281 uV rms	0.5802 uV rms	1.061 uV rms	2.053 uV rms	2.006 uV rms
		1.380 cnt rms	0.2439 cnt rms	0.4462 cnt rms	0.8632 cnt rms	0.8432 cnt rms

Table 39 Q330M+ 6641 Port B Self-Noise, gain 1x, 50 ohm, 500 ohm, and 4 kohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	1.612 uV rms	0.5858 uV rms	1.112 uV rms	1.599 uV rms	1.540 uV rms
		0.6808 cnt rms	0.2474 cnt rms	0.4698 cnt rms	0.6755 cnt rms	0.6506 cnt rms
	40 Hz	2.137 uV rms	0.5648 uV rms	1.068 uV rms	2.077 uV rms	2.035 uV rms
		0.9026 cnt rms	0.2386 cnt rms	0.4512 cnt rms	0.8775 cnt rms	0.8598 cnt rms
	100 Hz	3.261 uV rms	0.5554 uV rms	1.045 uV rms	2.035 uV rms	1.993 uV rms
		1.370 cnt rms	0.2333 cnt rms	0.4392 cnt rms	0.8551 cnt rms	0.8376 cnt rms
Channel 2 (N) 500 ohm	20 Hz	1.604 uV rms	0.5802 uV rms	1.108 uV rms	1.593 uV rms	1.535 uV rms
		0.6779 cnt rms	0.2452 cnt rms	0.4684 cnt rms	0.6732 cnt rms	0.6487 cnt rms
	40 Hz	2.128 uV rms	0.5595 uV rms	1.064 uV rms	2.070 uV rms	2.029 uV rms
		0.8992 cnt rms	0.2364 cnt rms	0.4498 cnt rms	0.8747 cnt rms	0.8573 cnt rms
	100 Hz	3.251 uV rms	0.5499 uV rms	1.041 uV rms	2.028 uV rms	1.987 uV rms
		1.367 cnt rms	0.2311 cnt rms	0.4376 cnt rms	0.8524 cnt rms	0.8352 cnt rms
Channel 3 (E) 4 kohm	20 Hz	1.614 uV rms	0.5874 uV rms	1.114 uV rms	1.602 uV rms	1.543 uV rms
		0.6822 cnt rms	0.2483 cnt rms	0.4710 cnt rms	0.6770 cnt rms	0.6520 cnt rms
	40 Hz	2.141 uV rms	0.5667 uV rms	1.070 uV rms	2.082 uV rms	2.039 uV rms
		0.9049 cnt rms	0.2395 cnt rms	0.4525 cnt rms	0.8800 cnt rms	0.8620 cnt rms
	100 Hz	3.271 uV rms	0.5571 uV rms	1.047 uV rms	2.040 uV rms	1.998 uV rms
		1.375 cnt rms	0.2342 cnt rms	0.4401 cnt rms	0.8576 cnt rms	0.8400 cnt rms

3.8.4.3 Gain 2x and 50 ohm, 500 ohm, and 4 kohm Terminators

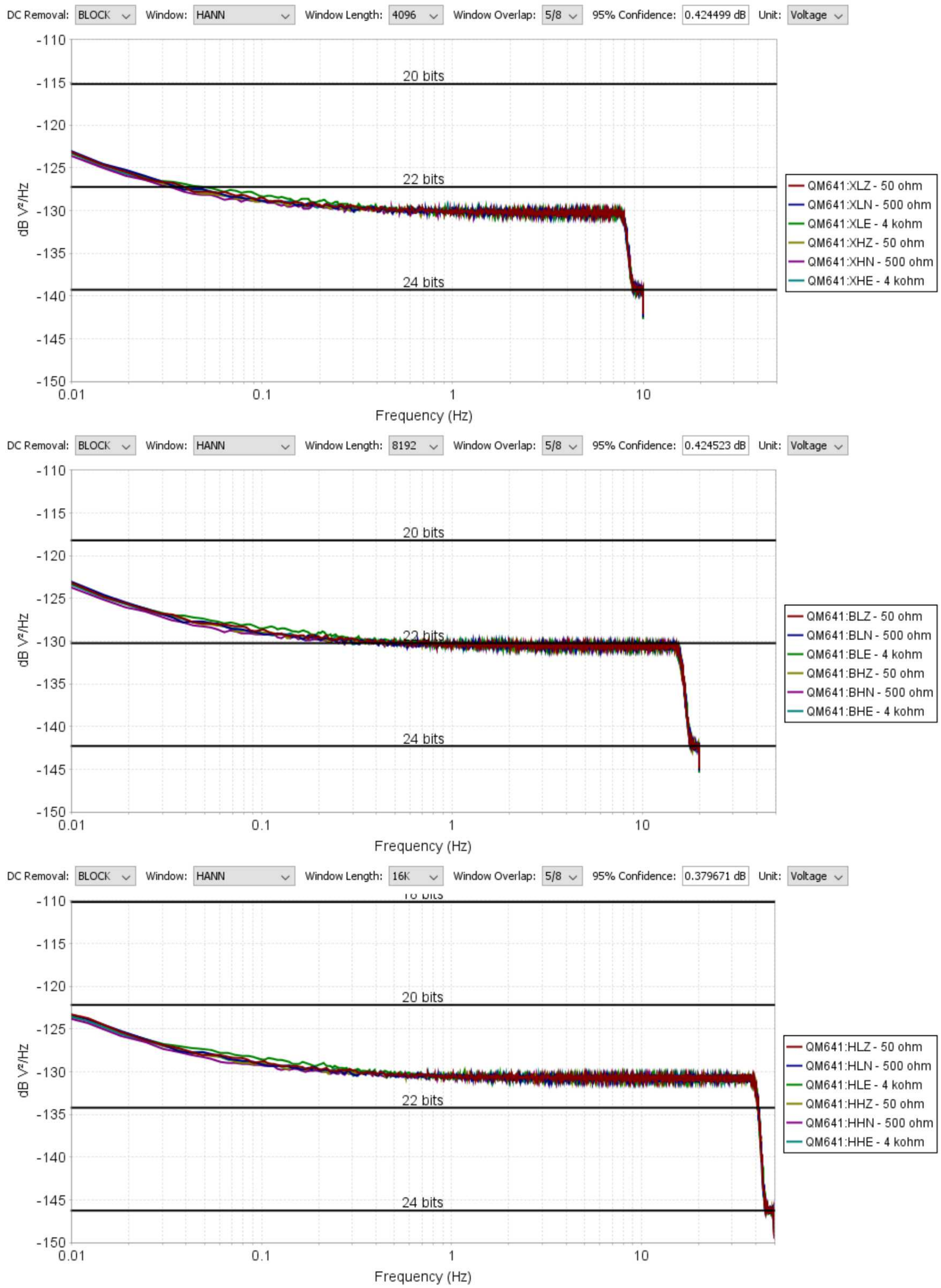


Figure 35 Q330M+ 6641 Self-Noise, gain 4x, 50 ohm, 500 ohm, and 4 kohm at 20 Hz, 40 Hz, and 100 Hz

Table 40 Q330M+ 6641 Self-Noise Power Spectra, gain 4x, 50 ohm, 500 ohm, and 4 kohm

Frequency	Port A			Port B		
	Channel 1 (Z) 50 ohm	Channel 2 (N) 500 ohm	Channel 3 (E) 4 kohm	Channel 1 (Z) 50 ohm	Channel 2 (N) 500 ohm	Channel 3 (E) 4 kohm
0.0100 Hz	-128.90 dB	-128.63 dB	-128.98 dB	-129.89 dB	-129.19 dB	-128.93 dB
0.0125 Hz	-129.16 dB	-128.90 dB	-129.25 dB	-129.89 dB	-129.33 dB	-129.54 dB
0.0160 Hz	-130.03 dB	-129.93 dB	-129.93 dB	-130.10 dB	-130.44 dB	-130.34 dB
0.0200 Hz	-130.63 dB	-130.61 dB	-130.54 dB	-130.56 dB	-130.91 dB	-130.85 dB
0.0250 Hz	-131.16 dB	-130.89 dB	-130.96 dB	-131.16 dB	-131.31 dB	-131.14 dB
0.0315 Hz	-131.65 dB	-131.71 dB	-131.54 dB	-131.39 dB	-131.78 dB	-131.24 dB
0.040 Hz	-131.77 dB	-131.99 dB	-131.71 dB	-131.73 dB	-131.92 dB	-131.76 dB
0.050 Hz	-132.23 dB	-132.33 dB	-132.02 dB	-132.23 dB	-132.32 dB	-132.30 dB
0.063 Hz	-132.43 dB	-132.45 dB	-132.27 dB	-132.54 dB	-132.77 dB	-132.57 dB
0.080 Hz	-132.89 dB	-132.87 dB	-132.60 dB	-132.78 dB	-133.18 dB	-132.81 dB
0.100 Hz	-133.00 dB	-133.10 dB	-132.77 dB	-132.90 dB	-133.16 dB	-132.81 dB
0.125 Hz	-133.06 dB	-133.12 dB	-132.91 dB	-133.14 dB	-133.24 dB	-133.15 dB
0.160 Hz	-133.19 dB	-133.38 dB	-133.08 dB	-133.25 dB	-133.50 dB	-133.35 dB
0.200 Hz	-133.42 dB	-133.46 dB	-133.21 dB	-133.43 dB	-133.51 dB	-133.39 dB
0.250 Hz	-133.51 dB	-133.55 dB	-133.39 dB	-133.55 dB	-133.63 dB	-133.46 dB
0.315 Hz	-133.70 dB	-133.65 dB	-133.50 dB	-133.71 dB	-133.75 dB	-133.63 dB
0.40 Hz	-133.71 dB	-133.73 dB	-133.65 dB	-133.70 dB	-133.81 dB	-133.73 dB
0.50 Hz	-133.74 dB	-133.79 dB	-133.81 dB	-133.79 dB	-133.90 dB	-133.73 dB
0.63 Hz	-133.90 dB	-133.91 dB	-133.85 dB	-133.93 dB	-133.97 dB	-133.81 dB
0.80 Hz	-133.92 dB	-133.92 dB	-133.88 dB	-133.97 dB	-133.96 dB	-133.86 dB
1.00 Hz	-133.92 dB	-133.92 dB	-133.98 dB	-134.00 dB	-133.91 dB	-133.90 dB
1.25 Hz	-133.95 dB	-133.97 dB	-134.00 dB	-134.01 dB	-133.94 dB	-133.94 dB
1.60 Hz	-133.97 dB	-134.00 dB	-134.03 dB	-133.98 dB	-134.00 dB	-133.97 dB
2.00 Hz	-134.02 dB	-133.99 dB	-134.01 dB	-134.00 dB	-134.03 dB	-134.02 dB
2.50 Hz	-134.02 dB	-134.00 dB	-134.03 dB	-134.03 dB	-134.05 dB	-134.03 dB
3.15 Hz	-134.02 dB	-134.02 dB	-134.05 dB	-134.07 dB	-134.06 dB	-134.04 dB
4.0 Hz	-134.05 dB	-134.06 dB	-134.08 dB	-134.08 dB	-134.09 dB	-134.07 dB
5.0 Hz	-134.05 dB	-134.08 dB	-134.08 dB	-134.11 dB	-134.11 dB	-134.07 dB
6.3 Hz	-134.07 dB	-134.06 dB	-134.09 dB	-134.10 dB	-134.11 dB	-134.08 dB
8.0 Hz	-134.07 dB	-134.06 dB	-134.07 dB	-134.09 dB	-134.10 dB	-134.08 dB
10.0 Hz	-134.08 dB	-134.09 dB	-134.06 dB	-134.09 dB	-134.10 dB	-134.08 dB
12.5 Hz	-134.07 dB	-134.06 dB	-134.06 dB	-134.09 dB	-134.09 dB	-134.06 dB
16.0 Hz	-134.09 dB	-134.07 dB	-134.07 dB	-134.10 dB	-134.10 dB	-134.08 dB
20.0 Hz	-134.07 dB	-134.07 dB	-134.07 dB	-134.11 dB	-134.11 dB	-134.10 dB
25.0 Hz	-134.07 dB	-134.08 dB	-134.08 dB	-134.10 dB	-134.11 dB	-134.09 dB
31.5 Hz	-134.08 dB	-134.08 dB	-134.09 dB	-134.10 dB	-134.12 dB	-134.08 dB
40.0 Hz	-135.11 dB	-135.13 dB	-135.11 dB	-135.14 dB	-135.17 dB	-135.16 dB

Table 41 Q330M+ 6641 Port A Self-Noise, gain 2x, 50 ohm, 500 ohm, and 4 kohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	0.9009 uV rms	0.3267 uV rms	0.6235 uV rms	0.8954 uV rms	0.8628 uV rms
		0.7613 cnt rms	0.2761 cnt rms	0.5269 cnt rms	0.7567 cnt rms	0.7291 cnt rms
	40 Hz	1.209 uV rms	0.3177 uV rms	0.6038 uV rms	1.179 uV rms	1.156 uV rms
		1.022 cnt rms	0.2685 cnt rms	0.5102 cnt rms	0.9966 cnt rms	0.9768 cnt rms
	100 Hz	1.863 uV rms	0.3134 uV rms	0.5942 uV rms	1.163 uV rms	1.140 uV rms
		1.566 cnt rms	0.2634 cnt rms	0.4994 cnt rms	0.9775 cnt rms	0.9580 cnt rms
Channel 2 (N) 500 ohm	20 Hz	0.8989 uV rms	0.3241 uV rms	0.6215 uV rms	0.8932 uV rms	0.8613 uV rms
		0.7595 cnt rms	0.2738 cnt rms	0.5252 cnt rms	0.7547 cnt rms	0.7277 cnt rms
	40 Hz	1.207 uV rms	0.3145 uV rms	0.6021 uV rms	1.177 uV rms	1.154 uV rms
		1.020 cnt rms	0.2658 cnt rms	0.5087 cnt rms	0.9943 cnt rms	0.9751 cnt rms
	100 Hz	1.859 uV rms	0.3104 uV rms	0.5922 uV rms	1.160 uV rms	1.138 uV rms
		1.563 cnt rms	0.2608 cnt rms	0.4977 cnt rms	0.9749 cnt rms	0.9560 cnt rms
Channel 3 (E) 4 kohm	20 Hz	0.9031 uV rms	0.3336 uV rms	0.6270 uV rms	0.8978 uV rms	0.8631 uV rms
		0.7632 cnt rms	0.2819 cnt rms	0.5298 cnt rms	0.7587 cnt rms	0.7294 cnt rms
	40 Hz	1.211 uV rms	0.3240 uV rms	0.6073 uV rms	1.181 uV rms	1.156 uV rms
		1.023 cnt rms	0.2738 cnt rms	0.5132 cnt rms	0.9983 cnt rms	0.9773 cnt rms
	100 Hz	1.863 uV rms	0.3204 uV rms	0.5977 uV rms	1.165 uV rms	1.140 uV rms
		1.566 cnt rms	0.2693 cnt rms	0.5024 cnt rms	0.9789 cnt rms	0.9580 cnt rms

Table 42 Q330M+ 6641 Port B Self-Noise, gain 2x, 50 ohm, 500 ohm, and 4 kohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	0.8968 uV rms	0.3234 uV rms	0.6205 uV rms	0.8912 uV rms	0.8595 uV rms
		0.7574 cnt rms	0.2732 cnt rms	0.5240 cnt rms	0.7527 cnt rms	0.7260 cnt rms
	40 Hz	1.203 uV rms	0.3150 uV rms	0.6014 uV rms	1.173 uV rms	1.150 uV rms
		1.016 cnt rms	0.2661 cnt rms	0.5079 cnt rms	0.9906 cnt rms	0.9713 cnt rms
	100 Hz	1.853 uV rms	0.3106 uV rms	0.5909 uV rms	1.156 uV rms	1.133 uV rms
		1.557 cnt rms	0.2609 cnt rms	0.4964 cnt rms	0.9710 cnt rms	0.9521 cnt rms
Channel 2 (N) 500 ohm	20 Hz	0.8932 uV rms	0.3200 uV rms	0.6172 uV rms	0.8883 uV rms	0.8574 uV rms
		0.7546 cnt rms	0.2703 cnt rms	0.5214 cnt rms	0.7504 cnt rms	0.7243 cnt rms
	40 Hz	1.201 uV rms	0.3108 uV rms	0.5972 uV rms	1.171 uV rms	1.149 uV rms
		1.014 cnt rms	0.2625 cnt rms	0.5045 cnt rms	0.9894 cnt rms	0.9709 cnt rms
	100 Hz	1.850 uV rms	0.3065 uV rms	0.5872 uV rms	1.154 uV rms	1.132 uV rms
		1.555 cnt rms	0.2575 cnt rms	0.4934 cnt rms	0.9698 cnt rms	0.9515 cnt rms
Channel 3 (E) 4 kohm	20 Hz	0.8994 uV rms	0.3256 uV rms	0.6219 uV rms	0.8941 uV rms	0.8620 uV rms
		0.7600 cnt rms	0.2752 cnt rms	0.5255 cnt rms	0.7556 cnt rms	0.7284 cnt rms
	40 Hz	1.208 uV rms	0.3168 uV rms	0.6032 uV rms	1.178 uV rms	1.155 uV rms
		1.021 cnt rms	0.2677 cnt rms	0.5097 cnt rms	0.9955 cnt rms	0.9761 cnt rms
	100 Hz	1.860 uV rms	0.3127 uV rms	0.5928 uV rms	1.161 uV rms	1.138 uV rms
		1.564 cnt rms	0.2628 cnt rms	0.4982 cnt rms	0.9758 cnt rms	0.9567 cnt rms

3.8.4.4 Gain 4x and 50 ohm, 500 ohm, and 4 kohm Terminators

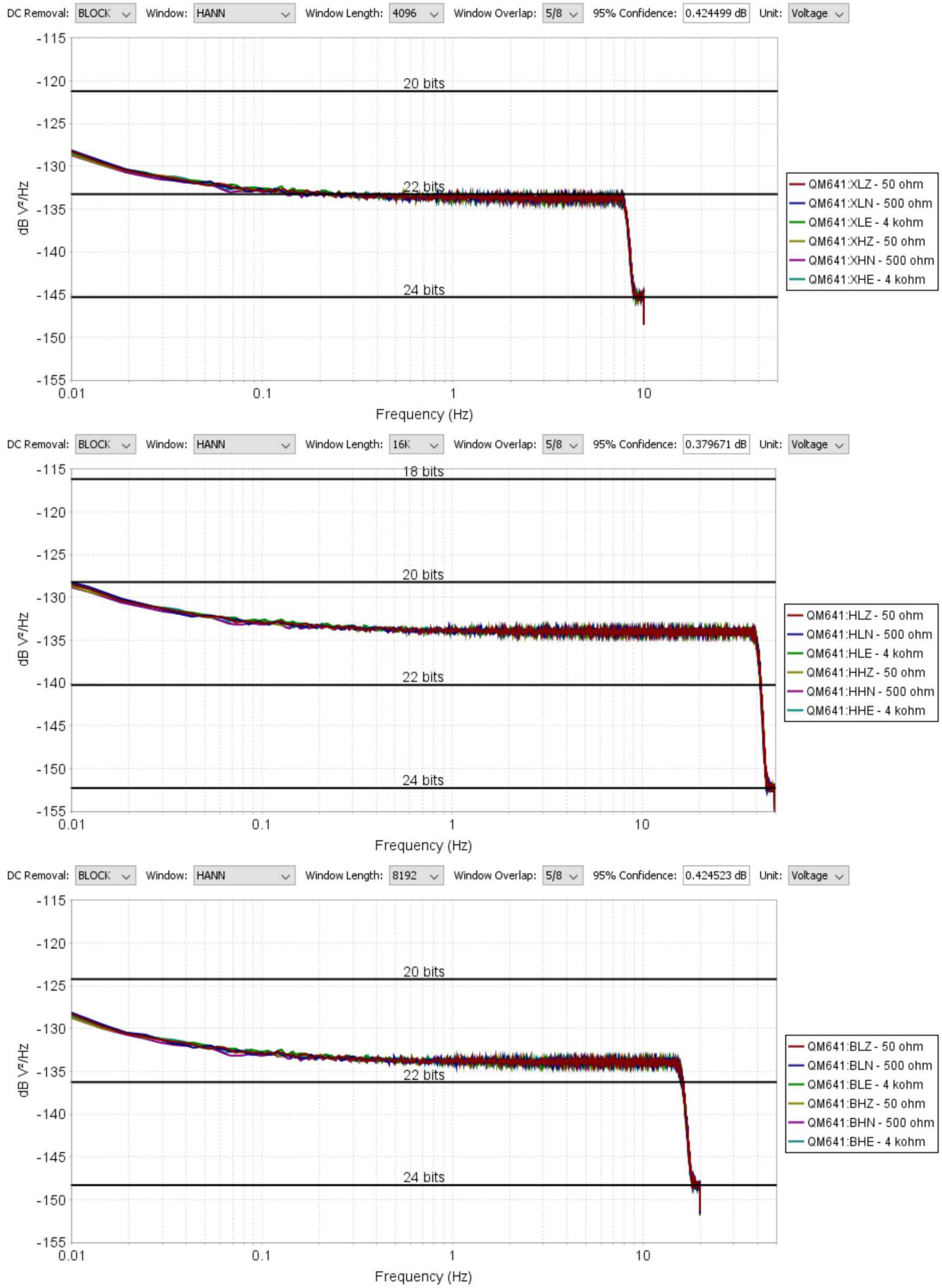


Figure 36 Q330M+ 6641 Self-Noise, gain 4x, 50 ohm, 500 ohm, and 4 kohm at 20 Hz, 40 Hz, and 100 Hz

Table 43 Q330M+ 6641 Self-Noise Power Spectra, gain 4x, 50 ohm, 500 ohm, and 4 kohm

Frequency	Port A			Port B		
	Channel 1 (Z) 50 ohm	Channel 2 (N) 500 ohm	Channel 3 (E) 4 kohm	Channel 1 (Z) 50 ohm	Channel 2 (N) 500 ohm	Channel 3 (E) 4 kohm
0.0100 Hz	-128.90 dB	-128.63 dB	-128.98 dB	-129.89 dB	-129.19 dB	-128.93 dB
0.0125 Hz	-129.16 dB	-128.90 dB	-129.25 dB	-129.89 dB	-129.33 dB	-129.54 dB
0.0160 Hz	-130.03 dB	-129.93 dB	-129.93 dB	-130.10 dB	-130.44 dB	-130.34 dB
0.0200 Hz	-130.63 dB	-130.61 dB	-130.54 dB	-130.56 dB	-130.91 dB	-130.85 dB
0.0250 Hz	-131.16 dB	-130.89 dB	-130.96 dB	-131.16 dB	-131.31 dB	-131.14 dB
0.0315 Hz	-131.65 dB	-131.71 dB	-131.54 dB	-131.39 dB	-131.78 dB	-131.24 dB
0.040 Hz	-131.77 dB	-131.99 dB	-131.71 dB	-131.73 dB	-131.92 dB	-131.76 dB
0.050 Hz	-132.23 dB	-132.33 dB	-132.02 dB	-132.23 dB	-132.32 dB	-132.30 dB
0.063 Hz	-132.43 dB	-132.45 dB	-132.27 dB	-132.54 dB	-132.77 dB	-132.57 dB
0.080 Hz	-132.89 dB	-132.87 dB	-132.60 dB	-132.78 dB	-133.18 dB	-132.81 dB
0.100 Hz	-133.00 dB	-133.10 dB	-132.77 dB	-132.90 dB	-133.16 dB	-132.81 dB
0.125 Hz	-133.06 dB	-133.12 dB	-132.91 dB	-133.14 dB	-133.24 dB	-133.15 dB
0.160 Hz	-133.19 dB	-133.38 dB	-133.08 dB	-133.25 dB	-133.50 dB	-133.35 dB
0.200 Hz	-133.42 dB	-133.46 dB	-133.21 dB	-133.43 dB	-133.51 dB	-133.39 dB
0.250 Hz	-133.51 dB	-133.55 dB	-133.39 dB	-133.55 dB	-133.63 dB	-133.46 dB
0.315 Hz	-133.70 dB	-133.65 dB	-133.50 dB	-133.71 dB	-133.75 dB	-133.63 dB
0.40 Hz	-133.71 dB	-133.73 dB	-133.65 dB	-133.70 dB	-133.81 dB	-133.73 dB
0.50 Hz	-133.74 dB	-133.79 dB	-133.81 dB	-133.79 dB	-133.90 dB	-133.73 dB
0.63 Hz	-133.90 dB	-133.91 dB	-133.85 dB	-133.93 dB	-133.97 dB	-133.81 dB
0.80 Hz	-133.92 dB	-133.92 dB	-133.88 dB	-133.97 dB	-133.96 dB	-133.86 dB
1.00 Hz	-133.92 dB	-133.92 dB	-133.98 dB	-134.00 dB	-133.91 dB	-133.90 dB
1.25 Hz	-133.95 dB	-133.97 dB	-134.00 dB	-134.01 dB	-133.94 dB	-133.94 dB
1.60 Hz	-133.97 dB	-134.00 dB	-134.03 dB	-133.98 dB	-134.00 dB	-133.97 dB
2.00 Hz	-134.02 dB	-133.99 dB	-134.01 dB	-134.00 dB	-134.03 dB	-134.02 dB
2.50 Hz	-134.02 dB	-134.00 dB	-134.03 dB	-134.03 dB	-134.05 dB	-134.03 dB
3.15 Hz	-134.02 dB	-134.02 dB	-134.05 dB	-134.07 dB	-134.06 dB	-134.04 dB
4.0 Hz	-134.05 dB	-134.06 dB	-134.08 dB	-134.08 dB	-134.09 dB	-134.07 dB
5.0 Hz	-134.05 dB	-134.08 dB	-134.08 dB	-134.11 dB	-134.11 dB	-134.07 dB
6.3 Hz	-134.07 dB	-134.06 dB	-134.09 dB	-134.10 dB	-134.11 dB	-134.08 dB
8.0 Hz	-134.07 dB	-134.06 dB	-134.07 dB	-134.09 dB	-134.10 dB	-134.08 dB
10.0 Hz	-134.08 dB	-134.09 dB	-134.06 dB	-134.09 dB	-134.10 dB	-134.08 dB
12.5 Hz	-134.07 dB	-134.06 dB	-134.06 dB	-134.09 dB	-134.09 dB	-134.06 dB
16.0 Hz	-134.09 dB	-134.07 dB	-134.07 dB	-134.10 dB	-134.10 dB	-134.08 dB
20.0 Hz	-134.07 dB	-134.07 dB	-134.07 dB	-134.11 dB	-134.11 dB	-134.10 dB
25.0 Hz	-134.07 dB	-134.08 dB	-134.08 dB	-134.10 dB	-134.11 dB	-134.09 dB
31.5 Hz	-134.08 dB	-134.08 dB	-134.09 dB	-134.10 dB	-134.12 dB	-134.08 dB
40.0 Hz	-135.11 dB	-135.13 dB	-135.11 dB	-135.14 dB	-135.17 dB	-135.16 dB

Table 44 Q330M+ 6641 Port A Self-Noise, gain 4x, 50 ohm, 500 ohm, and 4 kohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	0.5962 uV rms	0.2124 uV rms	0.4138 uV rms	0.5936 uV rms	0.5736 uV rms
		1.007 cnt rms	0.3587 cnt rms	0.6988 cnt rms	1.002 cnt rms	0.9686 cnt rms
	40 Hz	0.8162 uV rms	0.2085 uV rms	0.4062 uV rms	0.7994 uV rms	0.7851 uV rms
		1.378 cnt rms	0.3521 cnt rms	0.6860 cnt rms	1.350 cnt rms	1.326 cnt rms
	100 Hz	1.275 uV rms	0.2075 uV rms	0.4030 uV rms	0.7956 uV rms	0.7814 uV rms
		2.142 cnt rms	0.3485 cnt rms	0.6769 cnt rms	1.336 cnt rms	1.312 cnt rms
Channel 2 (N) 500 ohm	20 Hz	0.5967 uV rms	0.2116 uV rms	0.4138 uV rms	0.5940 uV rms	0.5741 uV rms
		1.008 cnt rms	0.3574 cnt rms	0.6988 cnt rms	1.003 cnt rms	0.9697 cnt rms
	40 Hz	0.8165 uV rms	0.2080 uV rms	0.4061 uV rms	0.7996 uV rms	0.7854 uV rms
		1.379 cnt rms	0.3514 cnt rms	0.6859 cnt rms	1.350 cnt rms	1.326 cnt rms
	100 Hz	1.276 uV rms	0.2069 uV rms	0.4030 uV rms	0.7959 uV rms	0.7819 uV rms
		2.144 cnt rms	0.3475 cnt rms	0.6770 cnt rms	1.337 cnt rms	1.313 cnt rms
Channel 3 (E) 4 kohm	20 Hz	0.5957 uV rms	0.2136 uV rms	0.4138 uV rms	0.5931 uV rms	0.5726 uV rms
		1.007 cnt rms	0.3609 cnt rms	0.6992 cnt rms	1.002 cnt rms	0.9675 cnt rms
	40 Hz	0.8163 uV rms	0.2102 uV rms	0.4064 uV rms	0.7994 uV rms	0.7847 uV rms
		1.379 cnt rms	0.3552 cnt rms	0.6866 cnt rms	1.351 cnt rms	1.326 cnt rms
	100 Hz	1.276 uV rms	0.2089 uV rms	0.4031 uV rms	0.7956 uV rms	0.7810 uV rms
		2.144 cnt rms	0.3510 cnt rms	0.6774 cnt rms	1.337 cnt rms	1.313 cnt rms

Table 45 Q330M+ 6641 Port B Self-Noise, gain 4x, 50 ohm, 500 ohm, and 4 kohm

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 50 ohm	20 Hz	0.5947 uV rms	0.2116 uV rms	0.4125 uV rms	0.5921 uV rms	0.5722 uV rms
		1.004 cnt rms	0.3571 cnt rms	0.6963 cnt rms	0.9995 cnt rms	0.9658 cnt rms
	40 Hz	0.8140 uV rms	0.2082 uV rms	0.4050 uV rms	0.7972 uV rms	0.7830 uV rms
		1.374 cnt rms	0.3514 cnt rms	0.6837 cnt rms	1.346 cnt rms	1.322 cnt rms
	100 Hz	1.272 uV rms	0.2069 uV rms	0.4019 uV rms	0.7933 uV rms	0.7792 uV rms
		2.136 cnt rms	0.3474 cnt rms	0.6748 cnt rms	1.332 cnt rms	1.308 cnt rms
Channel 2 (N) 500 ohm	20 Hz	0.5935 uV rms	0.2099 uV rms	0.4117 uV rms	0.5911 uV rms	0.5717 uV rms
		1.002 cnt rms	0.3545 cnt rms	0.6952 cnt rms	0.9982 cnt rms	0.9654 cnt rms
	40 Hz	0.8131 uV rms	0.2062 uV rms	0.4039 uV rms	0.7963 uV rms	0.7825 uV rms
		1.373 cnt rms	0.3482 cnt rms	0.6821 cnt rms	1.345 cnt rms	1.321 cnt rms
	100 Hz	1.271 uV rms	0.2050 uV rms	0.4008 uV rms	0.7925 uV rms	0.7788 uV rms
		2.134 cnt rms	0.3442 cnt rms	0.6732 cnt rms	1.331 cnt rms	1.308 cnt rms
Channel 3 (E) 4 kohm	20 Hz	0.5959 uV rms	0.2124 uV rms	0.4139 uV rms	0.5934 uV rms	0.5733 uV rms
		1.006 cnt rms	0.3587 cnt rms	0.6991 cnt rms	1.002 cnt rms	0.9684 cnt rms
	40 Hz	0.8162 uV rms	0.2087 uV rms	0.4059 uV rms	0.7994 uV rms	0.7852 uV rms
		1.379 cnt rms	0.3525 cnt rms	0.6856 cnt rms	1.350 cnt rms	1.326 cnt rms
	100 Hz	1.275 uV rms	0.2076 uV rms	0.4032 uV rms	0.7959 uV rms	0.7817 uV rms
		2.142 cnt rms	0.3488 cnt rms	0.6773 cnt rms	1.337 cnt rms	1.313 cnt rms

3.8.4.5 Gain 8xL and 500 ohm, 4 kohm, and 9.4 kohm Terminators

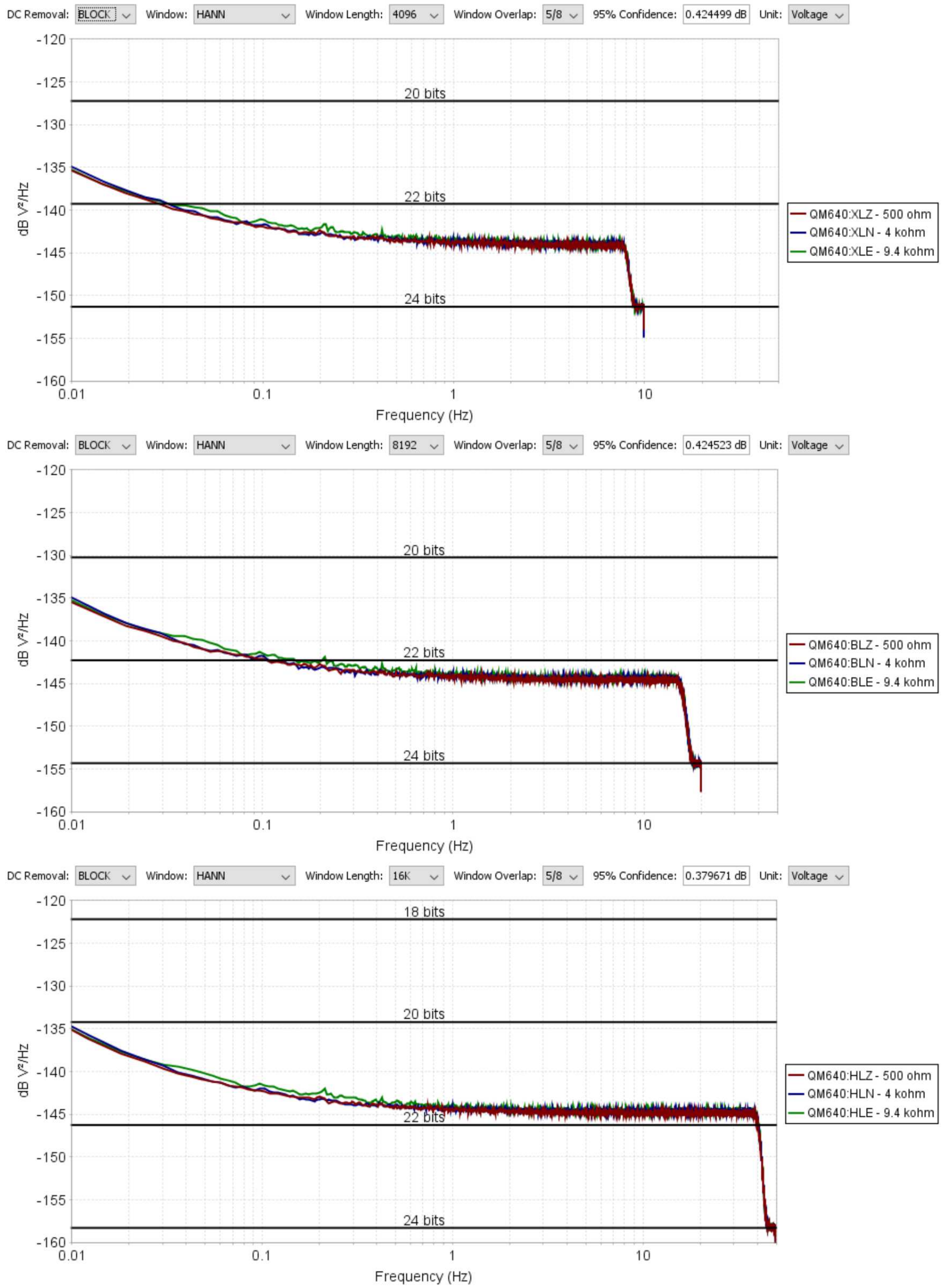


Figure 37 Q330M+ 6640 Self-Noise, gain 8xL, 500 ohm, 4k ohm, and 9.4 kohm at 20 Hz, 40 Hz, and 100 Hz

Table 46 Q330M+ 6640 Self-Noise, gain 8xL, 500 ohm, 4k ohm, and 9.4 kohm

Frequency	Channel 1 (Z) 500 ohm	Channel 2 (N) 4 kohm	Channel 3 (E) 9.4 kohm
0.0100 Hz	-136.27 dB	-135.63 dB	-136.63 dB
0.0125 Hz	-136.47 dB	-136.47 dB	-136.68 dB
0.0160 Hz	-137.72 dB	-137.00 dB	-137.51 dB
0.0200 Hz	-138.38 dB	-138.15 dB	-138.01 dB
0.0250 Hz	-138.85 dB	-138.73 dB	-138.82 dB
0.0315 Hz	-140.03 dB	-139.53 dB	-139.32 dB
0.040 Hz	-140.43 dB	-140.39 dB	-139.63 dB
0.050 Hz	-141.11 dB	-140.97 dB	-140.18 dB
0.063 Hz	-141.51 dB	-141.48 dB	-140.90 dB
0.080 Hz	-142.01 dB	-141.99 dB	-141.61 dB
0.100 Hz	-142.37 dB	-142.35 dB	-141.75 dB
0.125 Hz	-142.83 dB	-142.53 dB	-142.09 dB
0.160 Hz	-143.02 dB	-143.21 dB	-142.58 dB
0.200 Hz	-143.28 dB	-143.38 dB	-142.66 dB
0.250 Hz	-143.67 dB	-143.61 dB	-142.96 dB
0.315 Hz	-143.83 dB	-143.91 dB	-143.20 dB
0.40 Hz	-144.01 dB	-144.00 dB	-143.55 dB
0.50 Hz	-144.16 dB	-144.08 dB	-143.72 dB
0.63 Hz	-144.30 dB	-144.24 dB	-143.87 dB
0.80 Hz	-144.40 dB	-144.32 dB	-144.03 dB
1.00 Hz	-144.48 dB	-144.43 dB	-144.18 dB
1.25 Hz	-144.56 dB	-144.48 dB	-144.24 dB
1.60 Hz	-144.66 dB	-144.52 dB	-144.31 dB
2.00 Hz	-144.74 dB	-144.55 dB	-144.38 dB
2.50 Hz	-144.77 dB	-144.59 dB	-144.49 dB
3.15 Hz	-144.81 dB	-144.65 dB	-144.56 dB
4.0 Hz	-144.88 dB	-144.68 dB	-144.58 dB
5.0 Hz	-144.91 dB	-144.71 dB	-144.64 dB
6.3 Hz	-144.89 dB	-144.72 dB	-144.63 dB
8.0 Hz	-144.88 dB	-144.73 dB	-144.62 dB
10.0 Hz	-144.90 dB	-144.74 dB	-144.62 dB
12.5 Hz	-144.90 dB	-144.74 dB	-144.64 dB
16.0 Hz	-144.93 dB	-144.75 dB	-144.65 dB
20.0 Hz	-144.92 dB	-144.76 dB	-144.66 dB
25.0 Hz	-144.93 dB	-144.76 dB	-144.67 dB
31.5 Hz	-144.94 dB	-144.76 dB	-144.67 dB
40.0 Hz	-145.96 dB	-145.76 dB	-145.66 dB

Table 47 Q330M+ 6640 Self-Noise, gain 8xL

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 500 ohm	20 Hz	0.1868 uV rms	68.97 nV rms	0.1288 uV rms	0.1847 uV rms	0.1775 uV rms
		0.6305 cnt rms	0.2328 cnt rms	0.4346 cnt rms	0.6235 cnt rms	0.5991 cnt rms
	40 Hz	0.2443 uV rms	66.28 nV rms	0.1227 uV rms	0.2367 uV rms	0.2314 uV rms
		0.8246 cnt rms	0.2237 cnt rms	0.4143 cnt rms	0.7988 cnt rms	0.7812 cnt rms
	100 Hz	0.3689 uV rms	64.89 nV rms	0.1195 uV rms	0.2306 uV rms	0.2254 uV rms
		1.239 cnt rms	0.2179 cnt rms	0.4013 cnt rms	0.7741 cnt rms	0.7568 cnt rms
Channel 2 (N) 4 kohm	20 Hz	0.1895 uV rms	69.33 nV rms	0.1304 uV rms	0.1873 uV rms	0.1801 uV rms
		0.6396 cnt rms	0.2340 cnt rms	0.4401 cnt rms	0.6321 cnt rms	0.6078 cnt rms
	40 Hz	0.2485 uV rms	66.46 nV rms	0.1244 uV rms	0.2407 uV rms	0.2355 uV rms
		0.8386 cnt rms	0.2243 cnt rms	0.4200 cnt rms	0.8123 cnt rms	0.7949 cnt rms
	100 Hz	0.3761 uV rms	65.22 nV rms	0.1212 uV rms	0.2348 uV rms	0.2297 uV rms
		1.263 cnt rms	0.2189 cnt rms	0.4070 cnt rms	0.7881 cnt rms	0.7709 cnt rms
Channel 3 (E) 9.4 kohm	20 Hz	0.1923 uV rms	72.44 nV rms	0.1334 uV rms	0.1903 uV rms	0.1824 uV rms
		0.6490 cnt rms	0.2445 cnt rms	0.4501 cnt rms	0.6421 cnt rms	0.6155 cnt rms
	40 Hz	0.2519 uV rms	69.94 nV rms	0.1276 uV rms	0.2443 uV rms	0.2386 uV rms
		0.8503 cnt rms	0.2360 cnt rms	0.4308 cnt rms	0.8245 cnt rms	0.8051 cnt rms
	100 Hz	0.3809 uV rms	68.63 nV rms	0.1245 uV rms	0.2385 uV rms	0.2328 uV rms
		1.279 cnt rms	0.2304 cnt rms	0.4180 cnt rms	0.8006 cnt rms	0.7815 cnt rms

3.8.4.6 Gain 16x and 500 ohm, 4 kohm, and 9.4 kohm Terminators

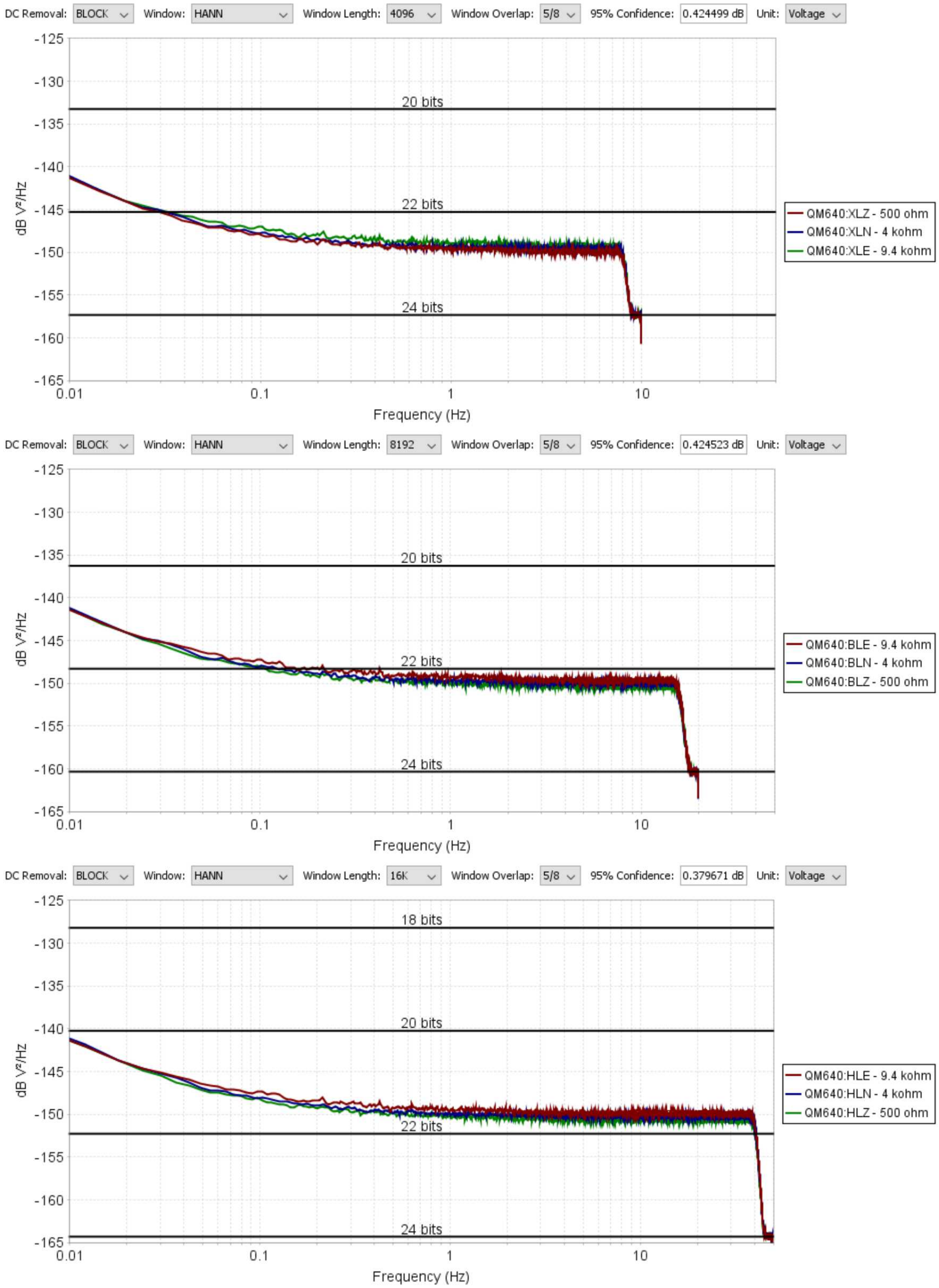


Figure 38 Q330M+ 6640 Self-Noise, gain 16x, 500 ohm, 4k ohm, and 9.4 kohm at 20 Hz, 40 Hz, and 100 Hz

Table 48 Q330M+ 6640 Self-Noise, gain 16x, 500 ohm, 4k ohm, and 9.4 kohm

Frequency	Channel 1 (Z) 500 ohm	Channel 2 (N) 4 kohm	Channel 3 (E) 9.4 kohm
0.0100 Hz	-142.19 dB	-141.72 dB	-142.28 dB
0.0125 Hz	-142.55 dB	-142.26 dB	-142.79 dB
0.0160 Hz	-142.99 dB	-143.15 dB	-143.43 dB
0.0200 Hz	-144.27 dB	-144.24 dB	-144.28 dB
0.0250 Hz	-144.61 dB	-144.81 dB	-145.09 dB
0.0315 Hz	-145.40 dB	-145.52 dB	-145.67 dB
0.040 Hz	-145.88 dB	-146.13 dB	-146.58 dB
0.050 Hz	-146.60 dB	-147.03 dB	-147.31 dB
0.063 Hz	-146.85 dB	-147.28 dB	-147.68 dB
0.080 Hz	-147.38 dB	-147.86 dB	-148.00 dB
0.100 Hz	-147.52 dB	-148.12 dB	-148.44 dB
0.125 Hz	-147.73 dB	-148.41 dB	-148.88 dB
0.160 Hz	-148.44 dB	-148.84 dB	-149.11 dB
0.200 Hz	-148.59 dB	-148.99 dB	-149.26 dB
0.250 Hz	-148.70 dB	-149.26 dB	-149.48 dB
0.315 Hz	-148.81 dB	-149.48 dB	-149.76 dB
0.40 Hz	-149.04 dB	-149.68 dB	-149.92 dB
0.50 Hz	-149.26 dB	-149.74 dB	-150.02 dB
0.63 Hz	-149.33 dB	-149.81 dB	-150.11 dB
0.80 Hz	-149.39 dB	-149.97 dB	-150.21 dB
1.00 Hz	-149.51 dB	-150.03 dB	-150.30 dB
1.25 Hz	-149.49 dB	-150.05 dB	-150.40 dB
1.60 Hz	-149.55 dB	-150.07 dB	-150.44 dB
2.00 Hz	-149.64 dB	-150.11 dB	-150.50 dB
2.50 Hz	-149.78 dB	-150.17 dB	-150.55 dB
3.15 Hz	-149.86 dB	-150.23 dB	-150.60 dB
4.0 Hz	-149.91 dB	-150.25 dB	-150.65 dB
5.0 Hz	-149.92 dB	-150.27 dB	-150.68 dB
6.3 Hz	-149.95 dB	-150.29 dB	-150.69 dB
8.0 Hz	-149.95 dB	-150.31 dB	-150.71 dB
10.0 Hz	-149.94 dB	-150.32 dB	-150.70 dB
12.5 Hz	-149.93 dB	-150.32 dB	-150.70 dB
16.0 Hz	-149.94 dB	-150.34 dB	-150.73 dB
20.0 Hz	-149.95 dB	-150.33 dB	-150.73 dB
25.0 Hz	-149.97 dB	-150.34 dB	-150.73 dB
31.5 Hz	-149.98 dB	-150.35 dB	-150.73 dB
40.0 Hz	-150.98 dB	-151.34 dB	-151.75 dB

Table 49 Q330M+ 6640 Self-Noise, gain 16x

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 500 ohm	20 Hz	95.07 nV rms	34.90 nV rms	65.61 nV rms	94.18 nV rms	90.60 nV rms
		0.6417 cnt rms	0.2356 cnt rms	0.4429 cnt rms	0.6357 cnt rms	0.6115 cnt rms
	40 Hz	0.1354 uV rms	36.56 nV rms	68.46 nV rms	0.1317 uV rms	0.1289 uV rms
		0.9138 cnt rms	0.2468 cnt rms	0.4620 cnt rms	0.8887 cnt rms	0.8697 cnt rms
	100 Hz	0.2063 uV rms	36.02 nV rms	67.03 nV rms	0.1292 uV rms	0.1264 uV rms
		1.385 cnt rms	0.2418 cnt rms	0.4500 cnt rms	0.8670 cnt rms	0.8483 cnt rms
Channel 2 (N) 4 kohm	20 Hz	98.43 nV rms	35.77 nV rms	67.88 nV rms	97.54 nV rms	93.91 nV rms
		0.6642 cnt rms	0.2414 cnt rms	0.4581 cnt rms	0.6582 cnt rms	0.6337 cnt rms
	40 Hz	0.1300 uV rms	34.53 nV rms	65.18 nV rms	0.1262 uV rms	0.1236 uV rms
		0.8770 cnt rms	0.2330 cnt rms	0.4399 cnt rms	0.8517 cnt rms	0.8341 cnt rms
	100 Hz	0.1976 uV rms	33.91 nV rms	63.64 nV rms	0.1234 uV rms	0.1208 uV rms
		1.326 cnt rms	0.2276 cnt rms	0.4271 cnt rms	0.8286 cnt rms	0.8111 cnt rms
Channel 3 (E) 9.4 kohm	20 Hz	0.1023 uV rms	37.85 nV rms	71.18 nV rms	0.1015 uV rms	97.61 nV rms
		0.6907 cnt rms	0.2554 cnt rms	0.4804 cnt rms	0.6851 cnt rms	0.6587 cnt rms
	40 Hz	0.1248 uV rms	33.59 nV rms	62.73 nV rms	0.1211 uV rms	0.1185 uV rms
		0.8423 cnt rms	0.2268 cnt rms	0.4234 cnt rms	0.8171 cnt rms	0.7998 cnt rms
	100 Hz	0.1891 uV rms	32.90 nV rms	61.15 nV rms	0.1181 uV rms	0.1156 uV rms
		1.269 cnt rms	0.2209 cnt rms	0.4105 cnt rms	0.7930 cnt rms	0.7759 cnt rms

3.8.4.7 Gain 32x and 500 ohm, 4 kohm, and 9.4 kohm Terminators

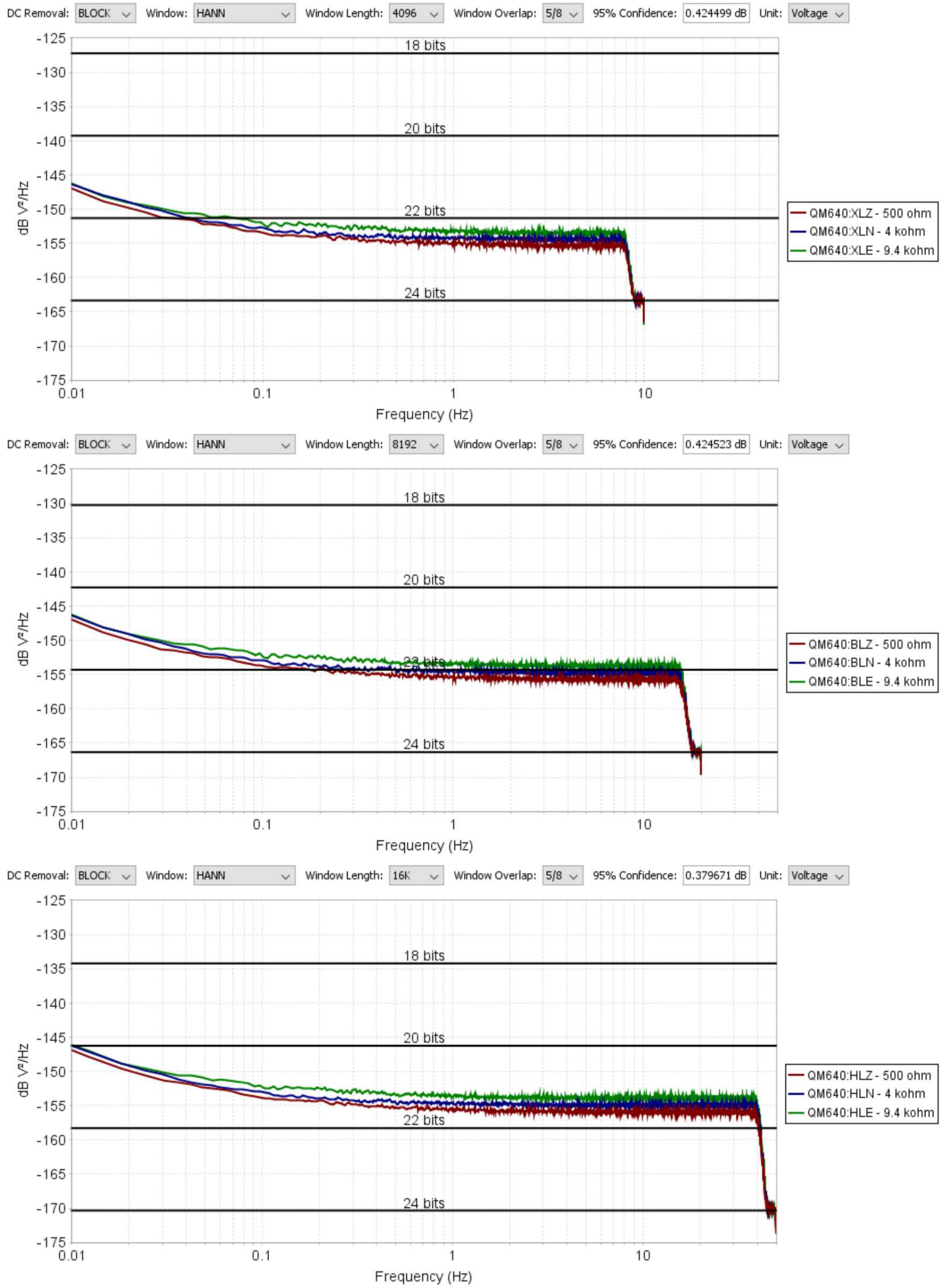


Figure 39 Q330M+ 6640 Self-Noise, gain 32x, 500 ohm, 4k ohm, and 9.4 kohm at 20 Hz, 40 Hz, and 100 Hz

Table 50 Q330M+ 6640 Self-Noise, gain 32x, 500 ohm, 4k ohm, and 9.4 kohm

Frequency	Channel 1 (Z) 500 ohm	Channel 2 (N) 4 kohm	Channel 3 (E) 9.4 kohm
0.0100 Hz	-147.81 dB	-147.15 dB	-146.77 dB
0.0125 Hz	-148.53 dB	-147.38 dB	-147.27 dB
0.0160 Hz	-149.18 dB	-148.42 dB	-148.92 dB
0.0200 Hz	-150.01 dB	-149.09 dB	-149.14 dB
0.0250 Hz	-150.68 dB	-149.97 dB	-149.56 dB
0.0315 Hz	-151.52 dB	-150.59 dB	-150.53 dB
0.040 Hz	-151.86 dB	-151.43 dB	-150.66 dB
0.050 Hz	-152.34 dB	-152.15 dB	-150.96 dB
0.063 Hz	-152.82 dB	-152.39 dB	-151.36 dB
0.080 Hz	-153.47 dB	-152.68 dB	-151.66 dB
0.100 Hz	-153.86 dB	-153.22 dB	-152.23 dB
0.125 Hz	-154.15 dB	-153.54 dB	-152.49 dB
0.160 Hz	-154.32 dB	-153.75 dB	-152.49 dB
0.200 Hz	-154.54 dB	-154.01 dB	-152.69 dB
0.250 Hz	-154.70 dB	-154.22 dB	-152.89 dB
0.315 Hz	-154.93 dB	-154.37 dB	-153.03 dB
0.40 Hz	-155.24 dB	-154.43 dB	-153.18 dB
0.50 Hz	-155.34 dB	-154.55 dB	-153.40 dB
0.63 Hz	-155.41 dB	-154.66 dB	-153.50 dB
0.80 Hz	-155.56 dB	-154.69 dB	-153.57 dB
1.00 Hz	-155.64 dB	-154.73 dB	-153.66 dB
1.25 Hz	-155.74 dB	-154.79 dB	-153.74 dB
1.60 Hz	-155.83 dB	-154.88 dB	-153.83 dB
2.00 Hz	-155.86 dB	-154.88 dB	-153.89 dB
2.50 Hz	-155.88 dB	-154.93 dB	-153.91 dB
3.15 Hz	-155.91 dB	-154.97 dB	-153.94 dB
4.0 Hz	-155.97 dB	-154.99 dB	-153.94 dB
5.0 Hz	-155.98 dB	-155.02 dB	-153.96 dB
6.3 Hz	-155.98 dB	-155.01 dB	-153.97 dB
8.0 Hz	-155.99 dB	-155.02 dB	-153.98 dB
10.0 Hz	-156.00 dB	-155.02 dB	-153.96 dB
12.5 Hz	-156.00 dB	-155.03 dB	-153.95 dB
16.0 Hz	-156.02 dB	-155.05 dB	-153.96 dB
20.0 Hz	-156.02 dB	-155.04 dB	-153.98 dB
25.0 Hz	-156.01 dB	-155.04 dB	-153.99 dB
31.5 Hz	-156.02 dB	-155.04 dB	-153.99 dB
40.0 Hz	-157.04 dB	-156.09 dB	-155.00 dB

Table 51 Q330M+ 6640 Self-Noise, gain 32x

Channel	Sample Rate	0 Hz - Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
Channel 1 (Z) 500 ohm	20 Hz	50.94 nV rms	18.78 nV rms	35.22 nV rms	50.45 nV rms	48.51 nV rms
		0.6877 cnt rms	0.2535 cnt rms	0.4755 cnt rms	0.6811 cnt rms	0.6549 cnt rms
	40 Hz	67.36 nV rms	18.10 nV rms	33.81 nV rms	65.44 nV rms	64.05 nV rms
		0.9094 cnt rms	0.2443 cnt rms	0.4565 cnt rms	0.8834 cnt rms	0.8647 cnt rms
	100 Hz	0.1027 uV rms	17.84 nV rms	33.12 nV rms	64.15 nV rms	62.77 nV rms
		1.379 cnt rms	0.2395 cnt rms	0.4448 cnt rms	0.8614 cnt rms	0.8429 cnt rms
Channel 2 (N) 4 kohm	20 Hz	55.83 nV rms	20.22 nV rms	38.57 nV rms	55.32 nV rms	53.29 nV rms
		0.7529 cnt rms	0.2727 cnt rms	0.5201 cnt rms	0.7460 cnt rms	0.7187 cnt rms
	40 Hz	74.65 nV rms	19.64 nV rms	37.33 nV rms	72.66 nV rms	71.21 nV rms
		1.007 cnt rms	0.2649 cnt rms	0.5034 cnt rms	0.9799 cnt rms	0.9603 cnt rms
	100 Hz	0.1147 uV rms	19.39 nV rms	36.69 nV rms	71.56 nV rms	70.13 nV rms
		1.538 cnt rms	0.2601 cnt rms	0.4922 cnt rms	0.9600 cnt rms	0.9407 cnt rms
Channel 3 (E) 9.4 kohm	20 Hz	62.03 nV rms	22.80 nV rms	43.11 nV rms	61.59 nV rms	59.28 nV rms
		0.8371 cnt rms	0.3077 cnt rms	0.5817 cnt rms	0.8311 cnt rms	0.8000 cnt rms
	40 Hz	83.74 nV rms	22.29 nV rms	42.00 nV rms	81.73 nV rms	80.07 nV rms
		1.130 cnt rms	0.3008 cnt rms	0.5667 cnt rms	1.103 cnt rms	1.081 cnt rms
	100 Hz	0.1294 uV rms	22.09 nV rms	41.46 nV rms	80.89 nV rms	79.25 nV rms
		1.737 cnt rms	0.2965 cnt rms	0.5564 cnt rms	1.086 cnt rms	1.064 cnt rms

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 as dB of 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.

The full scale value used for the largest signal comes from the manufacturer's nominal specifications, validated in section 3.5 AC Full Scale. The value for the smallest signal comes from the evaluated digitizer channel self noise determined in section 3.8 Self-Noise.

3.9.3 Analysis

The dynamic range over a given pass-band is:

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

Where

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

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

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

3.9.4 Result

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

Table 52 Dynamic Range: Q330M+ 6640

Gain	Channel	Sample Rate	0 -Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
1x	Channel 1 (Z) 50 ohm	20 Hz	138.79 dB	147.39 dB	142.02 dB	138.90 dB	139.26 dB
		40 Hz	136.38 dB	147.67 dB	142.36 dB	136.65 dB	136.84 dB
		100 Hz	132.74 dB	147.80 dB	142.54 dB	136.82 dB	137.02 dB
	Channel 2 (N) 50 ohm	20 Hz	138.72 dB	147.44 dB	141.97 dB	138.83 dB	139.18 dB
		40 Hz	136.29 dB	147.73 dB	142.31 dB	136.56 dB	136.75 dB
		100 Hz	132.64 dB	147.87 dB	142.49 dB	136.73 dB	136.93 dB
	Channel 3 (E) 50 ohm	20 Hz	138.69 dB	147.10 dB	141.87 dB	138.80 dB	139.20 dB
		40 Hz	136.28 dB	147.36 dB	142.21 dB	136.55 dB	136.77 dB
		100 Hz	132.65 dB	147.48 dB	142.39 dB	136.72 dB	136.94 dB
8xL	Channel 1 (Z) 500 ohm	20 Hz	139.52 dB	148.18 dB	142.75 dB	139.62 dB	139.97 dB
		40 Hz	137.19 dB	148.52 dB	143.17 dB	137.47 dB	137.66 dB
		100 Hz	133.61 dB	148.71 dB	143.40 dB	137.69 dB	137.89 dB
	Channel 2 (N) 4 kohm	20 Hz	139.40 dB	148.13 dB	142.64 dB	139.50 dB	139.84 dB
		40 Hz	137.04 dB	148.50 dB	143.05 dB	137.32 dB	137.51 dB
		100 Hz	133.44 dB	148.66 dB	143.28 dB	137.54 dB	137.73 dB
	Channel 3 (E) 9.4 kohm	20 Hz	139.27 dB	147.75 dB	142.45 dB	139.36 dB	139.73 dB
		40 Hz	136.92 dB	148.05 dB	142.83 dB	137.19 dB	137.40 dB
		100 Hz	133.33 dB	148.22 dB	143.04 dB	137.40 dB	137.61 dB
16x	Channel 1 (Z) 500 ohm	20 Hz	139.37 dB	148.07 dB	142.59 dB	139.45 dB	139.79 dB
		40 Hz	136.30 dB	147.67 dB	142.22 dB	136.54 dB	136.73 dB
		100 Hz	132.64 dB	147.80 dB	142.40 dB	136.71 dB	136.90 dB
	Channel 2 (N) 4 kohm	20 Hz	139.07 dB	147.86 dB	142.29 dB	139.14 dB	139.47 dB
		40 Hz	136.65 dB	148.16 dB	142.65 dB	136.91 dB	137.09 dB
		100 Hz	133.01 dB	148.32 dB	142.85 dB	137.10 dB	137.28 dB
	Channel 3 (E) 9.4 kohm	20 Hz	138.73 dB	147.37 dB	141.88 dB	138.80 dB	139.14 dB
		40 Hz	137.01 dB	148.40 dB	142.98 dB	137.27 dB	137.46 dB
		100 Hz	133.40 dB	148.58 dB	143.20 dB	137.48 dB	137.67 dB
32x	Channel 1 (Z) 500 ohm	20 Hz	138.77 dB	147.43 dB	141.97 dB	138.85 dB	139.19 dB
		40 Hz	136.34 dB	147.76 dB	142.33 dB	136.59 dB	136.78 dB
		100 Hz	132.68 dB	147.88 dB	142.50 dB	136.76 dB	136.95 dB
	Channel 2 (N) 4 kohm	20 Hz	137.97 dB	146.79 dB	141.18 dB	138.05 dB	138.37 dB
		40 Hz	135.45 dB	147.04 dB	141.47 dB	135.68 dB	135.86 dB
		100 Hz	131.72 dB	147.16 dB	141.62 dB	135.81 dB	135.99 dB
	Channel 3 (E) 9.4 kohm	20 Hz	137.06 dB	145.75 dB	140.22 dB	137.12 dB	137.45 dB
		40 Hz	134.45 dB	145.95 dB	140.44 dB	134.66 dB	134.84 dB
		100 Hz	130.67 dB	146.02 dB	140.56 dB	134.75 dB	134.93 dB

Table 53 Dynamic Range: Q330M+ 6641 Port A

Gain	Channel	Sample Rate	0 -Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
1x	Channel 1 (Z) 50 ohm	20 Hz	138.83 dB	147.62 dB	142.06 dB	138.90 dB	139.23 dB
		40 Hz	136.37 dB	147.93 dB	142.40 dB	136.62 dB	136.79 dB
		100 Hz	132.69 dB	148.08 dB	142.59 dB	136.79 dB	136.97 dB
	Channel 2 (N) 50 ohm	20 Hz	138.86 dB	147.66 dB	142.09 dB	138.93 dB	139.26 dB
		40 Hz	136.41 dB	147.97 dB	142.43 dB	136.65 dB	136.83 dB
		100 Hz	132.74 dB	148.12 dB	142.63 dB	136.83 dB	137.01 dB
	Channel 3 (E) 50 ohm	20 Hz	138.80 dB	147.37 dB	141.98 dB	138.87 dB	139.23 dB
		40 Hz	136.36 dB	147.66 dB	142.31 dB	136.60 dB	136.80 dB
		100 Hz	132.70 dB	147.80 dB	142.50 dB	136.78 dB	136.98 dB
1x	Channel 1 (Z) 50 ohm	20 Hz	138.83 dB	147.61 dB	142.06 dB	138.90 dB	139.23 dB
		40 Hz	136.38 dB	147.90 dB	142.40 dB	136.62 dB	136.80 dB
		100 Hz	132.70 dB	148.05 dB	142.59 dB	136.80 dB	136.98 dB
	Channel 2 (N) 500 ohm	20 Hz	138.85 dB	147.66 dB	142.07 dB	138.92 dB	139.25 dB
		40 Hz	136.41 dB	147.95 dB	142.42 dB	136.65 dB	136.83 dB
		100 Hz	132.74 dB	148.11 dB	142.61 dB	136.83 dB	137.01 dB
	Channel 3 (E) 4 kohm	20 Hz	138.79 dB	147.32 dB	141.97 dB	138.85 dB	139.22 dB
		40 Hz	136.35 dB	147.61 dB	142.31 dB	136.59 dB	136.79 dB
		100 Hz	132.69 dB	147.74 dB	142.49 dB	136.76 dB	136.97 dB
2x	Channel 1 (Z) 50 ohm	20 Hz	137.90 dB	146.71 dB	141.09 dB	137.95 dB	138.27 dB
		40 Hz	135.34 dB	146.95 dB	141.37 dB	135.56 dB	135.73 dB
		100 Hz	131.59 dB	147.07 dB	141.51 dB	135.68 dB	135.85 dB
	Channel 2 (N) 500 ohm	20 Hz	137.92 dB	146.78 dB	141.12 dB	137.97 dB	138.29 dB
		40 Hz	135.36 dB	147.04 dB	141.40 dB	135.58 dB	135.75 dB
		100 Hz	131.60 dB	147.15 dB	141.54 dB	135.70 dB	135.87 dB
	Channel 3 (E) 4 kohm	20 Hz	137.88 dB	146.52 dB	141.04 dB	137.93 dB	138.27 dB
		40 Hz	135.33 dB	146.78 dB	141.32 dB	135.54 dB	135.73 dB
		100 Hz	131.58 dB	146.88 dB	141.46 dB	135.67 dB	135.85 dB
4x	Channel 1 (Z) 50 ohm	20 Hz	135.46 dB	144.43 dB	138.63 dB	135.50 dB	135.80 dB
		40 Hz	132.73 dB	144.59 dB	138.79 dB	132.91 dB	133.07 dB
		100 Hz	128.86 dB	144.63 dB	138.86 dB	132.96 dB	133.11 dB
	Channel 2 (N) 500 ohm	20 Hz	135.45 dB	144.46 dB	138.63 dB	135.49 dB	135.79 dB
		40 Hz	132.73 dB	144.61 dB	138.80 dB	132.91 dB	133.07 dB
		100 Hz	128.85 dB	144.66 dB	138.86 dB	132.95 dB	133.11 dB
	Channel 3 (E) 4 kohm	20 Hz	135.47 dB	144.38 dB	138.63 dB	135.51 dB	135.81 dB
		40 Hz	132.73 dB	144.52 dB	138.79 dB	132.91 dB	133.08 dB
		100 Hz	128.85 dB	144.57 dB	138.86 dB	132.96 dB	133.12 dB

Table 54 Dynamic Range: Q330M+ 6641 Port B

Gain	Channel	Sample Rate	0 -Nyquist	20 mHz - 1 Hz	20 mHz - 4 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
1x	Channel 1 (Z) 50 ohm	20 Hz	138.87 dB	147.67 dB	142.09 dB	138.94 dB	139.26 dB
		40 Hz	136.41 dB	147.99 dB	142.45 dB	136.66 dB	136.83 dB
		100 Hz	132.74 dB	148.14 dB	142.64 dB	136.84 dB	137.02 dB
	Channel 2 (N) 50 ohm	20 Hz	138.92 dB	147.75 dB	142.15 dB	138.98 dB	139.30 dB
		40 Hz	136.46 dB	148.08 dB	142.50 dB	136.70 dB	136.87 dB
		100 Hz	132.77 dB	148.23 dB	142.69 dB	136.88 dB	137.06 dB
	Channel 3 (E) 50 ohm	20 Hz	138.84 dB	147.61 dB	142.06 dB	138.91 dB	139.24 dB
		40 Hz	136.39 dB	147.92 dB	142.41 dB	136.64 dB	136.82 dB
		100 Hz	132.71 dB	148.06 dB	142.60 dB	136.81 dB	136.99 dB
1x	Channel 1 (Z) 50 ohm	20 Hz	138.87 dB	147.66 dB	142.09 dB	138.93 dB	139.26 dB
		40 Hz	136.42 dB	147.97 dB	142.44 dB	136.66 dB	136.84 dB
		100 Hz	132.74 dB	148.12 dB	142.63 dB	136.84 dB	137.02 dB
	Channel 2 (N) 500 ohm	20 Hz	138.90 dB	147.74 dB	142.12 dB	138.97 dB	139.29 dB
		40 Hz	136.45 dB	148.06 dB	142.47 dB	136.69 dB	136.87 dB
		100 Hz	132.77 dB	148.21 dB	142.66 dB	136.87 dB	137.05 dB
	Channel 3 (E) 4 kohm	20 Hz	138.85 dB	147.63 dB	142.07 dB	138.92 dB	139.25 dB
		40 Hz	136.40 dB	147.94 dB	142.42 dB	136.64 dB	136.82 dB
		100 Hz	132.72 dB	148.09 dB	142.61 dB	136.82 dB	137.00 dB
2x	Channel 1 (Z) 50 ohm	20 Hz	137.94 dB	146.79 dB	141.14 dB	137.99 dB	138.30 dB
		40 Hz	135.39 dB	147.02 dB	141.41 dB	135.61 dB	135.78 dB
		100 Hz	131.63 dB	147.15 dB	141.56 dB	135.73 dB	135.90 dB
	Channel 2 (N) 500 ohm	20 Hz	137.97 dB	146.89 dB	141.18 dB	138.02 dB	138.33 dB
		40 Hz	135.40 dB	147.14 dB	141.47 dB	135.62 dB	135.78 dB
		100 Hz	131.65 dB	147.26 dB	141.61 dB	135.74 dB	135.91 dB
	Channel 3 (E) 4 kohm	20 Hz	137.91 dB	146.74 dB	141.12 dB	137.96 dB	138.28 dB
		40 Hz	135.35 dB	146.97 dB	141.38 dB	135.57 dB	135.74 dB
		100 Hz	131.60 dB	147.09 dB	141.53 dB	135.69 dB	135.87 dB
4x	Channel 1 (Z) 50 ohm	20 Hz	135.48 dB	144.46 dB	138.66 dB	135.52 dB	135.82 dB
		40 Hz	132.76 dB	144.60 dB	138.82 dB	132.94 dB	133.09 dB
		100 Hz	128.88 dB	144.65 dB	138.89 dB	132.98 dB	133.14 dB
	Channel 2 (N) 500 ohm	20 Hz	135.50 dB	144.53 dB	138.68 dB	135.54 dB	135.83 dB
		40 Hz	132.77 dB	144.68 dB	138.84 dB	132.95 dB	133.10 dB
		100 Hz	128.89 dB	144.74 dB	138.91 dB	132.99 dB	133.14 dB
	Channel 3 (E) 4 kohm	20 Hz	135.47 dB	144.43 dB	138.63 dB	135.50 dB	135.80 dB
		40 Hz	132.73 dB	144.58 dB	138.80 dB	132.91 dB	133.07 dB
		100 Hz	128.86 dB	144.62 dB	138.86 dB	132.95 dB	133.11 dB

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

There is no test configuration for the dynamic range test.

The time-series data and PSD are obtained from the evaluated digitizer channel self noise determined in section 3.8 Self-Noise.

3.10.3 Analysis

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

3.10.4 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.

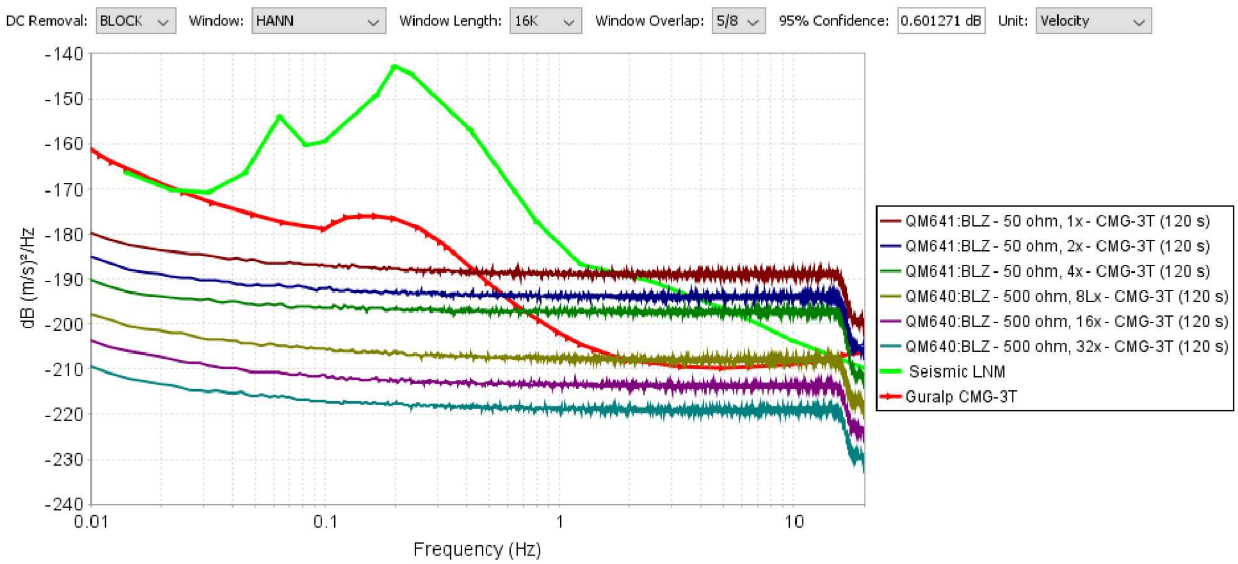


Figure 40 Seismic System Noise for Guralp CMG-3T (1500 V/(m/s) and 120 sec corner) at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

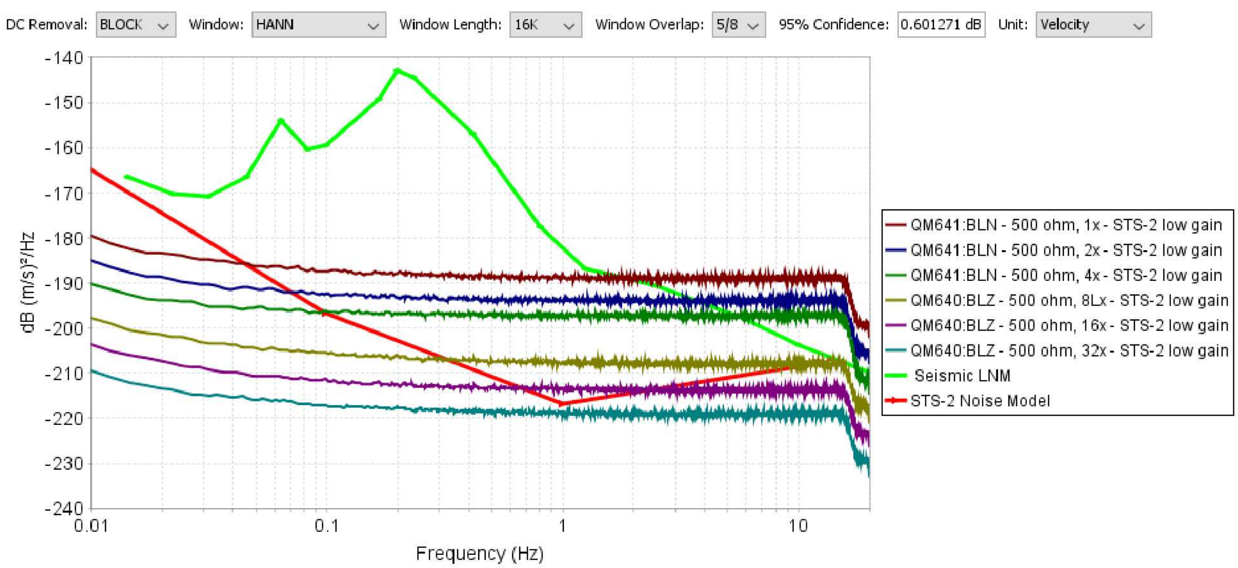


Figure 41 Seismic System Noise for STS-2 low gain at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

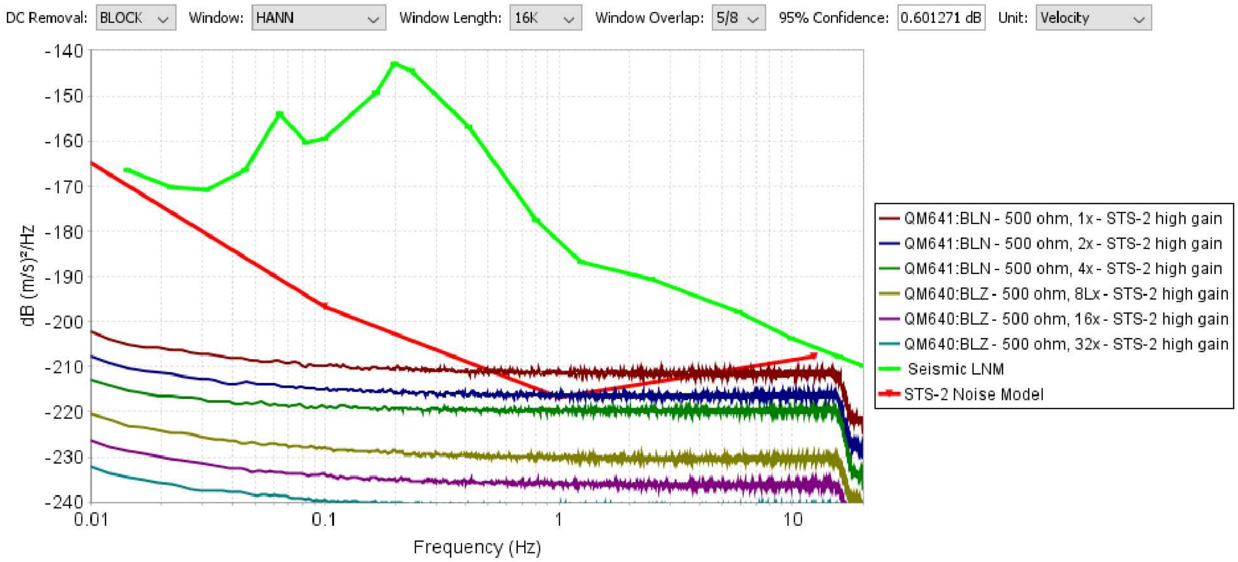


Figure 42 Seismic System Noise for STS-2 high gain at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

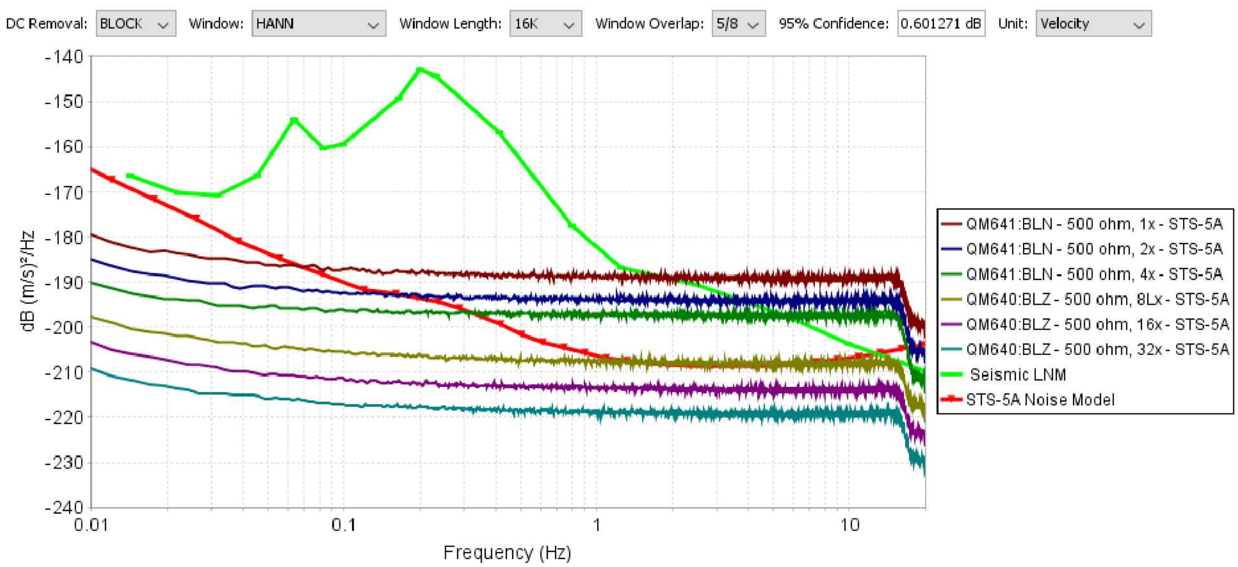


Figure 43 Seismic System Noise for Kinematics STS-5A at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

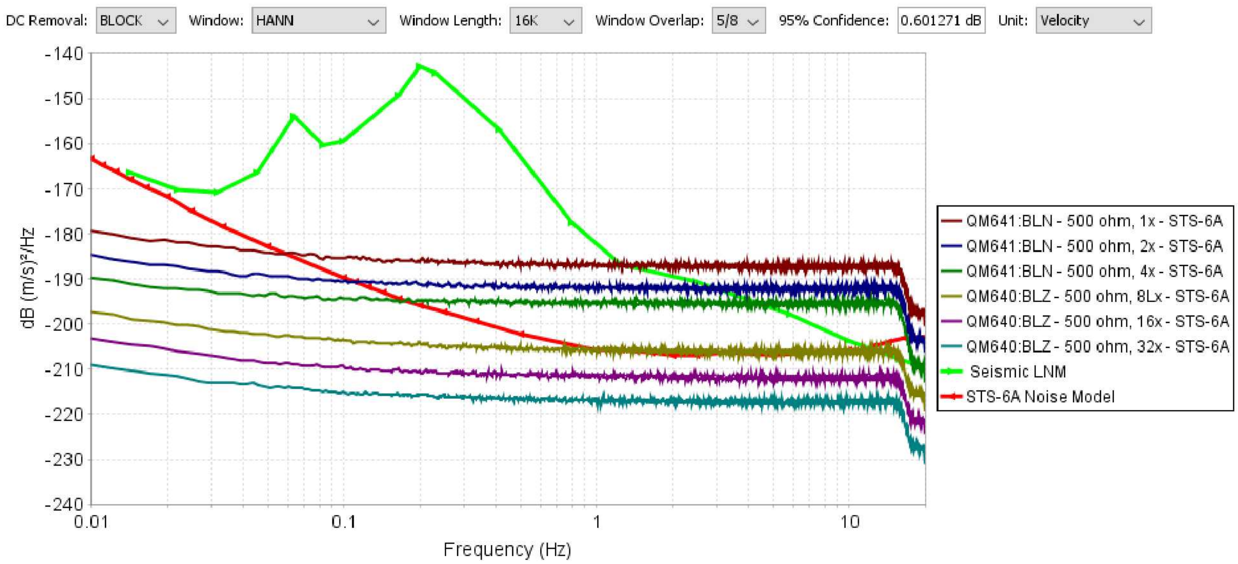


Figure 44 Seismic System Noise for Kinematrics STS-6A at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

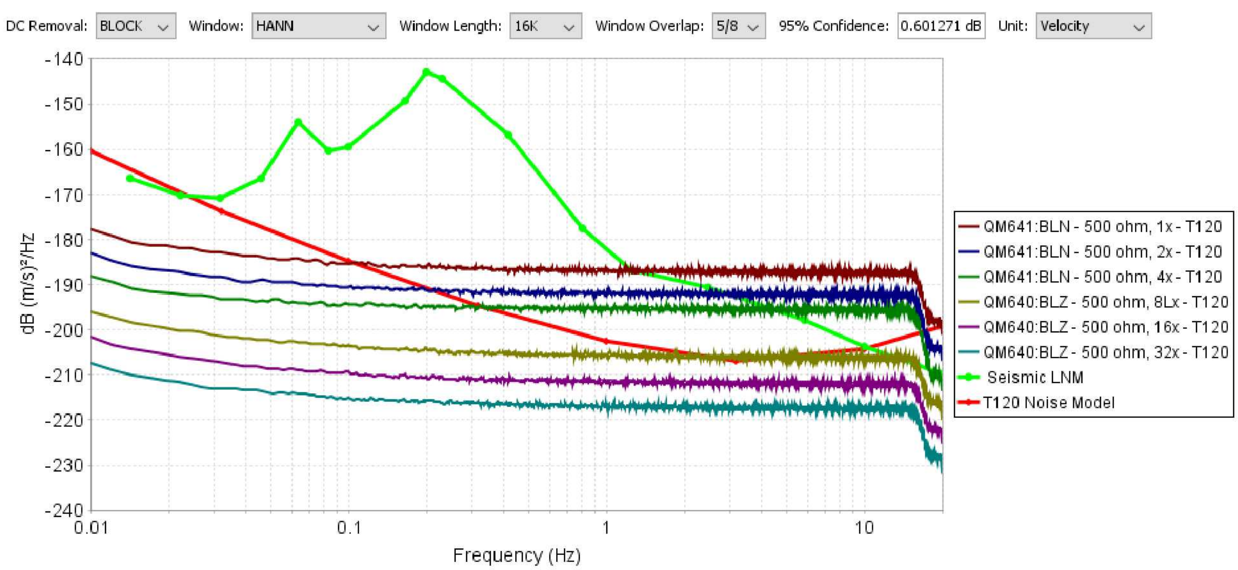


Figure 45 Seismic System Noise for Trillium 120 at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

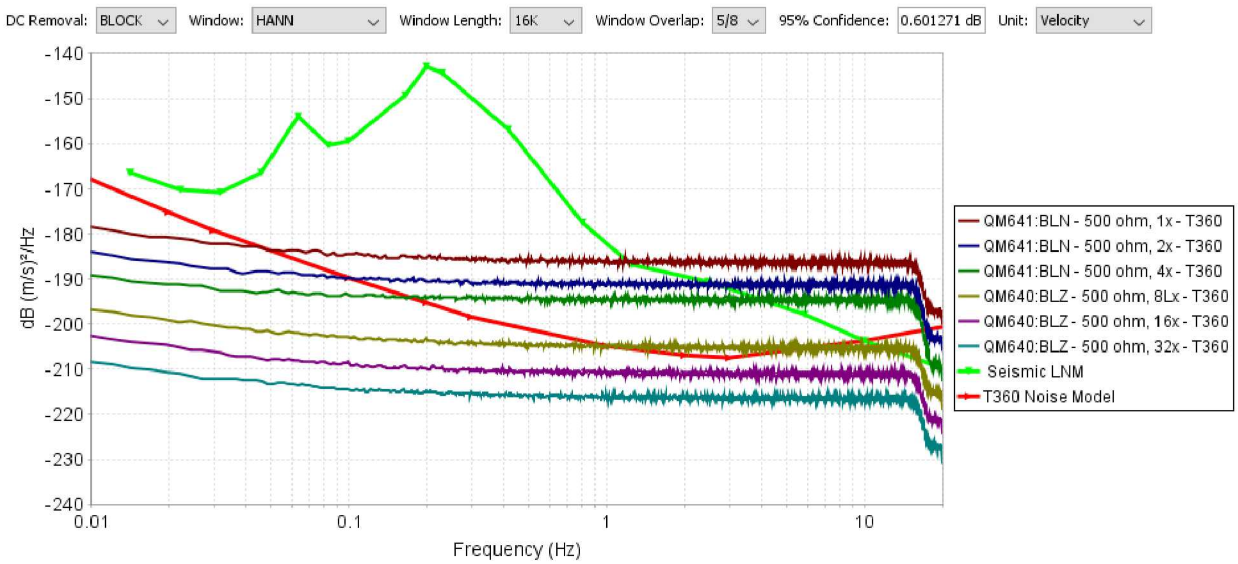


Figure 46 Seismic System Noise for Trillium 360 at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

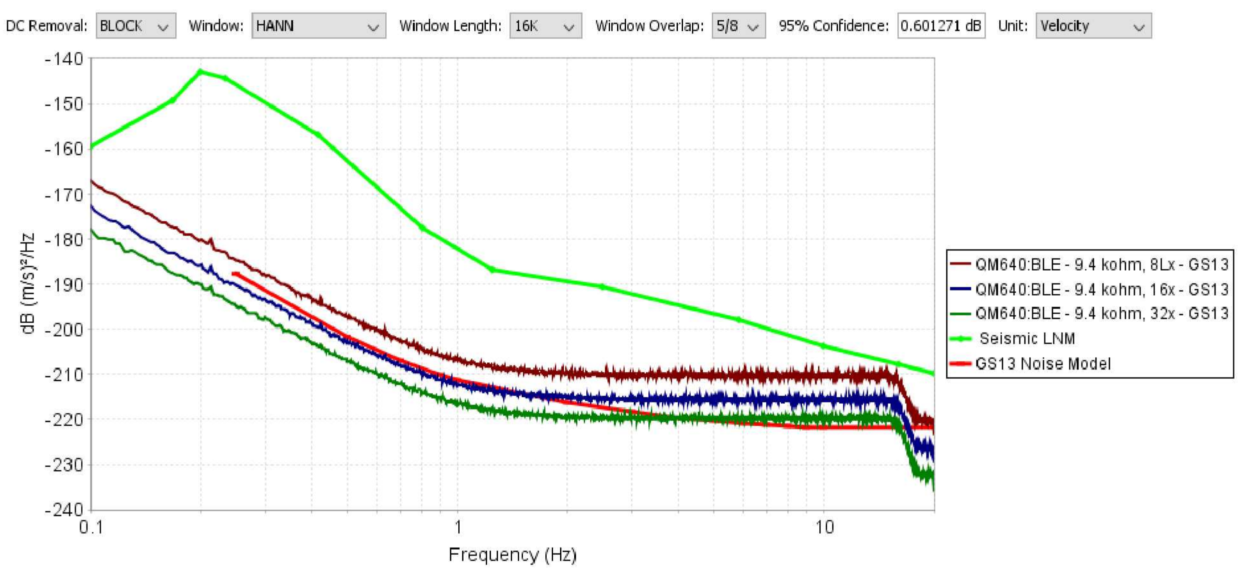


Figure 47 Seismic System Noise for Geotech GS13 at gains of 8xL, 16x, and 32x

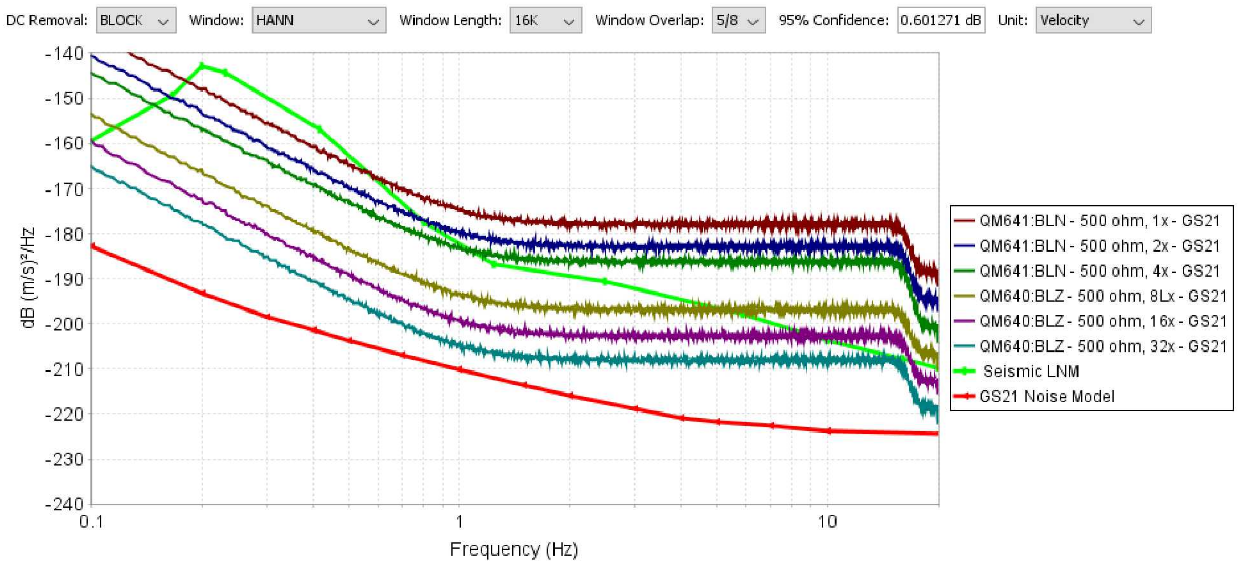


Figure 48 Seismic System Noise for Geotech GS21 at gains of 1x, 2x, 4x, 8xL, 16x, and 32x

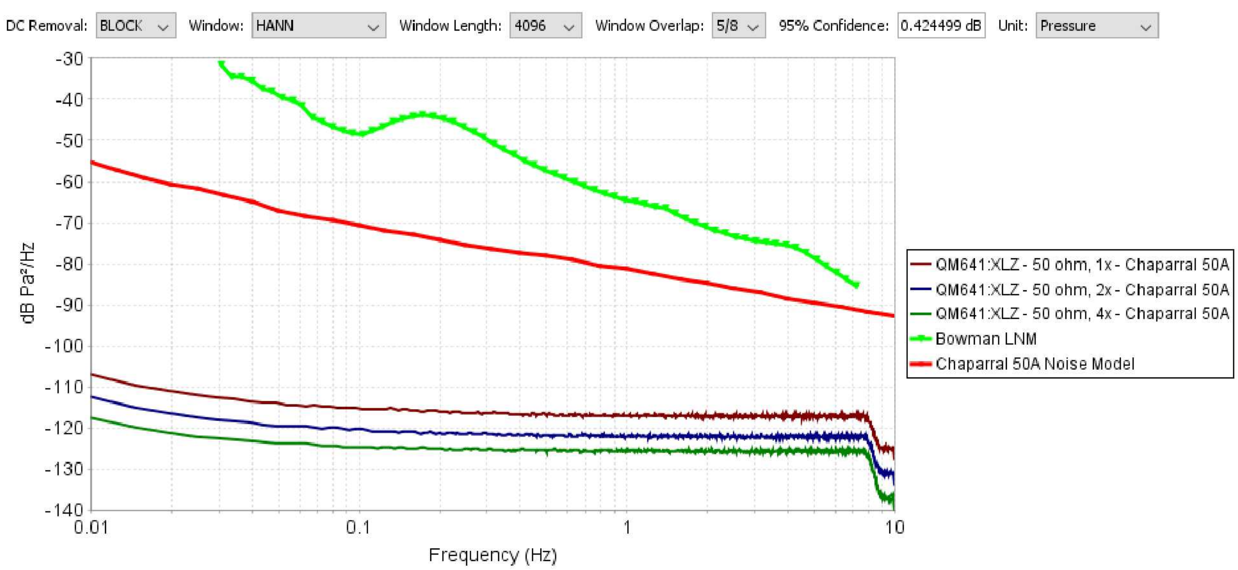


Figure 49 Infrasound System Noise for Chaparral 50A at gains of 1, 2, and 4

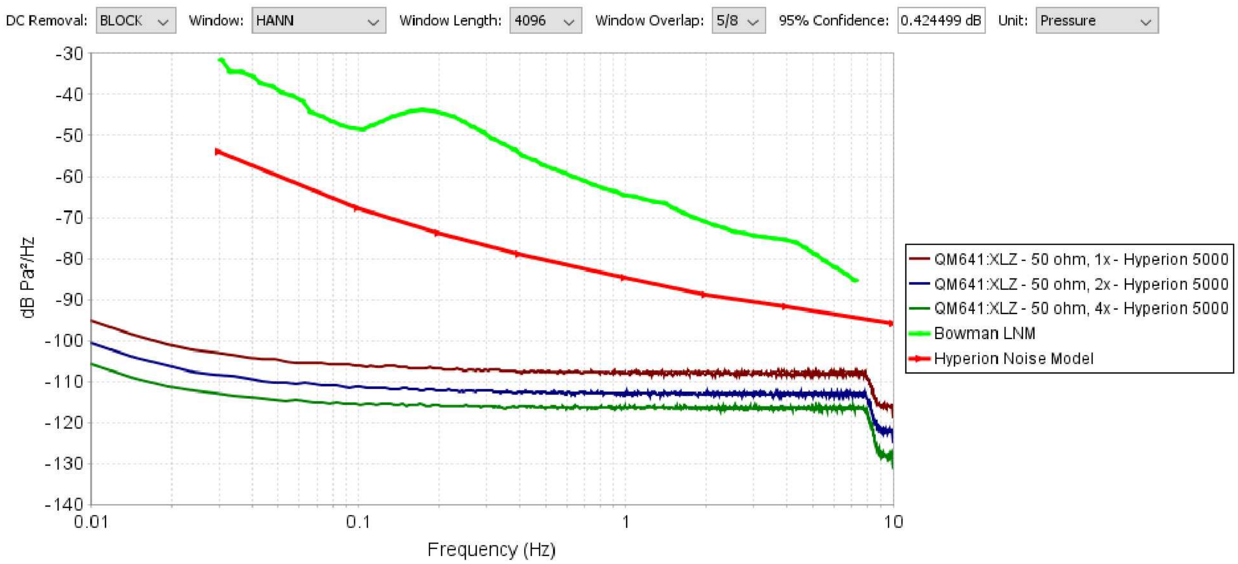


Figure 50 Infrasound System Noise for Hyperion 5000 at gains of 1, 2, and 4

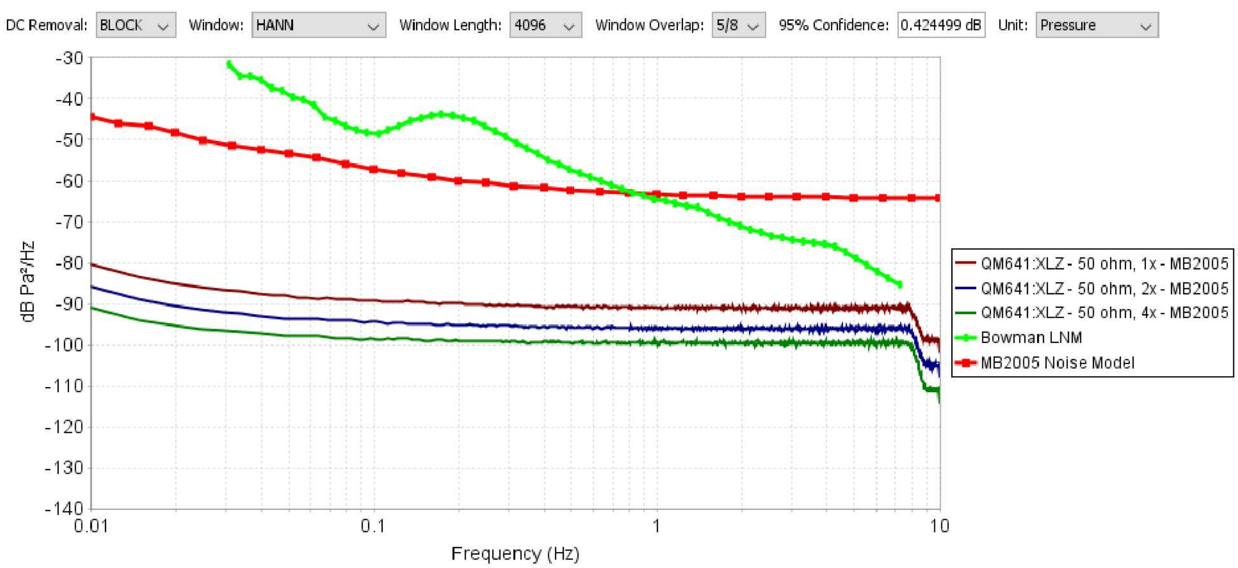


Figure 51 Infrasound System Noise for MB2005 at gains of 1, 2, and 4

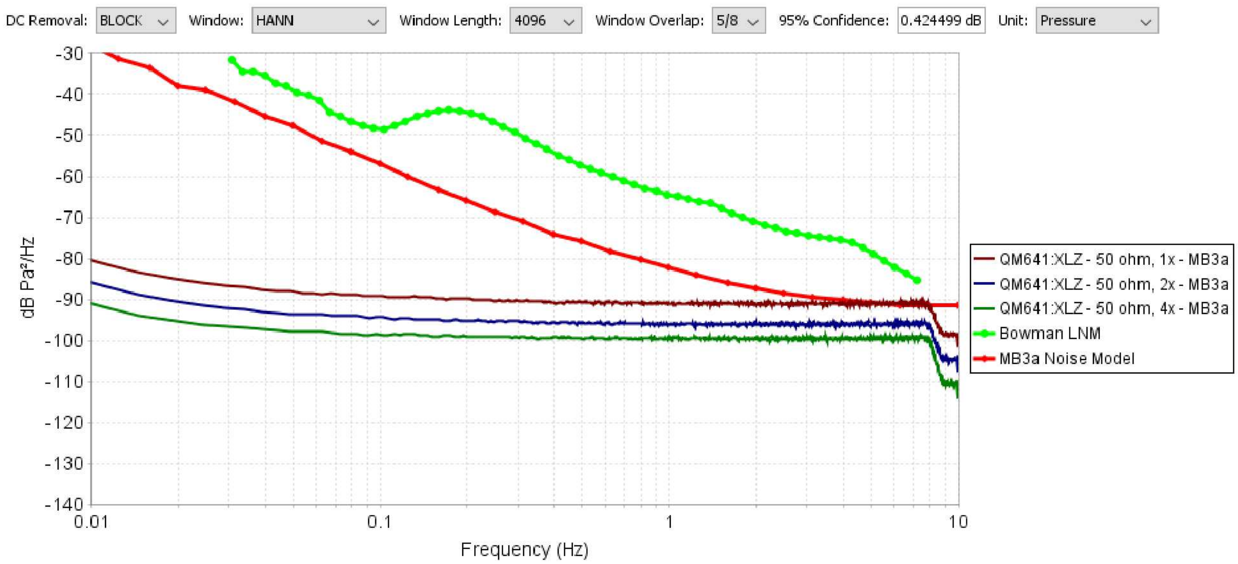


Figure 52 Infrasound System Noise for MB3a at gains of 1, 2, and 4

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. In addition, it is confirmed that the digitizer continues to operate across the tested temperature range.

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 53 Temperature Self Noise Configuration Diagram

Figure 54 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 55 Temperature Self Noise Configuration Picture

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

Table 55 Digitizer Temperature Self-Noise Terminator Configuration

	Gain	Z	N	E
Q330M+ 6640	32x	500 ohm	4 kohm	9.4 kohm
Q330M+ 6641, Port A	1x	50 ohm	500 ohm	4 kohm
Q330M+ 6641, Port B	8xL	50 ohm	500 ohm	4 kohm

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 56 Self Noise Testbed Equipment

	Manufacturer / Model
Temperature Chamber	ESPEC EPL-2H

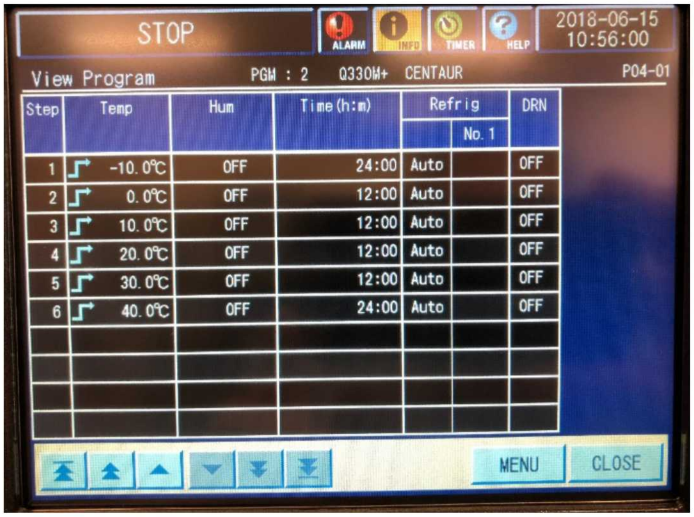


Figure 56 Temperature Chamber Program

3.11.3 Analysis

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

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

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 6640 and 6641 are shown below. Only the data from 100 Hz is shown as the other sample rates were otherwise identical.

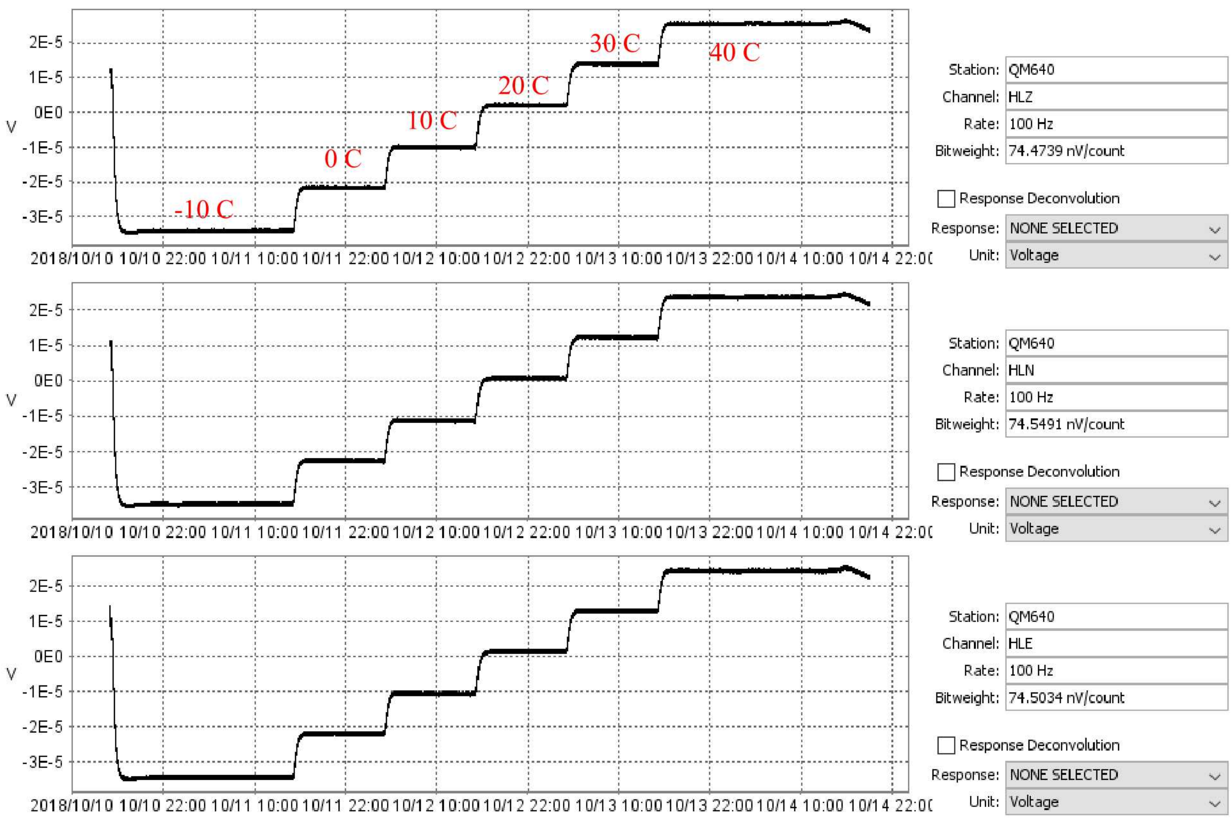


Figure 57 Temperature Self Noise Time Series, Q330M+ 6640, gain 32x

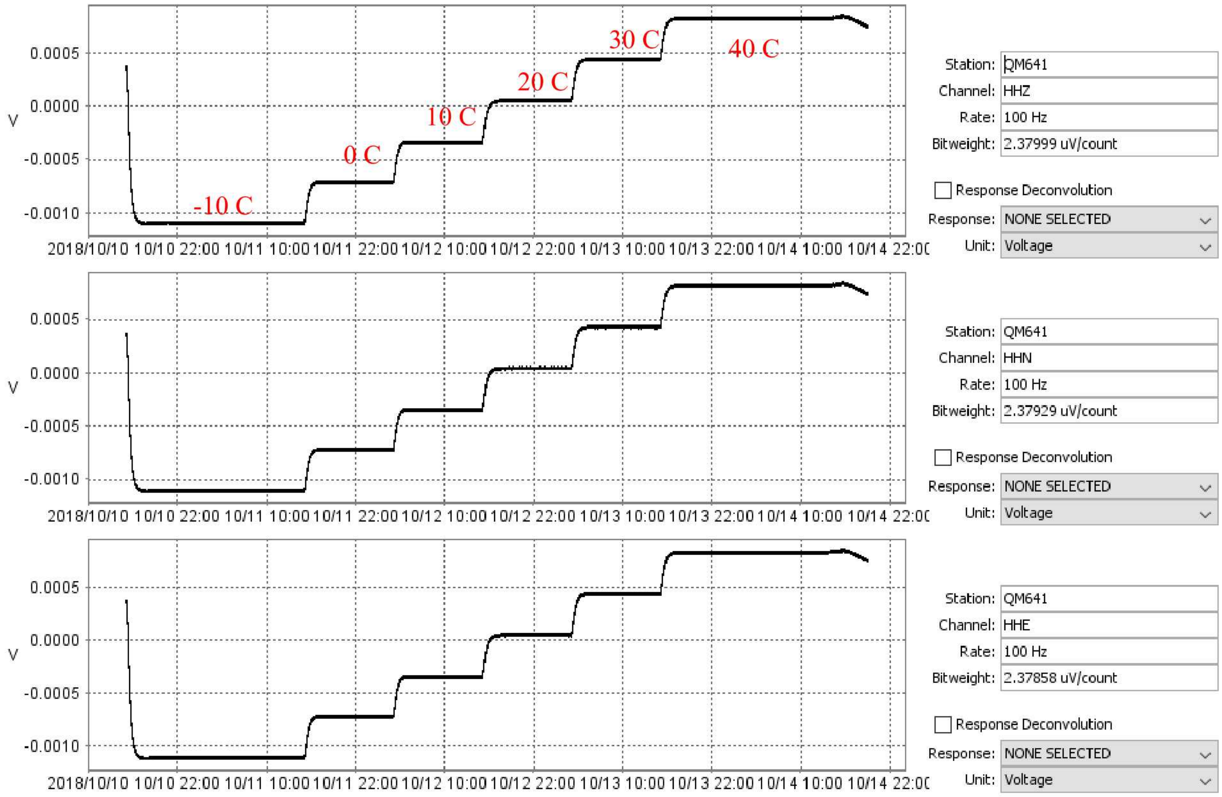


Figure 58 Temperature Self Noise Time Series, Q330M+ 6641, Port A, gain 1x

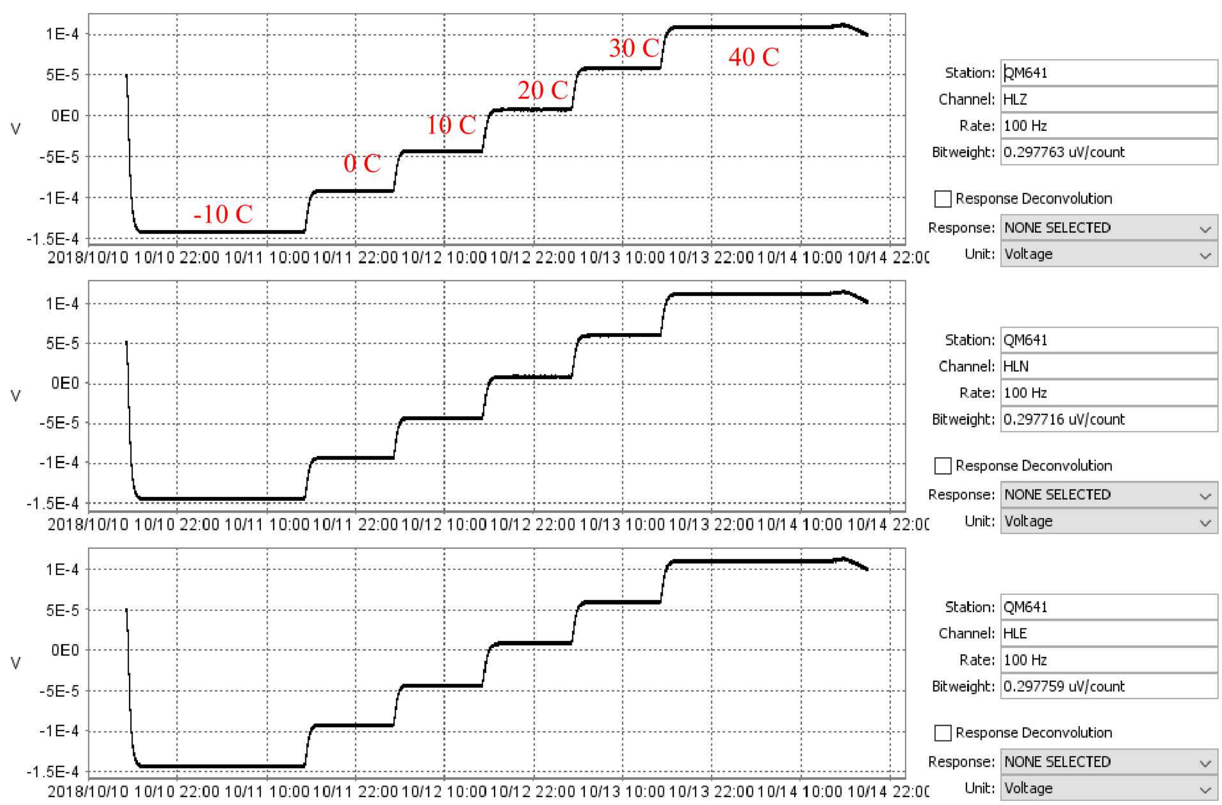


Figure 59 Temperature Self Noise Time Series, Q330M+ 6641, Port B, gain 8xL

There were no issues with the Q330M+ 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. A 10-hour window of data was used for computing the power spectra, selected from the time series after the temperature and DC offset had stabilized. The plot of power spectra includes a line shown in bright green representing the median self-noise observed earlier at that gain level.

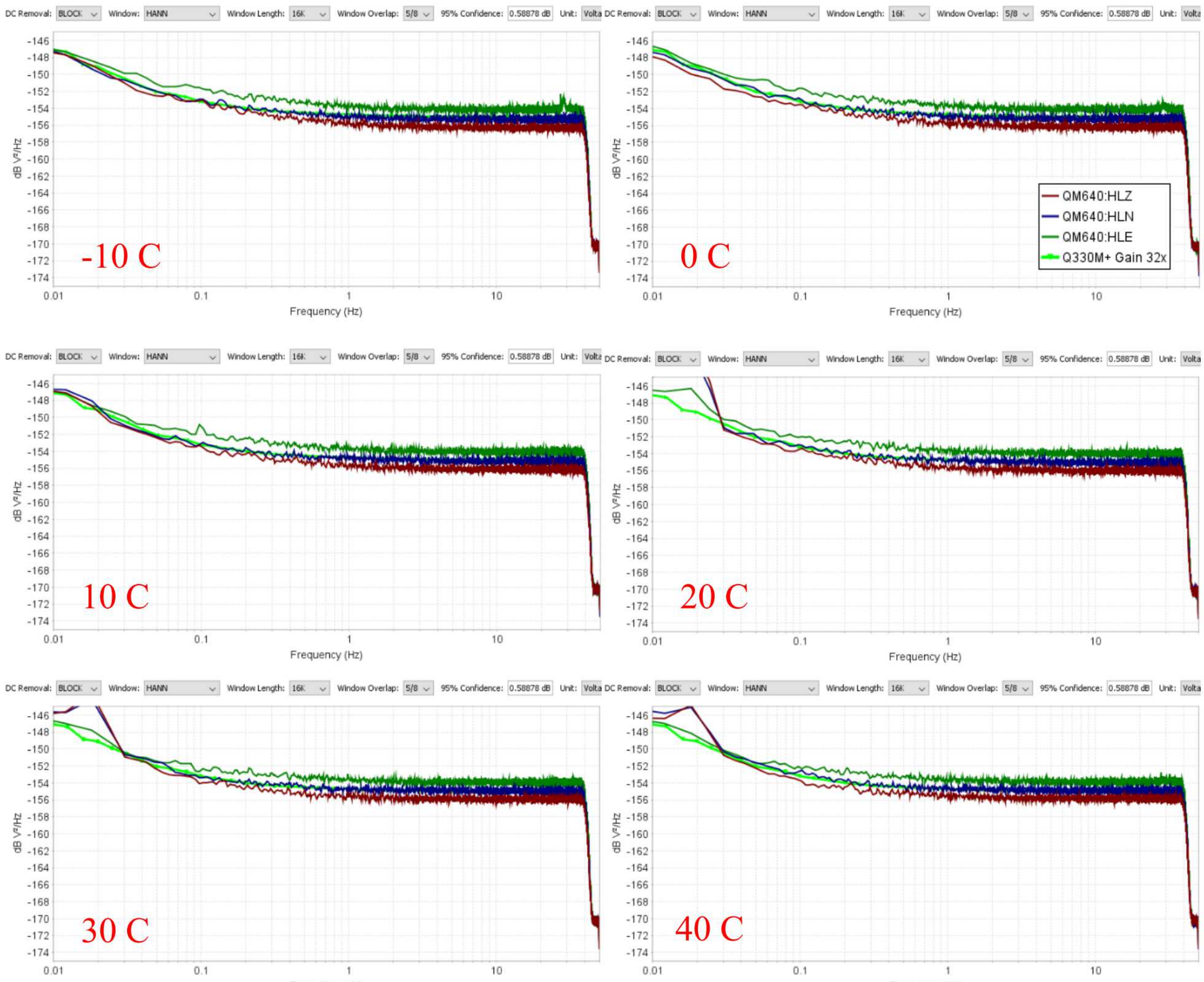


Figure 60 Temperature Self Noise Power Spectra, 6640, gain 32x at temperatures of -10 C, 0 C, 10 C, 20 C, 30 C, and 40 C

The self-noise across a range of temperatures at a gain of 32x was consistent with the prior measurements of self-noise in section 3.8 Self-Noise, with the exception some slight increases in noise at low frequencies, below 0.03 Hz, presumably associated with the ongoing variations in temperature.

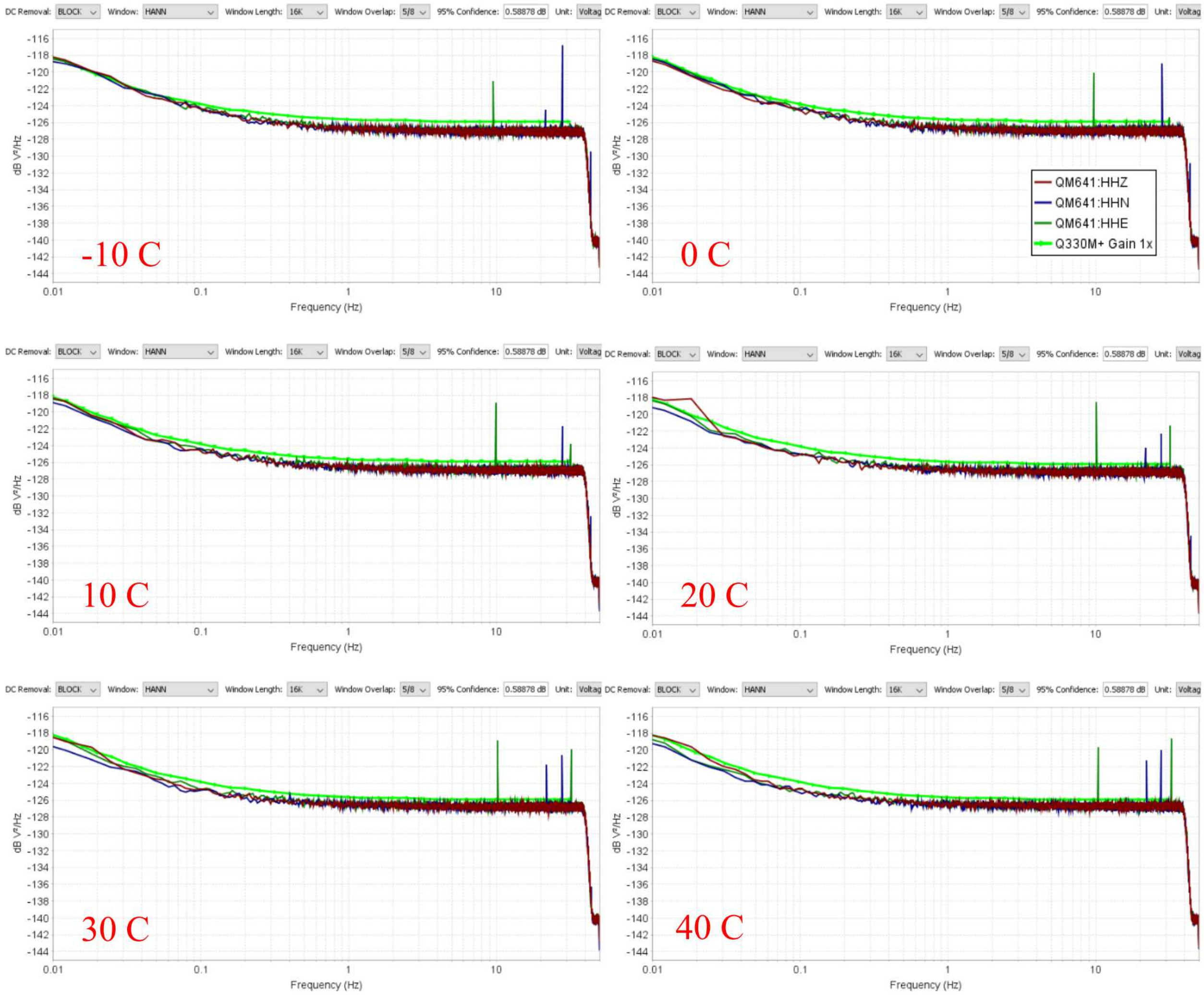


Figure 61 Temperature Self Noise Power Spectra, 6641, Port A, gain 1x at temperatures of -10 C, 0 C, 10 C, 20 C, 30 C, and 40 C

The self-noise across a range of temperatures at a gain of 1x was slightly lower than the prior measurements of self-noise in section 3.8 Self-Noise.

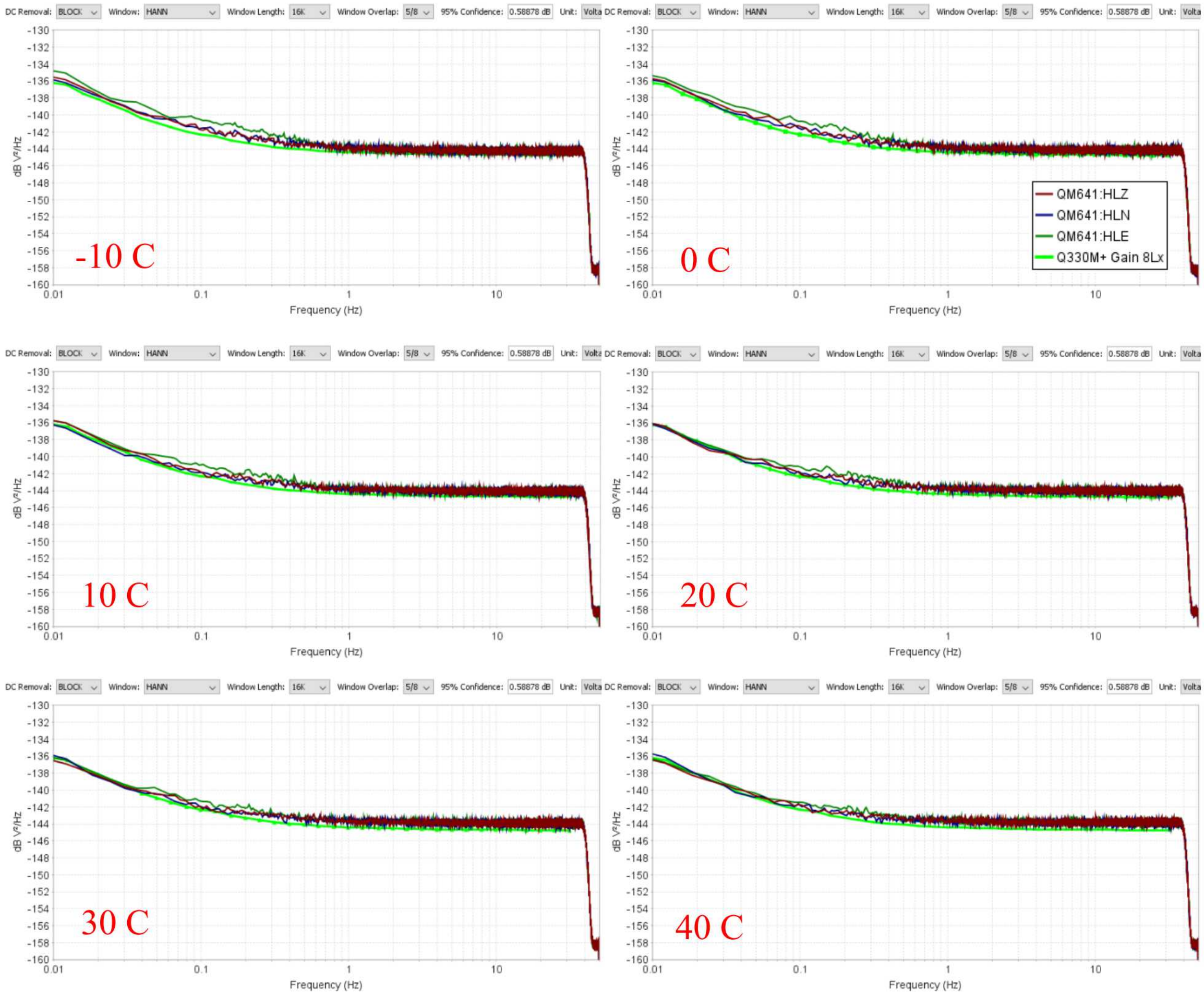


Figure 62 Temperature Self Noise Power Spectra, 6641, Port B, gain 8xL at temperatures of -10 C, 0 C, 10 C, 20 C, 30 C, and 40 C

The self-noise across a range of temperatures at a gain of 8xL was slightly higher than the prior measurements of self-noise in section 3.8 Self-Noise.

Overall, the self-noise power spectral density levels did not appear to change significantly as the temperature was varied. The only variation observed was a change in the DC offset related to temperature, shown in the tables below:

Table 57 Temperature Self Noise DC Offset, Q330M+ 6640, gain 32x

	-10 °C	0 °C	10 °C	20 °C	30 °C	40 C
Channel 1	-34.06 uV	-21.62 uV	-10.16 uV	2.031 uV	13.77 uV	25.35 uV
	Change:	1.24 uV/°C	1.15 uV/°C	1.22 uV/°C	1.17 uV/°C	1.16 uV/°C
Channel 2	-34.97 uV	-22.73 uV	-11.40 uV	0.6429 uV	12.25 uV	23.66 uV
	Change:	1.22 uV/°C	1.13 uV/°C	1.20 uV/°C	1.16 uV/°C	1.14 uV/°C
Channel 3	-34.41 uV	-22.15 uV	-10.81 uV	1.209 uV	12.73 uV	24.05 uV
	Change:	1.23 uV/°C	1.13 uV/°C	1.20 uV/°C	1.15 uV/°C	1.13 uV/°C

Table 58 Temperature Self Noise D°C Offset, Q330M+ 6641, Port A, gain 1x

	-10 °C	0 °C	10 °C	20 °C	30 °C	40 °C
Channel 1	-1105 uV	-718.3 uV	-343.2 uV	47.77 uV	435.0 uV	823.8 uV
	Change:	38.64 uV/°C	37.51 uV/°C	39.09 uV/°C	38.73 uV/°C	38.88 uV/°C
Channel 2	-1108 uV	-723.5 uV	-349.5 uV	40.65 uV	426.3 uV	815.8 uV
	Change:	38.44 uV/°C	37.40 uV/°C	39.02 uV/°C	38.56 uV/°C	38.95 uV/°C
Channel 3	-1113 uV	-724.4 uV	-347.3 uV	45.79 uV	435.2 uV	826.6 uV
	Change:	38.89 uV/°C	37.71 uV/°C	39.30 uV/°C	38.94 uV/°C	39.14 uV/°C

Table 59 Temperature Self Noise D°C Offset, Q330M+ 6641, Port B, gain 8xL

	-10 °C	0 °C	10 °C	20 °C	30 °C	40 °C
Channel 1	-142.7 uV	-92.32 uV	-43.46 uV	7.529 uV	58.07 uV	108.9 uV
	Change:	5.04 uV/°C	4.89 uV/°C	5.10 uV/°C	5.05 uV/°C	5.09 uV/°C
Channel 2	-146.0 uV	-94.46 uV	-44.45 uV	7.887 uV	59.78 uV	112.1 uV
	Change:	5.16 uV/°C	5.00 uV/°C	5.23 uV/°C	5.19 uV/°C	5.23 uV/°C
Channel 3	-143.4 uV	-92.72 uV	-43.62 uV	7.836 uV	58.69 uV	109.7 uV
	Change:	5.07 uV/°C	4.91 uV/°C	5.15 uV/°C	5.09 uV/°C	5.11 uV/°C

There appears to be a consistent rate of change in the DC offset with respect to temperature of approximately 39 uV/°C at a gain of 1x, 5.1 uV/°C at a gain of 8xL, and 1.2 uV/°C at a gain of 32x.

These rate of change values scale linearly with the gain level, suggesting that the change in DC offset is a function of counts per °C. By scaling the offset rate of change by the bit weight at each gain level, it appears that there is an offset change of between 16 and 17 counts per °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 relative amplitude and relative phase in degrees versus frequency for each digitizer channel relative to the first channel.

3.12.2 Configuration

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

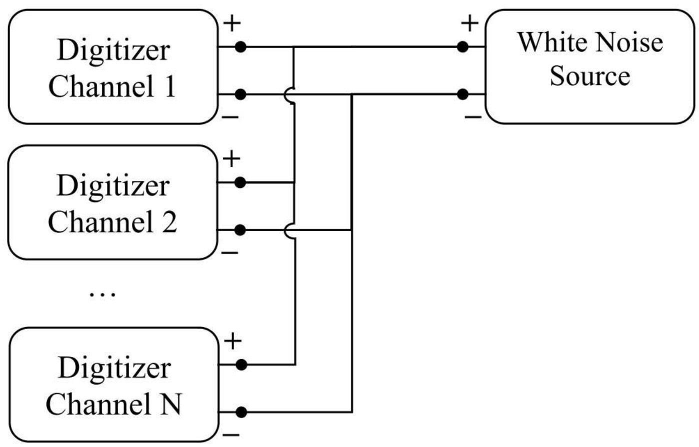


Figure 63 Response Verification Configuration Diagram

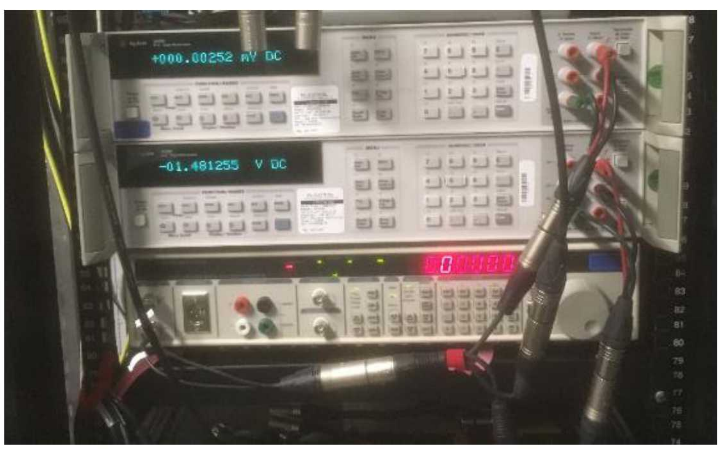


Figure 64 Response Verification Configuration Picture

Table 60 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. Thirty minutes of data is recorded.

3.12.3 Analysis

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

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

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

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

3.12.4 Result

The coherence and relative amplitude and phase response were computed between channel 1 and the remaining channels for all the evaluated sample rate and gain configurations. In all cases, the coherence was identically 1.0 across the entire pass-band. The coherence, relative amplitude, and relative phase are shown in the plots below. The results were consistent for all of the sample rates, so only the 100 Hz sample rate results are shown.

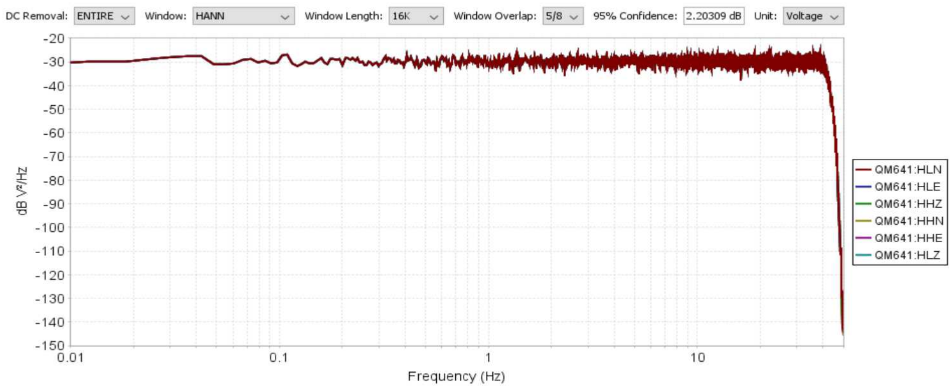


Figure 65 White Noise Power Spectra, Q330M+ 6641, gain 1x, 100 Hz

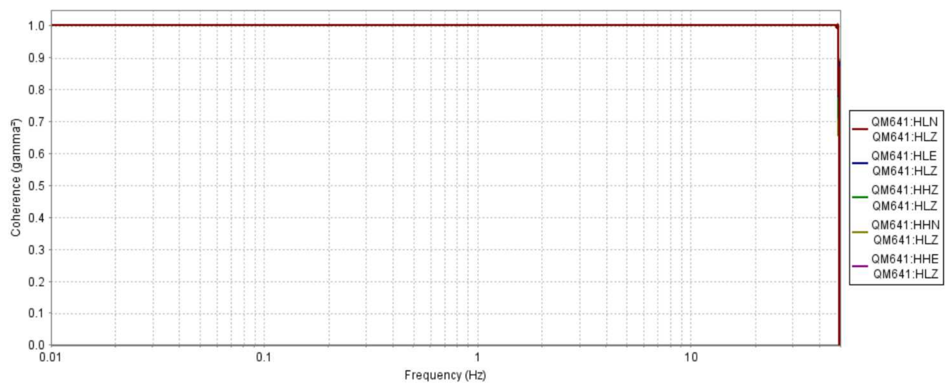


Figure 66 White Noise Coherence, Q330M+ 6641, gain 1x, 100 Hz

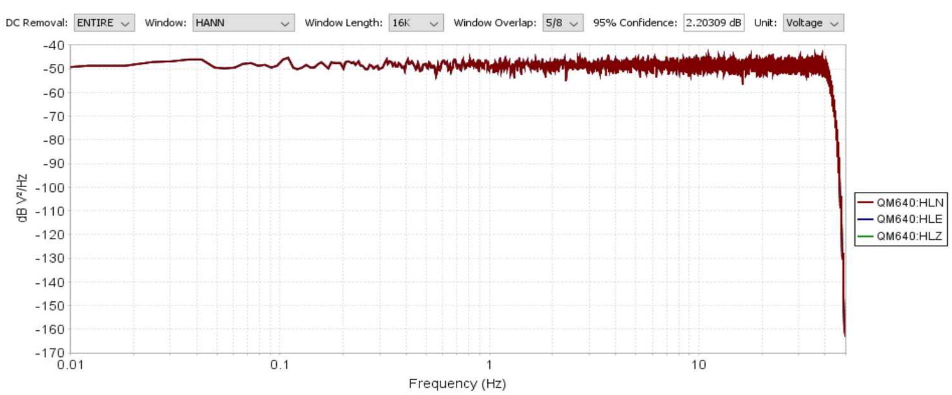


Figure 67 White Noise Power Spectra, Q330M+ 6640, gain 8x, 100 Hz

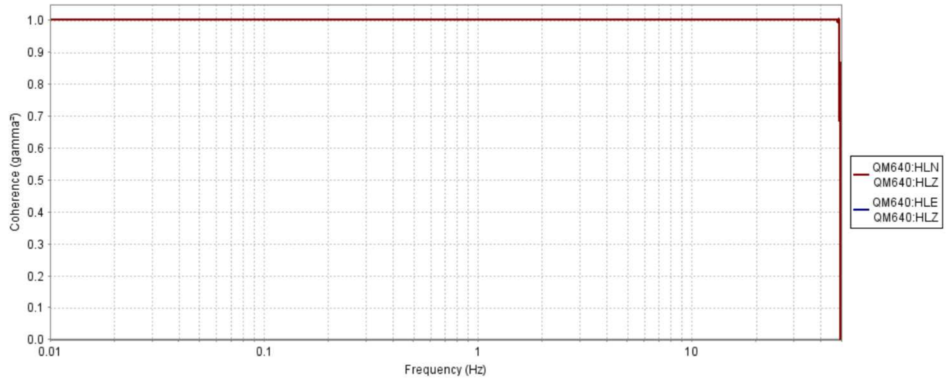


Figure 68 White Noise Coherence, Q330M+ 6640, gain 8x, 100 Hz

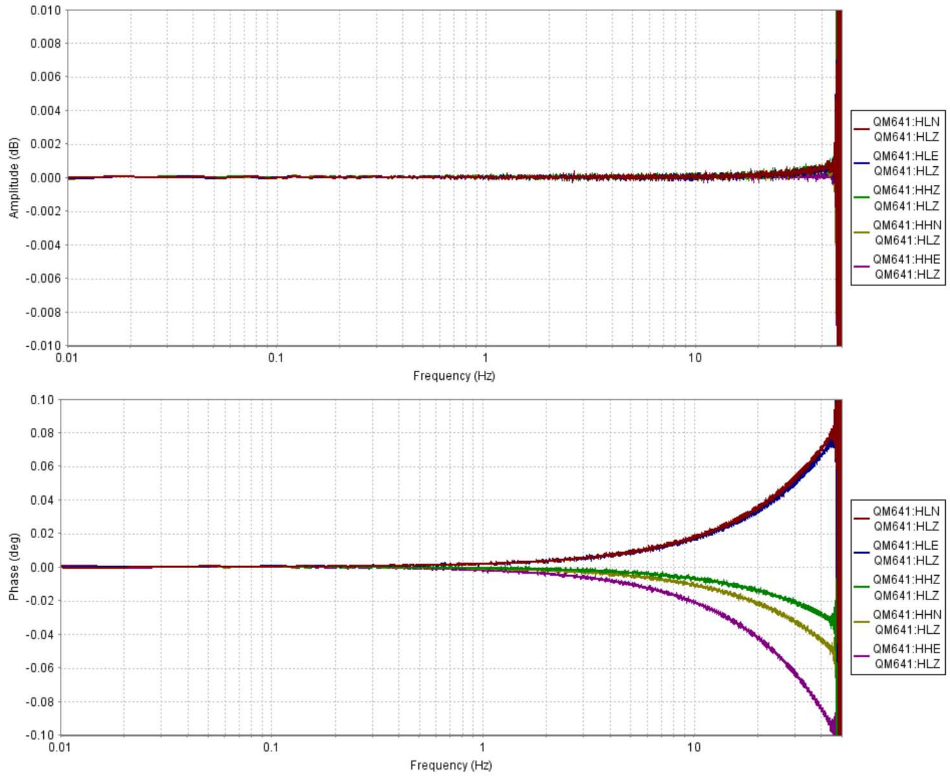


Figure 69 Relative Amplitude and Phase, Q330M+ 6641, gain 1x, 100 Hz

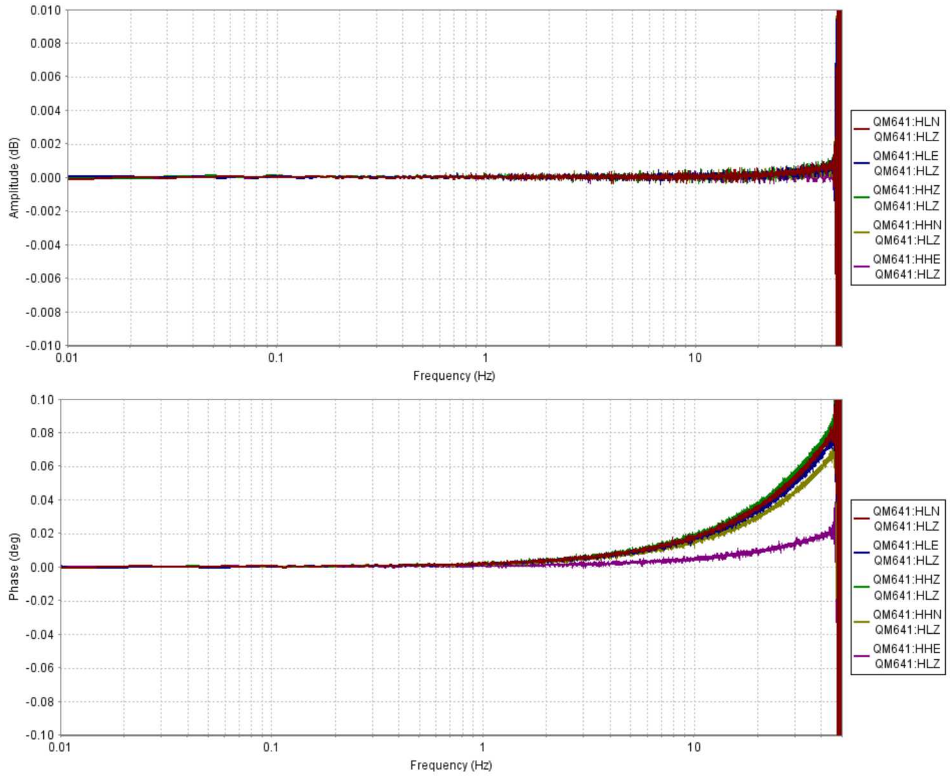


Figure 70 Relative Amplitude and Phase, Q330M+ 6641, gain 2x, 100 Hz

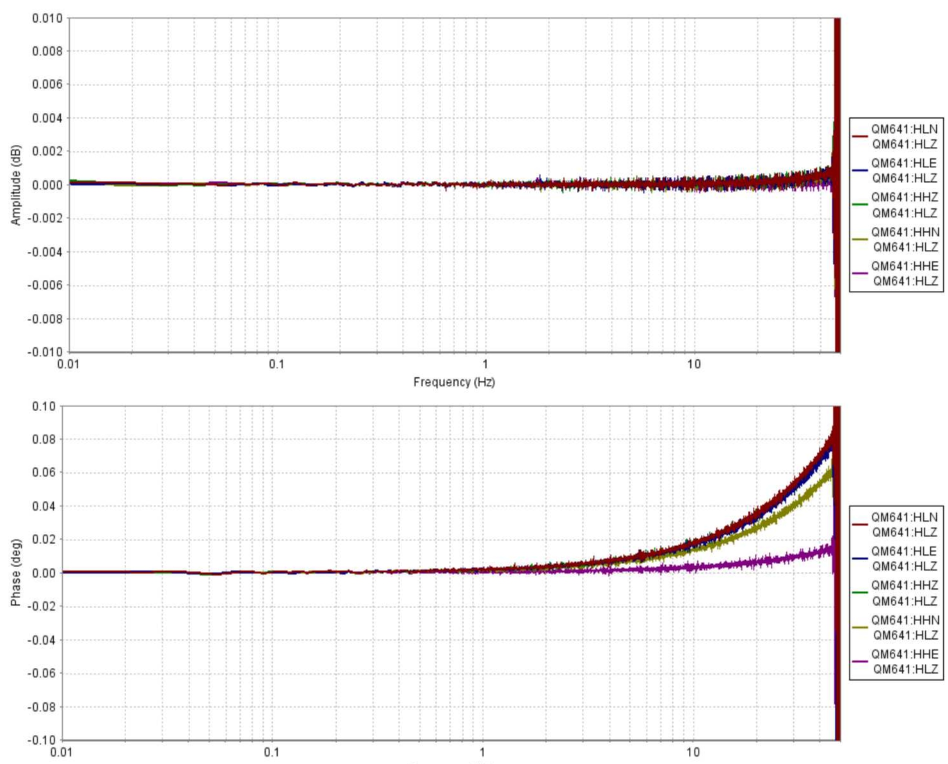


Figure 71 Relative Amplitude and Phase, Q330M+ 6641, gain 4x, 100 Hz

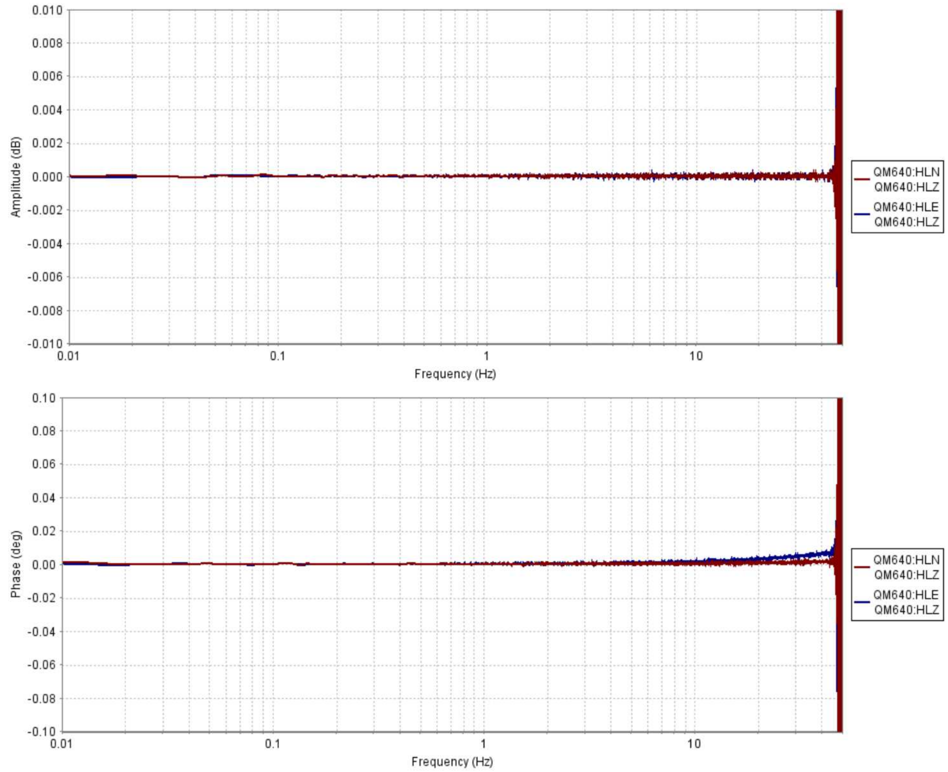


Figure 72 Relative Amplitude and Phase, Q330M+ 6640, gain 8xL, 100 Hz

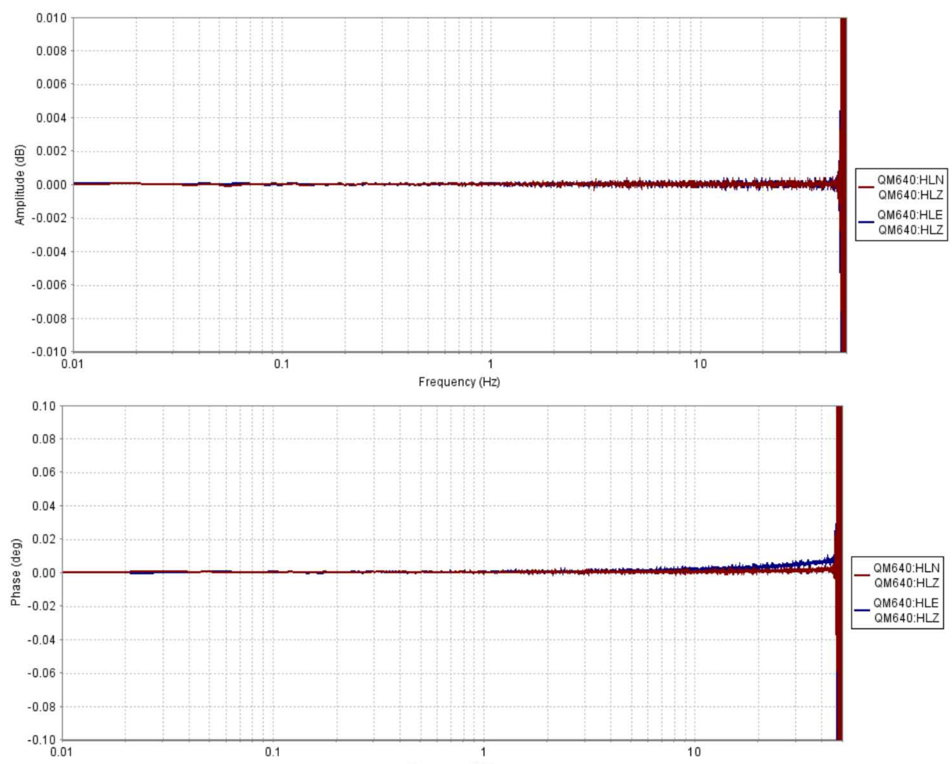


Figure 73 Relative Amplitude and Phase, Q330M+ 6640, gain 16x, 100 Hz

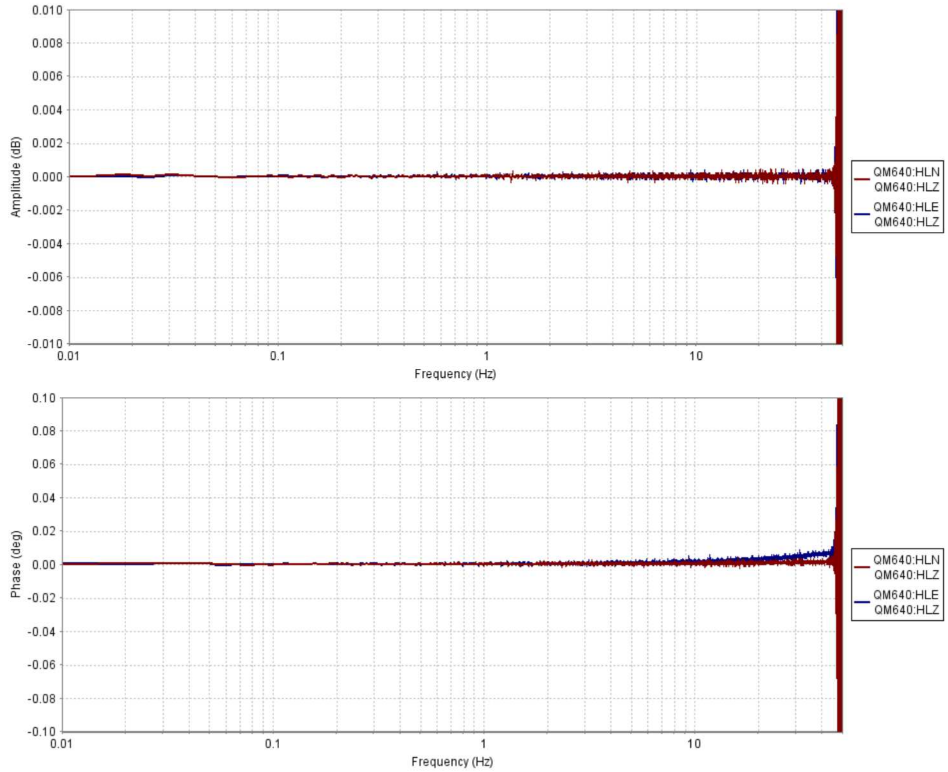


Figure 74 Relative Amplitude and Phase, Q330M+ 6640, gain 32x, 100 Hz

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

3.13 Relative Transfer Function

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

3.13.1 Measurand

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

3.13.2 Configuration

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

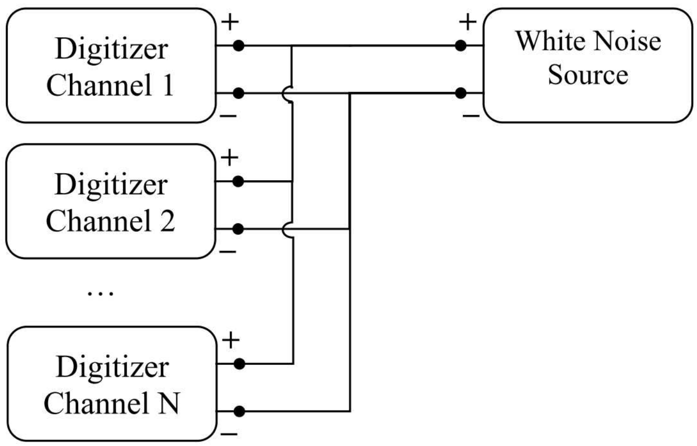


Figure 75 Relative Transfer Function Configuration Diagram

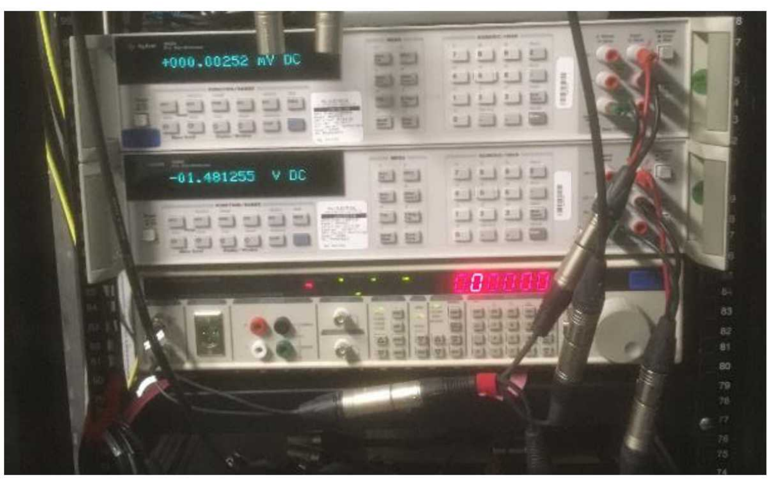


Figure 76 Relative Transfer Function Configuration Picture

Table 61 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. Thirty minutes of data is recorded.

3.13.3 Analysis

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

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

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

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

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

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

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

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

3.13.4 Result

The phase delay versus frequency is shown for gains 1x and 8xL at 100 Hz in the plots below. To the extent that the delay is a constant time offset, the phase delay is observed to be linear with respect to frequency.

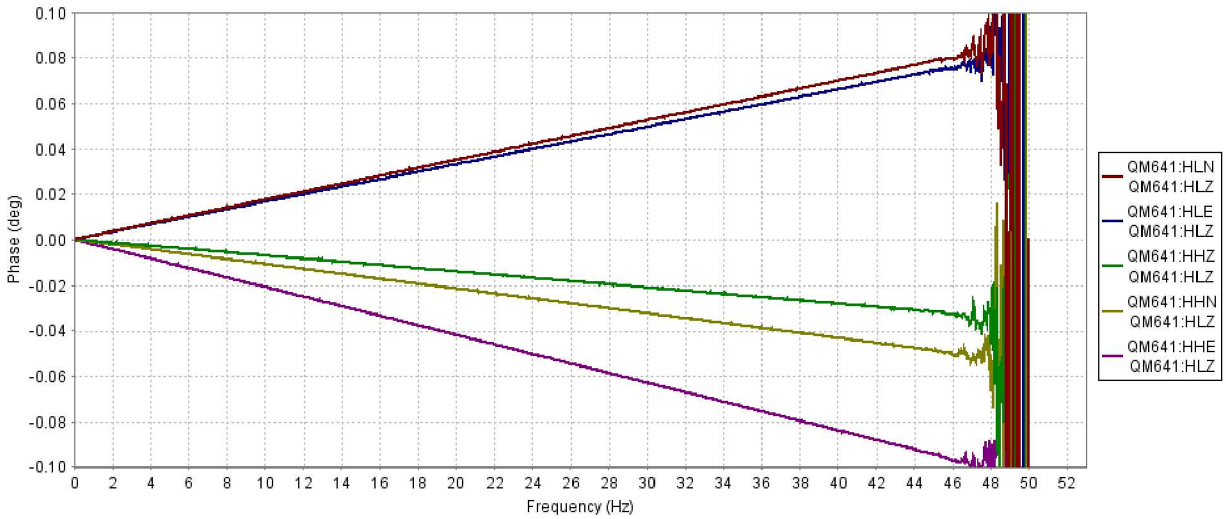


Figure 77 Relative Transfer Function Relative Phase, Q330M+ 6641, gain 1x, 100 Hz

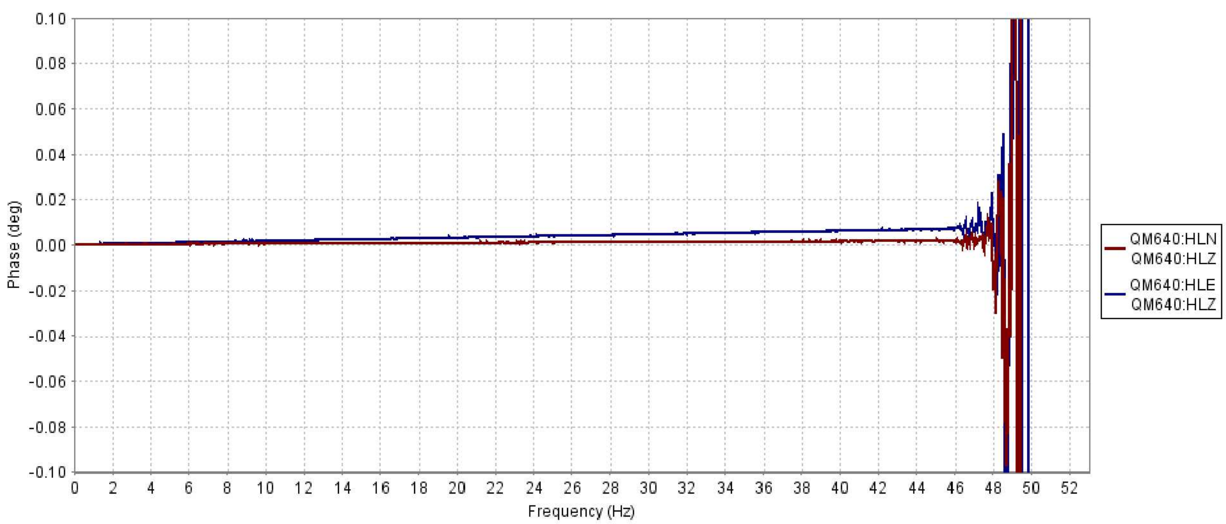


Figure 78 Relative Transfer Function Relative Phase, Q330M+ 6640, gain 8xL, 100 Hz

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

Table 62 Relative Transfer Function Timing Skew relative to Channel 1, Q330M+ 6640

Channel	Sample Rate	Gain 8L	Gain 16	Gain 32
Channel 2 (N)	20 Hz	0.0961 us	0.0979 us	0.106 us
	40 Hz	0.100 us	0.0975 us	0.104 us
	100 Hz	0.0978 us	0.0972 us	0.0991 us
Channel 3 (E)	20 Hz	0.429 us	0.426 us	0.442 us
	40 Hz	0.430 us	0.430 us	0.431 us
	100 Hz	0.425 us	0.425 us	0.426 us

Table 63 Relative Transfer Function Timing Skew relative to Channel 1 on Port A, Q330M+ 6641 Port A

Channel	Sample Rate	Gain 1	Gain 2	Gain 4
Channel 2 (N)	20 Hz	4.84 us	4.86 us	4.85 us
	40 Hz	4.85 us	4.85 us	4.85 us
	100 Hz	4.84 us	4.85 us	4.84 us
Channel 3 (E)	20 Hz	4.57 us	4.61 us	4.59 us
	40 Hz	4.58 us	4.59 us	4.59 us
	100 Hz	4.58 us	4.58 us	4.58 us

Table 64 Relative Transfer Function Timing Skew relative to Channel 1 on Port A, Q330M+ 6641 Port B

Channel	Sample Rate	Gain 8L	Gain 16	Gain 32
Channel 1 (Z)	20 Hz	-1.97 us	5.12 us	4.71 us
	40 Hz	-1.96 us	5.13 us	4.72 us
	100 Hz	-1.96 us	5.13 us	4.72 us
Channel 2 (N)	20 Hz	-3.00 us	4.09 us	3.67 us
	40 Hz	-3.00 us	4.09 us	3.67 us
	100 Hz	-3.00 us	4.08 us	3.67 us
Channel 3 (E)	20 Hz	-5.83 us	1.26 us	0.841 us
	40 Hz	-5.82 us	1.26 us	0.842 us
	100 Hz	-5.83 us	1.25 us	0.844 us

All the channels were observed to have a timing skew that was within 5 microseconds 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.

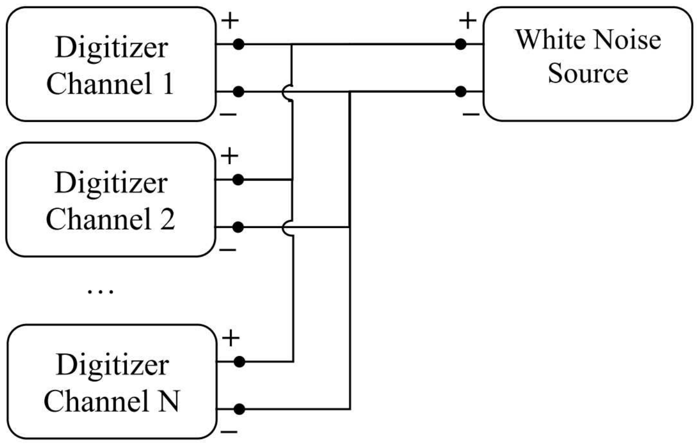


Figure 79 Analog Bandwidth Configuration Diagram

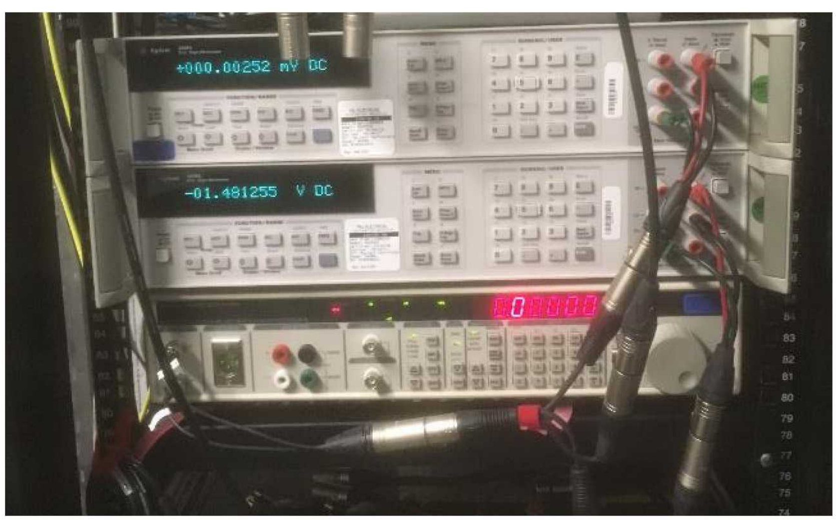


Figure 80 Analog Bandwidth Configuration Picture

Table 65 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. Thirty minutes of data is recorded

3.14.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series 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.

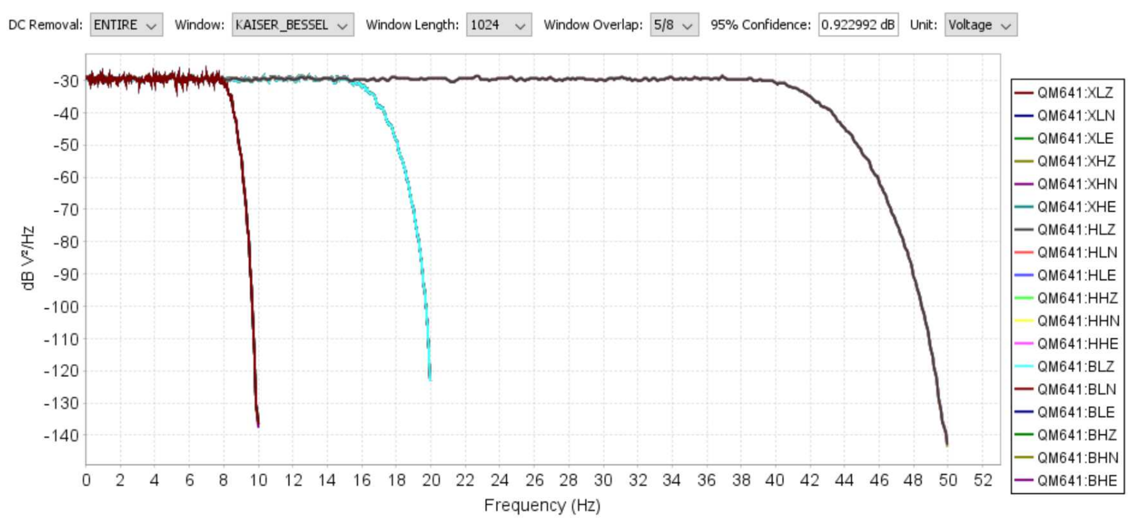


Figure 81 Analog Bandwidth Gain 1: Q330M+ 6641

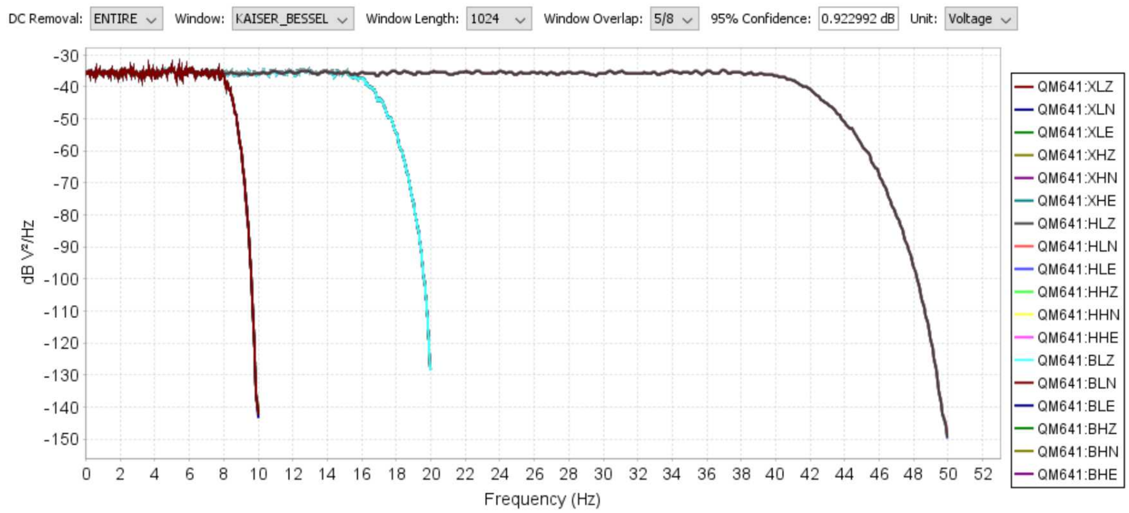


Figure 82 Analog Bandwidth Gain 2: Q330M+ 6641

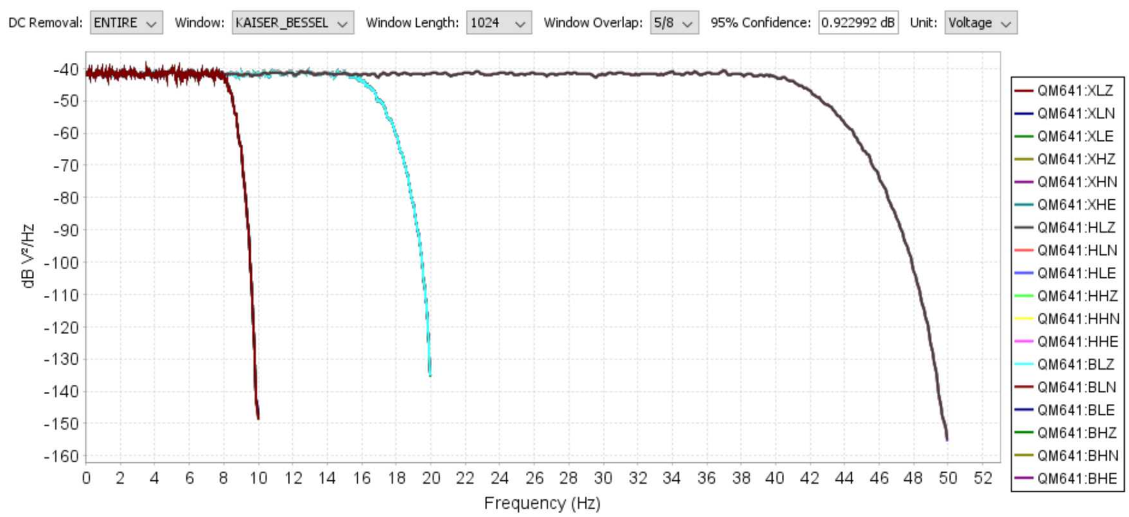


Figure 83 Analog Bandwidth Gain 4: Q330M+ 6641

Figure 84 Analog Bandwidth Gain 8L: Q330M+ 6640

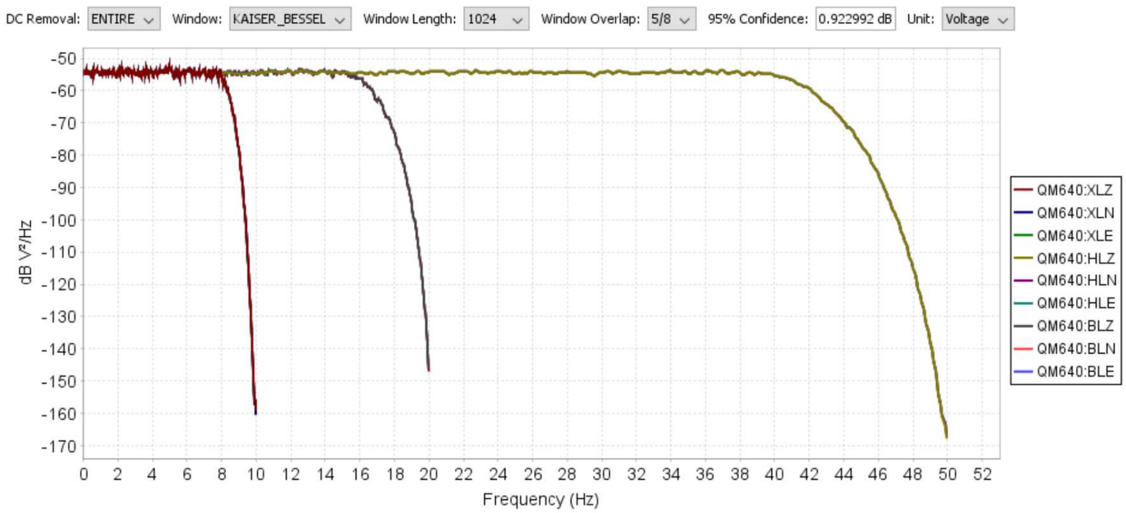


Figure 85 Analog Bandwidth Gain 16: Q330M+ 6640

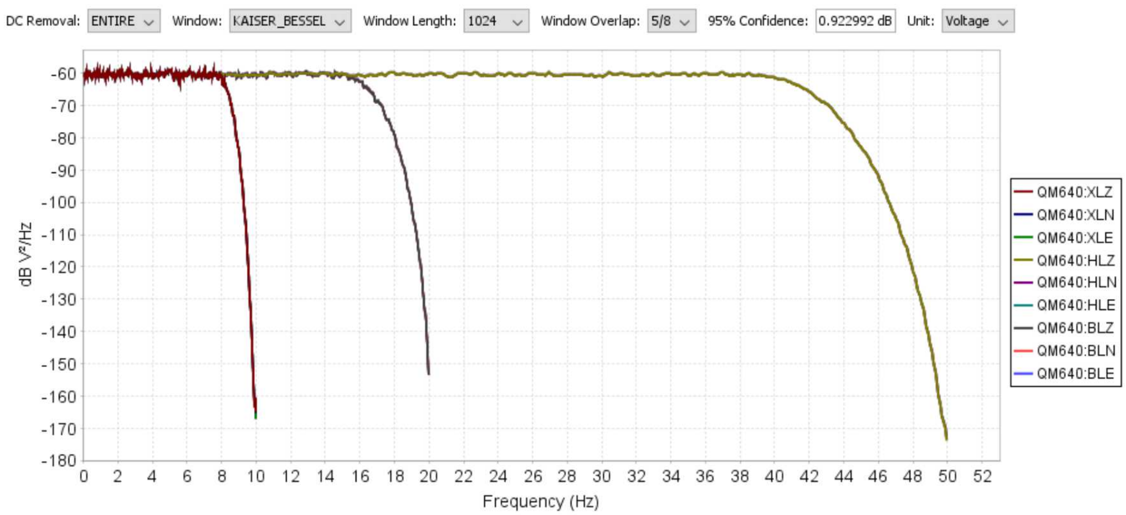


Figure 86 Analog Bandwidth Gain 32: Q330M+ 6640

Table 66 Analog Bandwidth: Q330M+ 6640

Sample Rate	Channel	Gain 8xL		Gain 16x		Gain 32x	
		3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist
20 Hz	Channel 1 (Z)	8.09 Hz	80.90%	8.07 Hz	80.70%	8.07 Hz	80.70%
	Channel 2 (N)	8.09 Hz	80.90%	8.07 Hz	80.70%	8.07 Hz	80.70%
	Channel 3 (E)	8.09 Hz	80.90%	8.07 Hz	80.70%	8.07 Hz	80.70%
40 Hz	Channel 1 (Z)	16.10 Hz	80.50%	16.30 Hz	81.50%	16.10 Hz	80.50%
	Channel 2 (N)	16.10 Hz	80.50%	16.30 Hz	81.50%	16.10 Hz	80.50%
	Channel 3 (E)	16.10 Hz	80.50%	16.30 Hz	81.50%	16.10 Hz	80.50%
100 Hz	Channel 1 (Z)	41.30 Hz	82.60%	41.30 Hz	82.60%	41.30 Hz	82.60%
	Channel 2 (N)	41.30 Hz	82.60%	41.30 Hz	82.60%	41.30 Hz	82.60%

	Channel 3 (E)	41.30 Hz	82.60%	41.30 Hz	82.60%	41.30 Hz	82.60%

Table 67 Analog Bandwidth: Q330M+ 6641, Port A

Sample Rate	Channel	Gain 1x		Gain 2x		Gain 4x	
		3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist
20 Hz	Channel 1 (Z)	8.16 Hz	81.60%	8.07 Hz	80.70%	8.09 Hz	80.90%
	Channel 2 (N)	8.16 Hz	81.60%	8.07 Hz	80.70%	8.09 Hz	80.90%
	Channel 3 (E)	8.16 Hz	81.60%	8.07 Hz	80.70%	8.09 Hz	80.90%
40 Hz	Channel 1 (Z)	16.20 Hz	81.00%	16.30 Hz	81.50%	16.20 Hz	81.00%
	Channel 2 (N)	16.20 Hz	81.00%	16.30 Hz	81.50%	16.20 Hz	81.00%
	Channel 3 (E)	16.20 Hz	81.00%	16.30 Hz	81.50%	16.20 Hz	81.00%
100 Hz	Channel 1 (Z)	41.40 Hz	82.80%	41.30 Hz	82.60%	41.30 Hz	82.60%
	Channel 2 (N)	41.40 Hz	82.80%	41.30 Hz	82.60%	41.30 Hz	82.60%
	Channel 3 (E)	41.40 Hz	82.80%	41.30 Hz	82.60%	41.30 Hz	82.60%

Table 68 Analog Bandwidth: Q330M+ 6641, Port B

Sample Rate	Channel	Gain 1x		Gain 2x		Gain 4x	
		3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist	3dB Frequency	% of Nyquist
20 Hz	Channel 1 (Z)	8.16 Hz	81.60%	8.07 Hz	80.70%	8.09 Hz	80.90%
	Channel 2 (N)	8.16 Hz	81.60%	8.07 Hz	80.70%	8.09 Hz	80.90%
	Channel 3 (E)	8.16 Hz	81.60%	8.07 Hz	80.70%	8.09 Hz	80.90%
40 Hz	Channel 1 (Z)	16.20 Hz	81.00%	16.30 Hz	81.50%	16.20 Hz	81.00%
	Channel 2 (N)	16.20 Hz	81.00%	16.30 Hz	81.50%	16.20 Hz	81.00%
	Channel 3 (E)	16.20 Hz	81.00%	16.30 Hz	81.50%	16.20 Hz	81.00%
100 Hz	Channel 1 (Z)	41.40 Hz	82.80%	41.30 Hz	82.60%	41.30 Hz	82.60%
	Channel 2 (N)	41.40 Hz	82.80%	41.30 Hz	82.60%	41.30 Hz	82.60%
	Channel 3 (E)	41.40 Hz	82.80%	41.30 Hz	82.60%	41.30 Hz	82.60%

All of the channels were observed to have similar high frequency passband limits for a common sample rate and gain setting to within 0.5% of the Nyquist rate. The passband limits were consistently between 80.5% and 82.8% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, and 100 Hz. There was no significant difference in passband across the gain levels.

3.15 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.

3.15.1 Measurand

The quantity being measured is the digitizer input channels linearity expressed in decibels.

3.15.2 Configuration

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

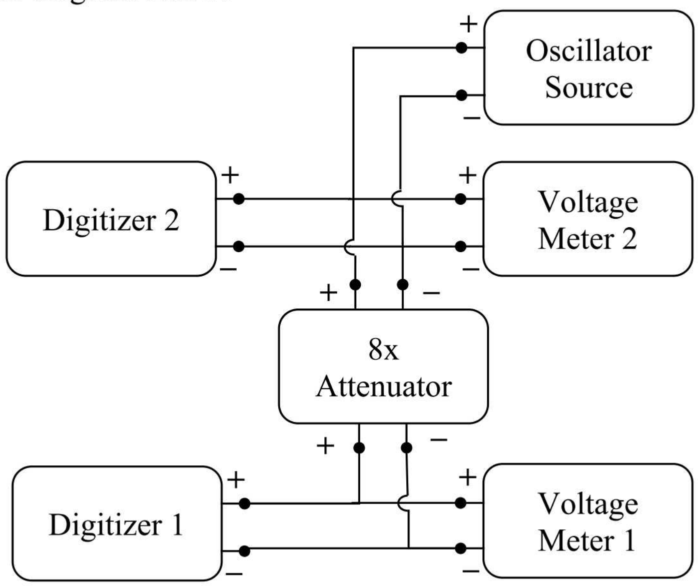


Figure 87 Total Harmonic Distortion Configuration Diagram

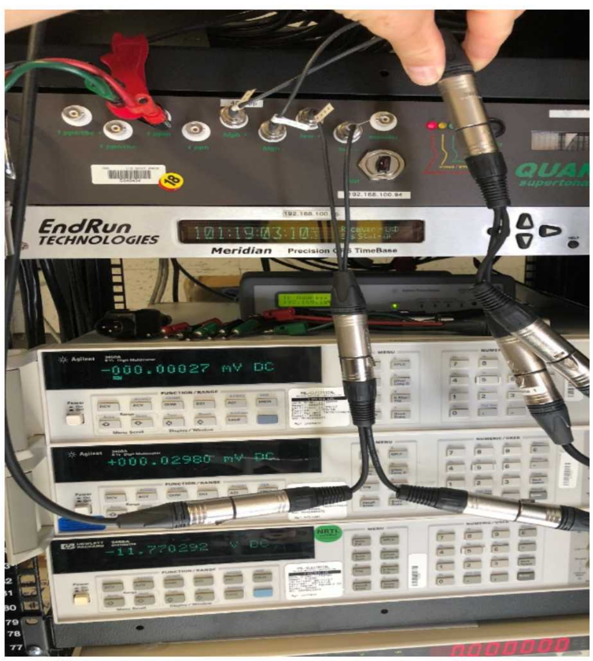


Figure 88 Total Harmonic Distortion Configuration

Table 69 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 corrupted with noise from electronics that refresh at a 1 Hz multiple.

The Quanterra supertonal has both a high and low output with the low output providing a signal that 8x less than the high output. 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 6640 at gains of 8xL, 16x, and 32x and on 6641 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.

3.15.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 16k-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 power in the harmonics to the power in the fundamental:

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

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

3.15.4 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.

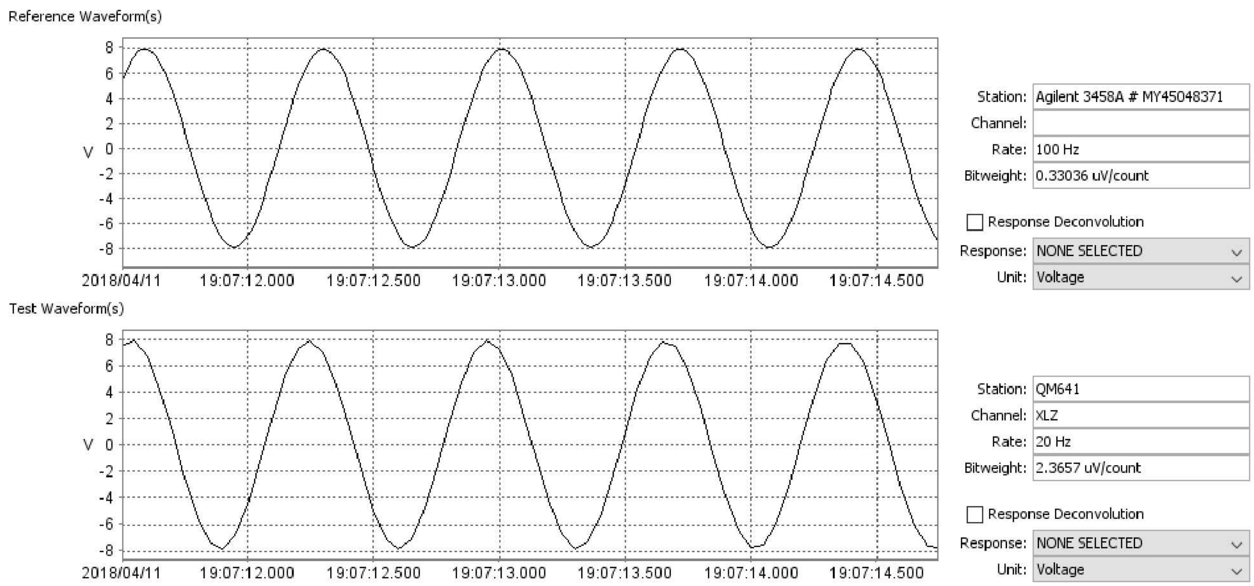


Figure 89 THD Waveform Time Series

The figures below show the THD for the channels evaluated. The three sample rates, 20 Hz, 40 Hz, and 100 Hz, are shown together within each of the plots.

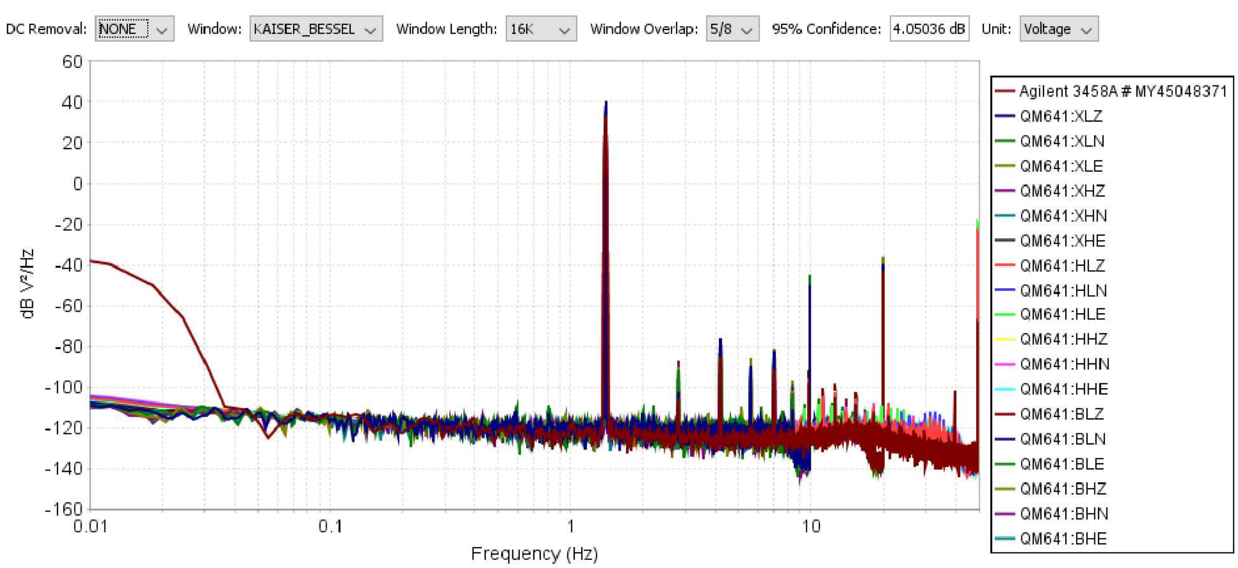


Figure 90 Analog Bandwidth Gain 1: Q330M+ 6641

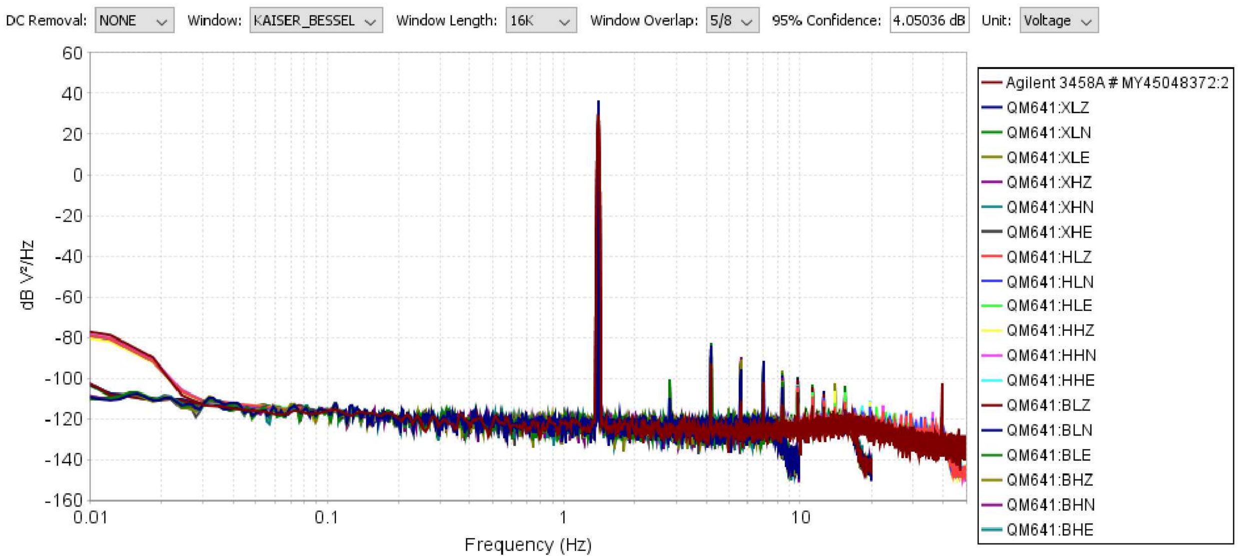


Figure 91 Analog Bandwidth Gain 2: Q330M+ 6641

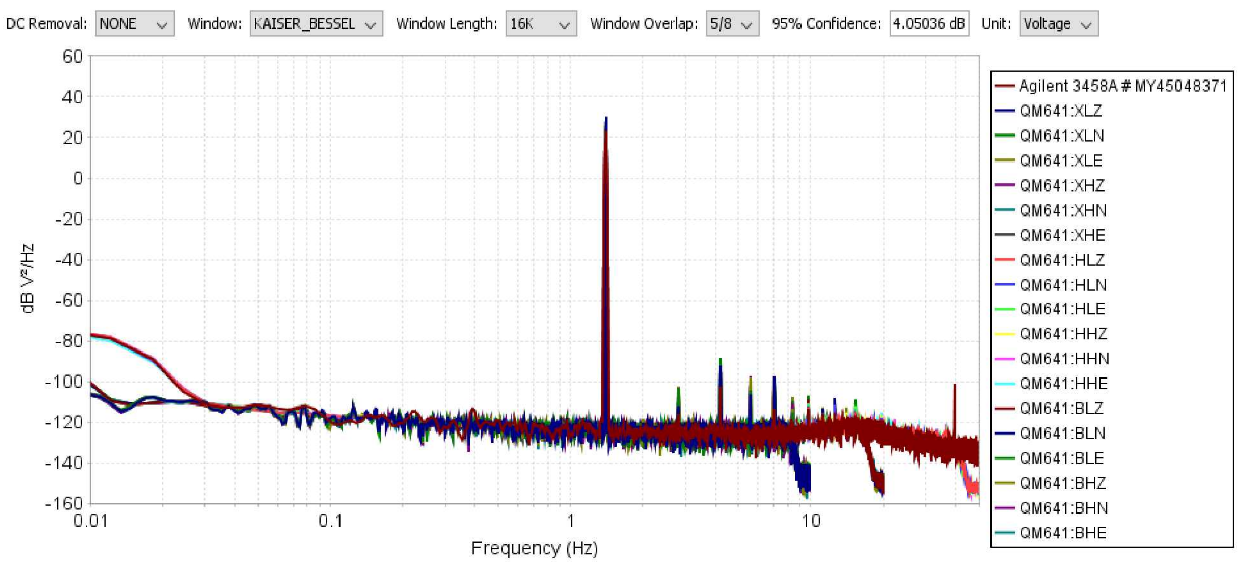


Figure 92 Analog Bandwidth Gain 4: Q330M+ 6641

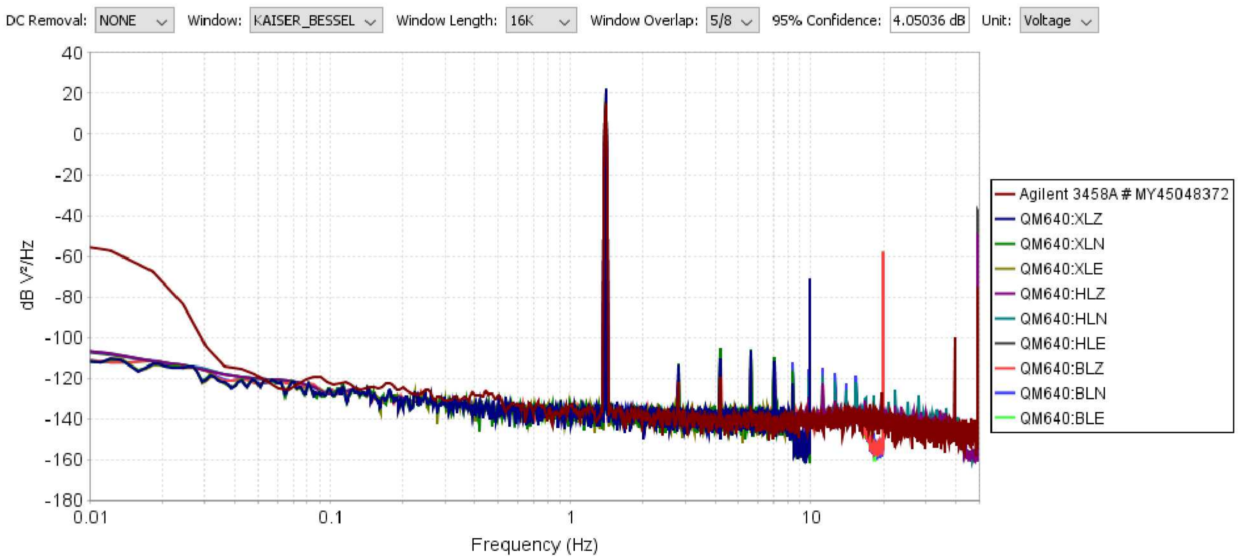


Figure 93 Analog Bandwidth Gain 8L: Q330M+ 6640

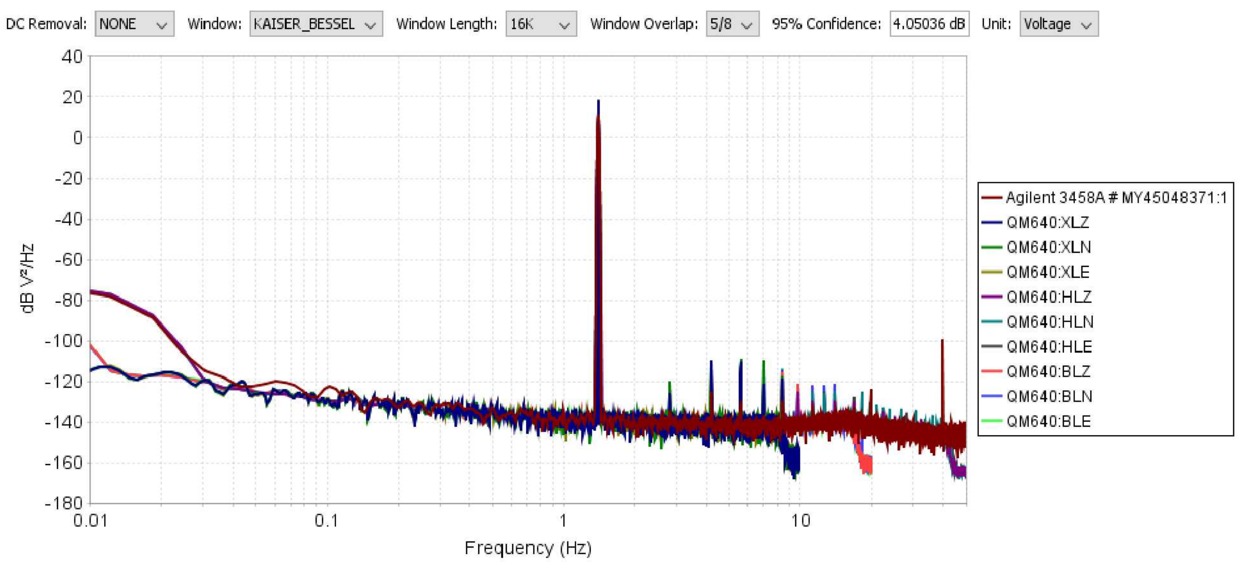


Figure 94 Analog Bandwidth Gain 16: Q330M+ 6640

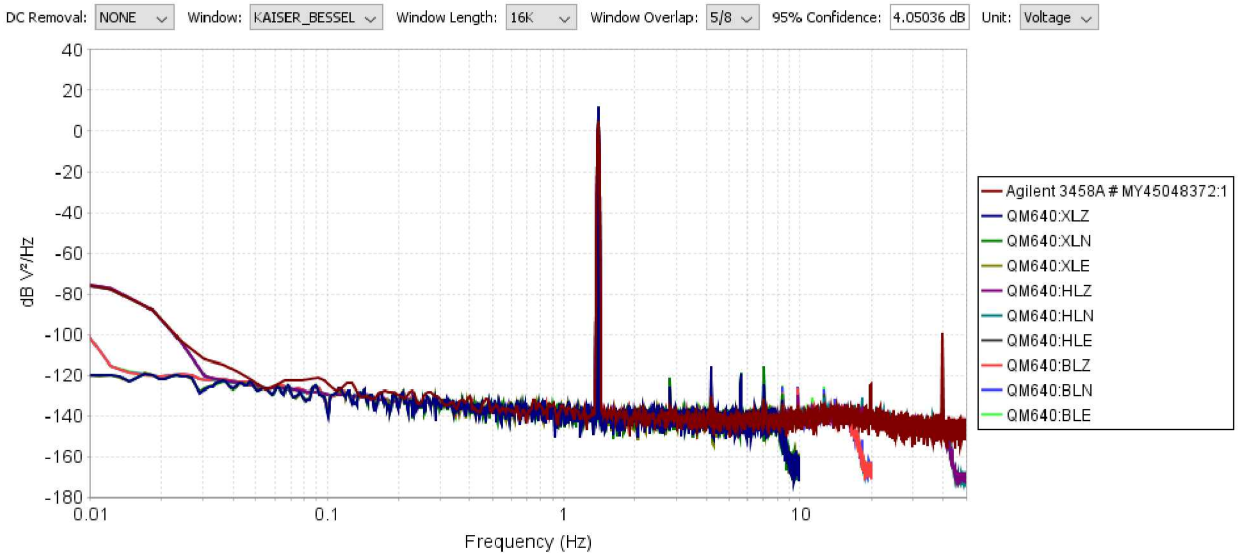


Figure 95 Analog Bandwidth Gain 32: Q330M+ 6640

Table 70 Total Harmonic Distortion, Q330M+ 6640

Channel	Sample Rate	Gain 8L	Gain 16	Gain 32
Reference	100 Hz	-132.53 dB	-132.52 dB	-130.65 dB
Channel 1 (Z)	20 Hz	-125.81 dB	-124.37 dB	-125.40 dB
	40 Hz	-125.19 dB	-123.19 dB	-124.25 dB
	100 Hz	-124.93 dB	-122.89 dB	-123.84 dB
Channel 2 (N)	20 Hz	-123.26 dB	-122.94 dB	-123.60 dB
	40 Hz	-121.83 dB	-121.55 dB	-122.47 dB
	100 Hz	-121.74 dB	-121.41 dB	-121.95 dB
Channel 3 (E)	20 Hz	-125.39 dB	-126.84 dB	-127.99 dB
	40 Hz	-124.68 dB	-124.52 dB	-125.60 dB
	100 Hz	-124.44 dB	-124.12 dB	-124.83 dB

Table 71 Total Harmonic Distortion, Q330M+ 6641, Port A

Channel	Sample Rate	Gain 1	Gain 2	Gain 4
Reference	100 Hz	-117.03 dB	-121.19 dB	-124.45 dB
Channel 1 (Z)	20 Hz	-115.21 dB	-119.14 dB	-120.90 dB
	40 Hz	-114.91 dB	-118.71 dB	-120.60 dB
	100 Hz	-114.84 dB	-118.62 dB	-120.23 dB
Channel 2 (N)	20 Hz	-115.19 dB	-118.15 dB	-118.29 dB
	40 Hz	-114.89 dB	-117.77 dB	-118.03 dB
	100 Hz	-114.81 dB	-117.68 dB	-117.83 dB
Channel 3 (E)	20 Hz	-114.88 dB	-118.52 dB	-119.92 dB
	40 Hz	-114.62 dB	-117.92 dB	-119.51 dB
	100 Hz	-114.55 dB	-117.82 dB	-119.19 dB

Table 72 Total Harmonic Distortion, Q330M+ 6641, Port B

Channel	Sample Rate	Gain 1	Gain 2	Gain 4
Reference	100 Hz	-117.03 dB	-121.19 dB	-124.45 dB
Channel 1 (Z)	20 Hz	-114.78 dB	-117.84 dB	-119.45 dB
	40 Hz	-114.47 dB	-117.36 dB	-119.00 dB
	100 Hz	-114.40 dB	-117.28 dB	-118.78 dB
Channel 2 (N)	20 Hz	-115.05 dB	-118.46 dB	-120.11 dB
	40 Hz	-114.75 dB	-117.92 dB	-119.69 dB
	100 Hz	-114.68 dB	-117.82 dB	-119.42 dB
Channel 3 (E)	20 Hz	-115.37 dB	-118.79 dB	-121.53 dB
	40 Hz	-115.04 dB	-118.36 dB	-121.00 dB
	100 Hz	-114.96 dB	-118.24 dB	-120.59 dB

At gain levels of 1x and 2x, the reference signal has distortion that is only a few decibels less than what was measured in the digitizer channels, making it difficult to distinguish between the source of the distortion.

At the higher gain levels, 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 a high level of -114.5 dB to -118.8 dB at gains of 1x and 2x to as low as -118 to -128 dB at higher gain levels.

3.16 Modified Noise Power Ratio

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

3.16.1 Measurand

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

3.16.2 Configuration

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

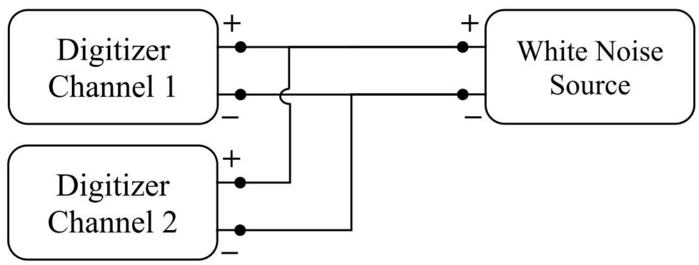


Figure 96 Modified Noise Power Ratio Configuration Diagram

Table 73 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. Twenty minutes of data is recorded at each amplitude level.

The Modified Noise Power Ratio test was performed on Q330M+ #6641 at a gain of 1x and on #6640 at a gain of 8xL.

3.16.3 Analysis

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

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

The 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).

3.16.4 Result

A representative waveform time series plot is shown below for Q330M+ 6641 channels Z and N sampled at 100 Hz.

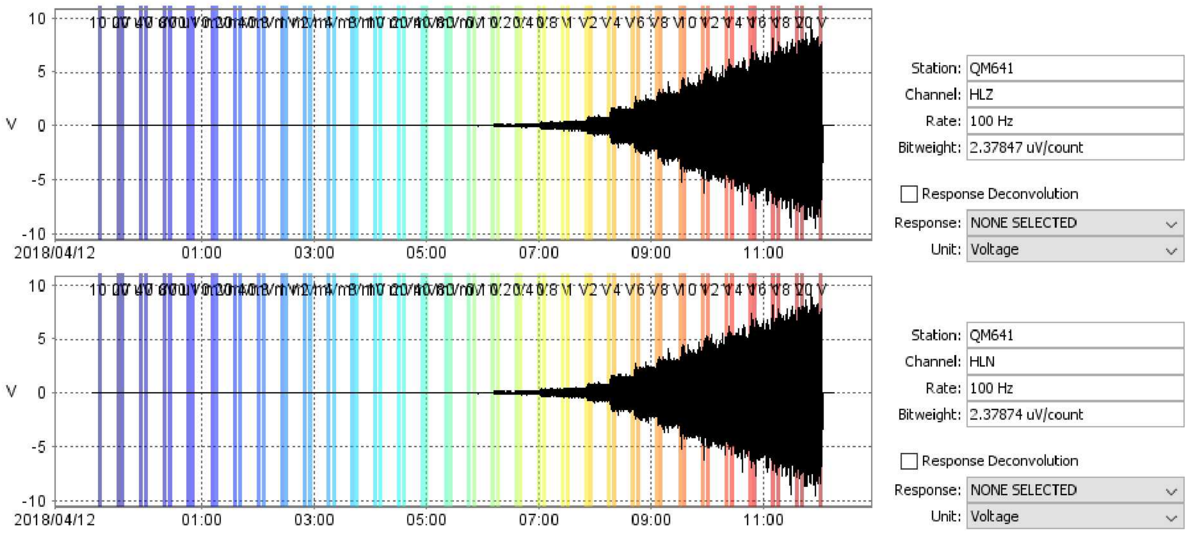


Figure 97 Modified Noise Power Ratio Time Series: Q330M+ 6641, Z and N, gain 1x

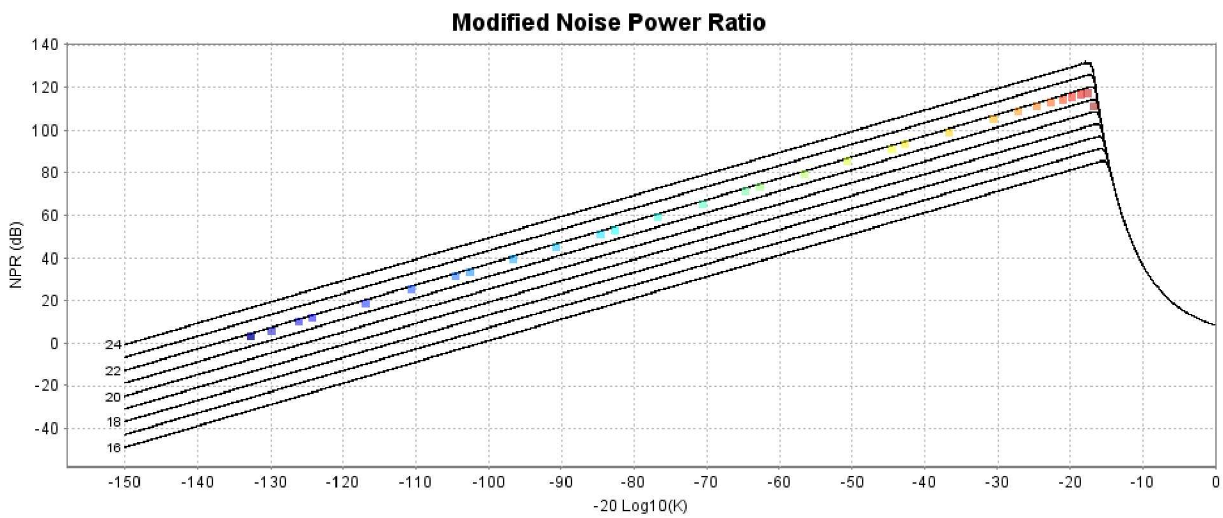


Figure 98 Modified Noise Power Ratio: Q330M+ 6641, Z and N, gain 1x

The figure above shows the resulted of the Modified Noise Power Ratio test between channels Z and N on Port A of # 6641 at a gain of 1x. The results were also computed between channel Z and the remaining 4 channels (E on Port A and Z, N, and E on Port B). However, the results were nearly identical and therefore not reported on.

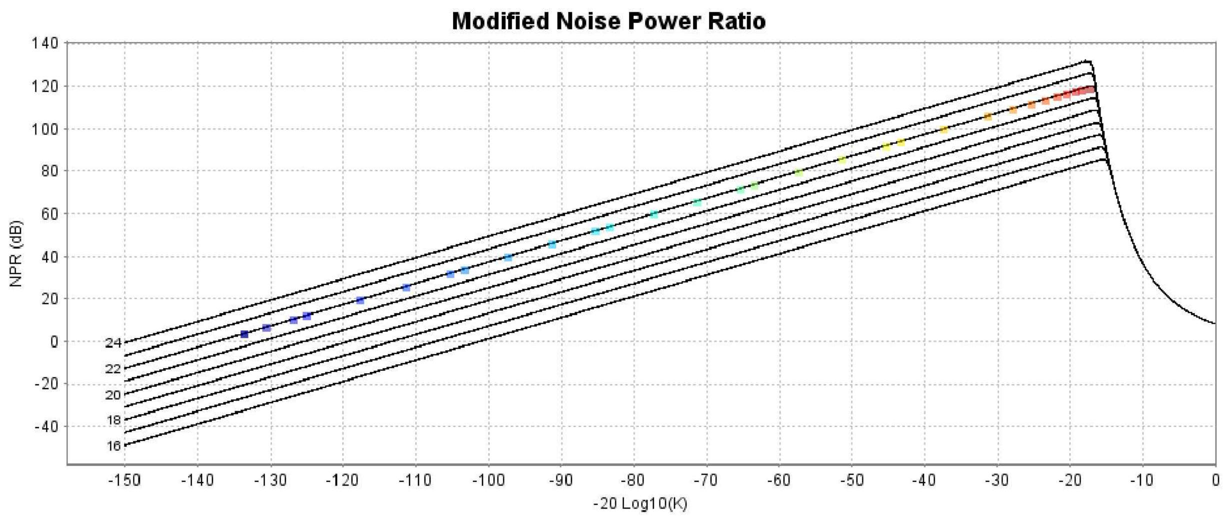


Figure 99 Modified Noise Power Ratio: Q330M+ 6640, Z and N, gain 8xL

The figure above shows the resulted of the Modified Noise Power Ratio test between channels Z and N on # 6640 at a gain of 8xL. The results were also computed between channel Z and E. However, the results were nearly identical and therefore not reported on.

The Modified Noise Power Ratio results indicate that the two digitizers perform similarly with just under 22 bits of performance across the entire range of amplitudes.

Table 74 Modified Noise Power Ratio: 6641, gain 1x

RMS Amplitude	-20 log K	NPR: Z1 - N1	NPR: Z1 - E1	NPR: Z1 - Z2	NPR: Z1 - N2	NPR: Z1 - E2
3.275 uV rms	-132.71	3.52 dB	3.51 dB	3.52 dB	3.51 dB	3.51 dB
3.283 uV rms	-132.69	3.51 dB	3.50 dB	3.50 dB	3.53 dB	3.50 dB
4.570 uV rms	-129.81	5.97 dB	5.98 dB	5.99 dB	5.97 dB	5.97 dB
7.108 uV rms	-125.98	9.81 dB	9.79 dB	9.82 dB	9.83 dB	9.75 dB
8.665 uV rms	-124.26	11.53 dB	11.48 dB	11.54 dB	11.54 dB	11.50 dB
20.14 uV rms	-116.93	18.83 dB	18.78 dB	18.83 dB	18.84 dB	18.81 dB
41.92 uV rms	-110.56	25.22 dB	25.21 dB	25.23 dB	25.21 dB	25.19 dB
83.62 uV rms	-104.56	31.18 dB	31.17 dB	31.23 dB	31.21 dB	31.18 dB
0.1046 mV rms	-102.62	33.14 dB	33.13 dB	33.14 dB	33.16 dB	33.12 dB
0.2086 mV rms	-96.62	39.15 dB	39.14 dB	39.15 dB	39.13 dB	39.11 dB
0.4173 mV rms	-90.60	45.19 dB	45.15 dB	45.15 dB	45.20 dB	45.15 dB
0.8352 mV rms	-84.57	51.20 dB	51.17 dB	51.19 dB	51.22 dB	51.17 dB
1.042 mV rms	-82.65	53.10 dB	53.06 dB	53.10 dB	53.14 dB	53.09 dB
2.089 mV rms	-76.61	59.15 dB	59.15 dB	59.21 dB	59.20 dB	59.15 dB
4.172 mV rms	-70.60	65.17 dB	65.14 dB	65.17 dB	65.19 dB	65.14 dB
8.332 mV rms	-64.60	71.15 dB	71.16 dB	71.17 dB	71.20 dB	71.16 dB
10.43 mV rms	-62.65	73.07 dB	73.09 dB	73.13 dB	73.10 dB	73.09 dB
20.84 mV rms	-56.63	79.10 dB	79.09 dB	79.11 dB	79.12 dB	79.10 dB
41.71 mV rms	-50.61	85.13 dB	85.12 dB	85.11 dB	85.14 dB	85.11 dB
83.42 mV rms	-44.59	91.15 dB	91.13 dB	91.16 dB	91.18 dB	91.14 dB
0.1042 V rms	-42.65	93.11 dB	93.04 dB	93.12 dB	93.09 dB	93.08 dB
0.2087 V rms	-36.62	99.08 dB	99.09 dB	99.08 dB	99.10 dB	99.11 dB
0.4172 V rms	-30.60	105.13 dB	105.10 dB	105.12 dB	105.13 dB	105.16 dB
0.6255 V rms	-27.09	108.53 dB	108.56 dB	108.51 dB	108.59 dB	108.62 dB
0.8340 V rms	-24.59	111.02 dB	110.95 dB	110.87 dB	111.04 dB	111.09 dB
1.043 V rms	-22.65	112.80 dB	112.80 dB	112.59 dB	112.90 dB	112.97 dB
1.251 V rms	-21.07	114.25 dB	114.26 dB	113.83 dB	114.35 dB	114.48 dB
1.460 V rms	-19.73	115.36 dB	115.40 dB	114.77 dB	115.53 dB	115.66 dB
1.669 V rms	-18.56	116.32 dB	116.43 dB	115.52 dB	116.56 dB	116.75 dB
1.876 V rms	-17.55	117.13 dB	117.29 dB	116.09 dB	117.44 dB	117.72 dB
2.083 V rms	-16.64	111.01 dB	111.11 dB	110.77 dB	112.77 dB	117.87 dB

Table 75 Modified Noise Power Ratio: Q330M+ 6640, gain 8xL

RMS Amplitude	-20 log K	NPR: Z - N	NPR: Z - E
0.3693 uV rms	-133.60	3.45 dB	3.44 dB
0.3689 uV rms	-133.61	3.44 dB	3.46 dB
0.5219 uV rms	-130.60	6.07 dB	6.06 dB
0.8174 uV rms	-126.70	9.93 dB	9.96 dB
0.9982 uV rms	-124.96	11.71 dB	11.67 dB
2.327 uV rms	-117.61	18.98 dB	19.00 dB
4.840 uV rms	-111.25	25.36 dB	25.38 dB
9.664 uV rms	-105.25	31.37 dB	31.38 dB
12.09 uV rms	-103.30	33.32 dB	33.33 dB
24.10 uV rms	-97.31	39.34 dB	39.34 dB
48.21 uV rms	-91.29	45.31 dB	45.29 dB
96.50 uV rms	-85.26	51.37 dB	51.34 dB
0.1204 mV rms	-83.34	53.26 dB	53.32 dB
0.2414 mV rms	-77.29	59.31 dB	59.33 dB
0.4821 mV rms	-71.29	65.35 dB	65.36 dB
0.9626 mV rms	-65.28	71.34 dB	71.35 dB
1.205 mV rms	-63.33	73.30 dB	73.30 dB
2.408 mV rms	-57.32	79.30 dB	79.29 dB
4.819 mV rms	-51.29	85.31 dB	85.32 dB
9.638 mV rms	-45.27	91.32 dB	91.37 dB
12.04 mV rms	-43.34	93.26 dB	93.29 dB
24.11 mV rms	-37.30	99.33 dB	99.32 dB
48.20 mV rms	-31.29	105.30 dB	105.34 dB
72.26 mV rms	-27.77	108.79 dB	108.83 dB
96.35 mV rms	-25.27	111.34 dB	111.38 dB
0.1205 V rms	-23.33	113.22 dB	113.26 dB
0.1445 V rms	-21.75	114.78 dB	114.85 dB
0.1686 V rms	-20.41	115.99 dB	116.19 dB
0.1929 V rms	-19.24	117.18 dB	117.39 dB
0.2167 V rms	-18.23	118.13 dB	118.34 dB
0.2407 V rms	-17.32	118.64 dB	118.71 dB

3.17 Common Mode Rejection

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

3.17.1 Measurand

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

3.17.2 Configuration

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

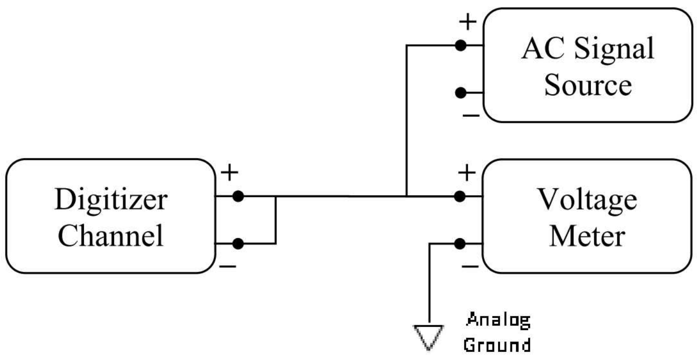


Figure 100 Common Mode Rejection Configuration Diagram

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 76 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.

3.17.3 Analysis

A 10 cycle, or 10 seconds at 1 Hz, window is defined on the data for the recorded signal segment. A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference meter in Volts in order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

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

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

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

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

3.17.4 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.

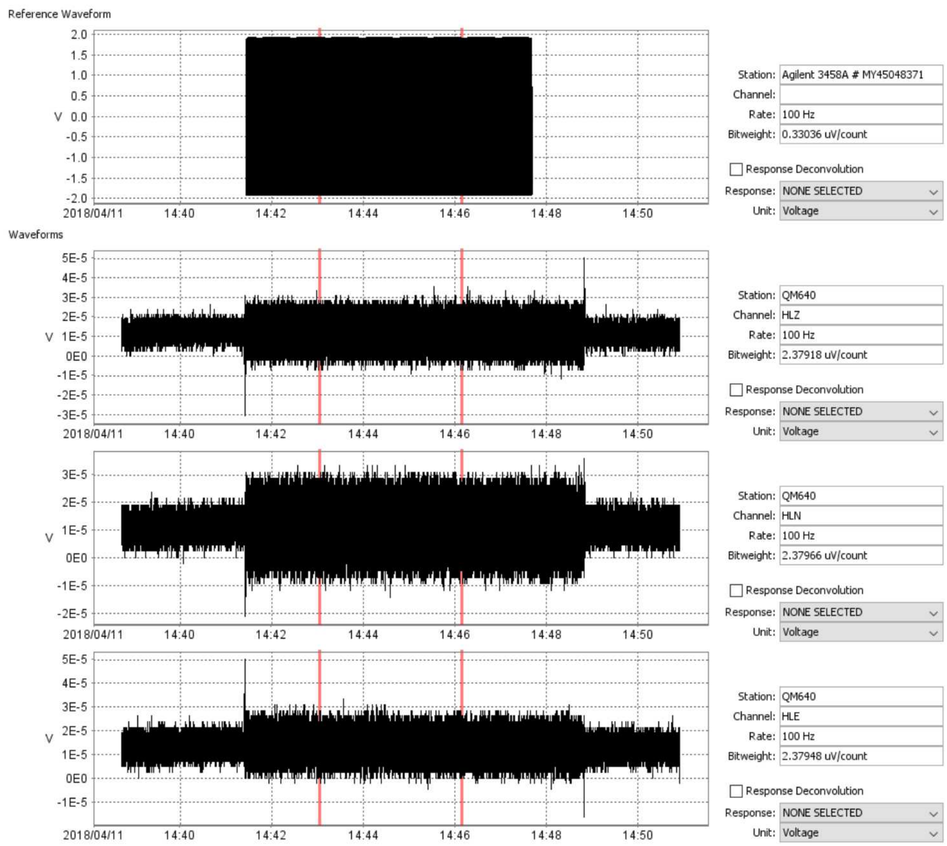


Figure 101 Common Mode Rejection Time Series

The following tables contain the computed common mode noise and rejection ratio.

Table 77 Common Mode Rejection Ratio, Q330M+ 6640

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Signal Amplitude	100 Hz	1.913 V	0.9576 V	0.4780 V	0.2390 V	0.2474 V	0.1238 V	61.81 mV
Channel 1 (Z)	20 Hz	105.60 dB	100.59 dB	100.09 dB	99.44 dB	96.81 dB	98.95 dB	100.33 dB
	40 Hz	105.61 dB	100.59 dB	100.12 dB	99.46 dB	96.82 dB	98.98 dB	100.35 dB
	100 Hz	105.63 dB	100.61 dB	100.14 dB	99.47 dB	96.83 dB	99.00 dB	100.36 dB
Channel 2 (N)	20 Hz	103.78 dB	111.35 dB	113.37 dB	112.49 dB	97.23 dB	100.32 dB	102.13 dB
	40 Hz	103.80 dB	111.37 dB	113.34 dB	112.48 dB	97.24 dB	100.33 dB	102.16 dB
	100 Hz	103.81 dB	111.36 dB	113.37 dB	112.50 dB	97.26 dB	100.35 dB	102.18 dB
Channel 3 (E)	20 Hz	109.31 dB	96.94 dB	92.91 dB	91.75 dB	89.87 dB	94.51 dB	98.25 dB
	40 Hz	109.30 dB	96.96 dB	92.93 dB	91.77 dB	89.89 dB	94.53 dB	98.28 dB
	100 Hz	109.34 dB	96.98 dB	92.95 dB	91.78 dB	89.90 dB	94.55 dB	98.28 dB

Table 78 Common Mode Rejection Ratio, Q330M+ 6641, Port A

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Signal Amplitude	100 Hz	1.913 V	0.9576 V	0.4780 V	0.2390 V	0.2474 V	0.1238 V	61.81 mV
Channel 1 (Z)	20 Hz	86.54 dB	86.80 dB	86.32 dB	86.28 dB	86.25 dB	86.03 dB	85.94 dB
	40 Hz	86.56 dB	86.82 dB	86.34 dB	86.30 dB	86.26 dB	86.05 dB	85.96 dB
	100 Hz	86.58 dB	86.84 dB	86.35 dB	86.31 dB	86.28 dB	86.07 dB	85.98 dB
Channel 2 (N)	20 Hz	114.44 dB	111.99 dB	111.18 dB	111.24 dB	110.20 dB	108.21 dB	107.39 dB
	40 Hz	114.50 dB	111.96 dB	111.21 dB	111.21 dB	110.21 dB	108.22 dB	107.41 dB
	100 Hz	114.53 dB	112.02 dB	111.27 dB	111.24 dB	110.23 dB	108.23 dB	107.43 dB
Channel 3 (E)	20 Hz	93.33 dB	93.83 dB	93.88 dB	93.89 dB	98.36 dB	97.83 dB	97.64 dB
	40 Hz	93.34 dB	93.84 dB	93.89 dB	93.91 dB	98.38 dB	97.86 dB	97.66 dB
	100 Hz	93.36 dB	93.85 dB	93.91 dB	93.93 dB	98.40 dB	97.87 dB	97.67 dB

Table 79 Common Mode Rejection Ratio, Q330M+ 6641, Port B

	Sample Rate	Gain 1x	Gain 2x	Gain 4x	Gain 8xH	Gain 8xL	Gain 16x	Gain 32x
Signal Amplitude	100 Hz	1.913 V	0.9576 V	0.4780 V	0.2390 V	0.2474 V	0.1238 V	61.81 mV
Channel 1 (Z)	20 Hz	100.02 dB	101.45 dB	102.19 dB	103.18 dB	101.65 dB	103.96 dB	104.84 dB
	40 Hz	100.04 dB	101.47 dB	102.21 dB	103.18 dB	101.67 dB	103.98 dB	104.83 dB
	100 Hz	100.05 dB	101.48 dB	102.22 dB	103.21 dB	101.69 dB	103.99 dB	104.85 dB
Channel 2 (N)	20 Hz	90.99 dB	90.56 dB	90.59 dB	90.52 dB	94.22 dB	93.83 dB	93.66 dB
	40 Hz	91.01 dB	90.58 dB	90.62 dB	90.54 dB	94.24 dB	93.85 dB	93.67 dB
	100 Hz	91.03 dB	90.59 dB	90.63 dB	90.56 dB	94.26 dB	93.86 dB	93.69 dB
Channel 3 (E)	20 Hz	106.40 dB	105.60 dB	106.27 dB	106.19 dB	98.73 dB	98.51 dB	98.42 dB
	40 Hz	106.41 dB	105.61 dB	106.27 dB	106.21 dB	98.76 dB	98.51 dB	98.45 dB
	100 Hz	106.45 dB	105.64 dB	106.32 dB	106.23 dB	98.77 dB	98.54 dB	98.47 dB

The observed common mode rejection was between 86 dB and 114.5 dB. As expected, the rejection ratio is largely unique to the physical input channel and does not change significantly with sample rate or gain setting.

3.18 Crosstalk

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

3.18.1 Measurand

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

3.18.2 Configuration

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

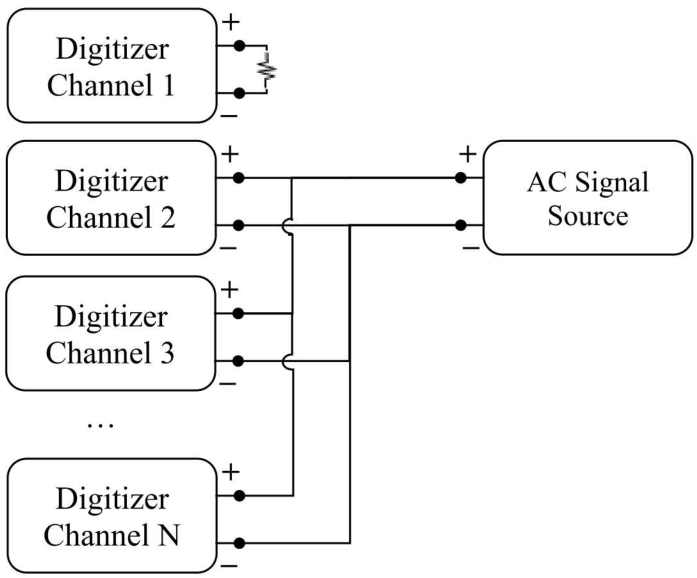


Figure 102 Crosstalk Configuration Diagram

Figure 103 Crosstalk Configuration Picture

Table 80 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	123669	1 Hz AC, 50% Full Scale
Resistors	N/A	N/A	50 (25x2) ohm

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

3.18.3 Analysis

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

$$x[n]$$

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

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

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

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

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

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

3.18.4 Result

The figure below shows a representative waveform time series for the recording made on the digitizer channels under test. All the results were similar to the waveforms shown below.

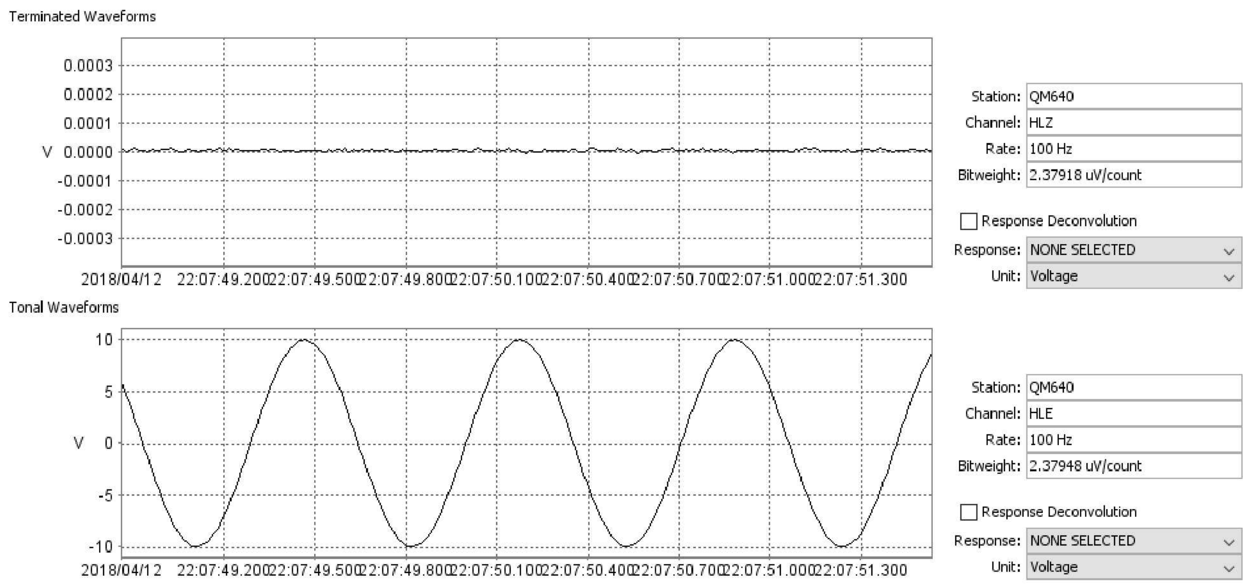


Figure 104 Crosstalk Time Series

The figures below show representative power spectra of one of the tonal channels and all three sample rates of the terminated channels. All the results were similar to the power spectra shown below.

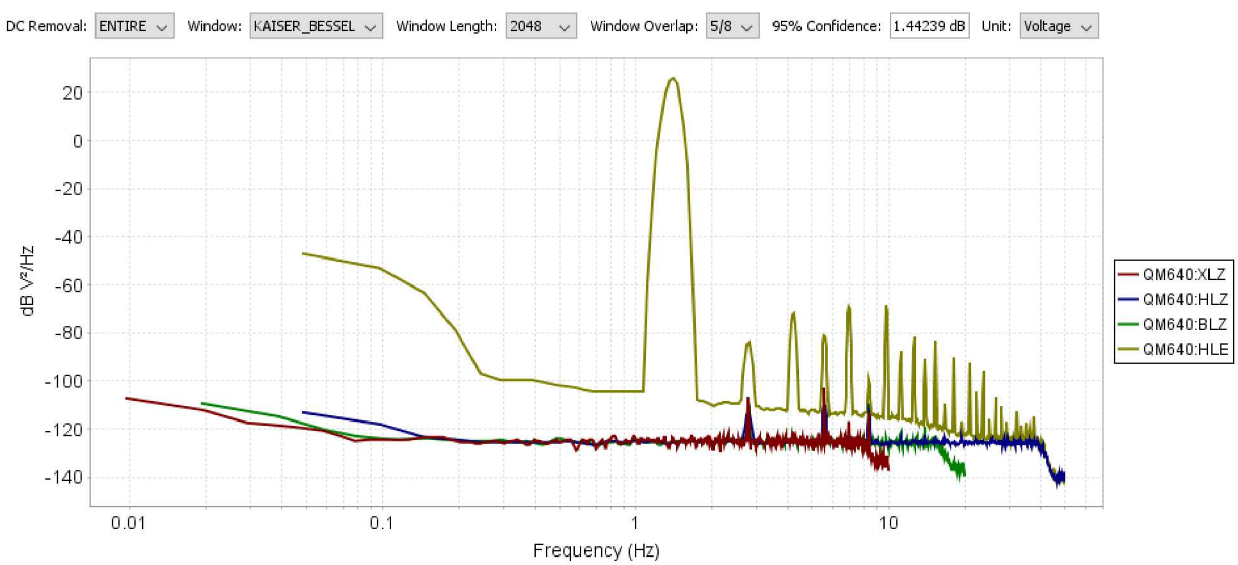


Figure 105 Crosstalk Power Spectra, Q330M+ 6640, Z Terminated

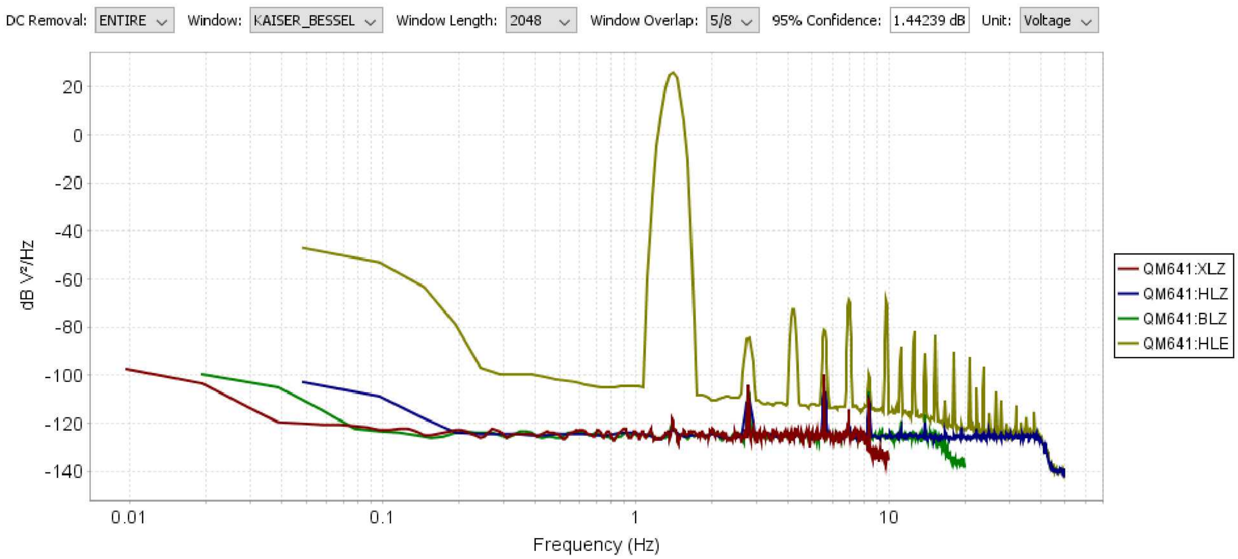


Figure 106 Crosstalk Power Spectra, Q330M+ 6641 Port B, Z Terminated

The following table contains the computed crosstalk ratios.

Table 81 Q330M+ Crosstalk Ratios

Digitizer	Gain	Sample Rate	Terminated Channel		
			Z	N	E
6640	1x	20 Hz	-153.41 dB	-153.43 dB	-154.49 dB
		40 Hz	-155.47 dB	-153.86 dB	-156.92 dB
		100 Hz	-150.18 dB	-149.14 dB	-150.22 dB
6641 Port A	1x	20 Hz	-157.00 dB	-155.86 dB	-155.71 dB
		40 Hz	-150.06 dB	-149.81 dB	-152.95 dB
		100 Hz	-153.54 dB	-152.17 dB	-149.70 dB
6641 Port B	1x	20 Hz	-150.17 dB	-154.62 dB	-155.68 dB
		40 Hz	-148.44 dB	-153.79 dB	-154.16 dB
		100 Hz	-146.85 dB	-150.12 dB	-150.02 dB

The observed levels of crosstalk were all between -146.85 dB and -157 dB. With the exception of the Z channel on 6641 Port B, none of the evaluated channels appeared to contain any sign of crosstalk at the fundamental frequency indicating that the evaluated crosstalk levels represent an upper bound on what the actual crosstalk levels may be. The observed crosstalk on Z channel on 6641 Port B was very minor, if any, and was still better than -146 dB.

3.19 Timing Accuracy

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

3.19.1 Measurand

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

3.19.2 Configuration

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

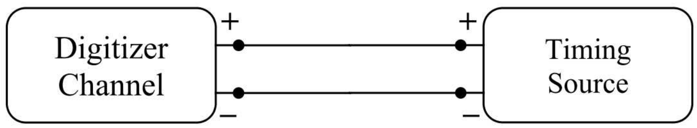


Figure 107 Time Tag Accuracy Configuration Diagram

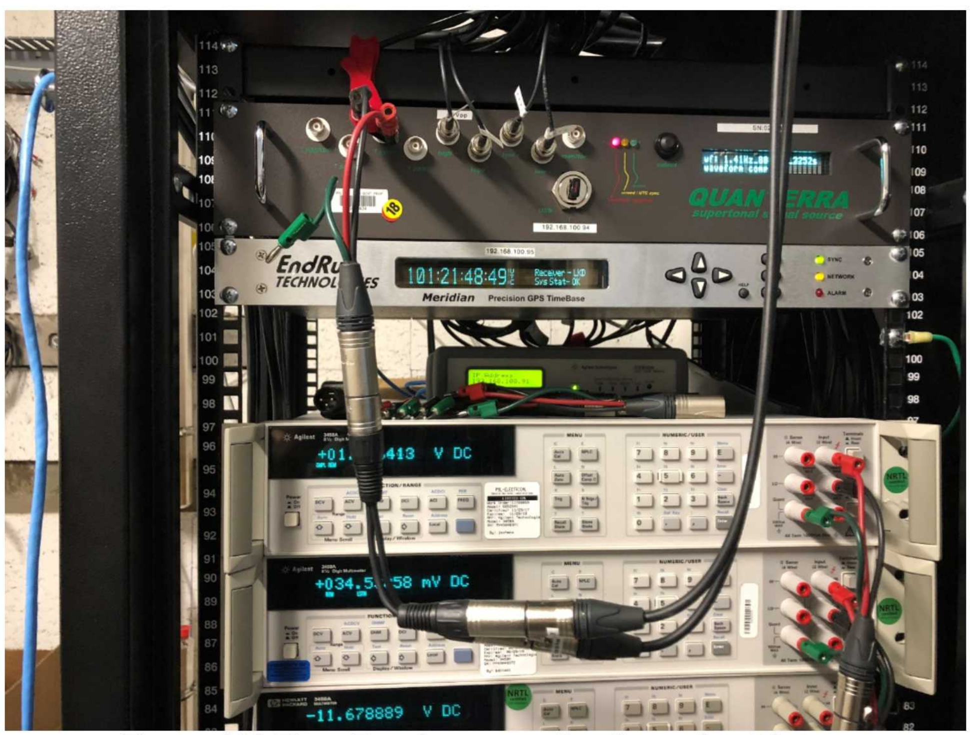


Figure 108 Time Tag Accuracy Configuration Picture

Table 82 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
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.

Both digitizers were evaluated simultaneously. However, only a single channel on each digitizer is recording the time-synchronized PPM in order to minimize any capacitive delay of the timing pulse.

3.19.3 Analysis

The difference between the digitizers actual and expected time stamps are measured by evaluating the unique characteristics of the signal being recorded (Merchant, 2011). The average time tag error is computed over a minimum of 30 minutes.

3.19.4 Result

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

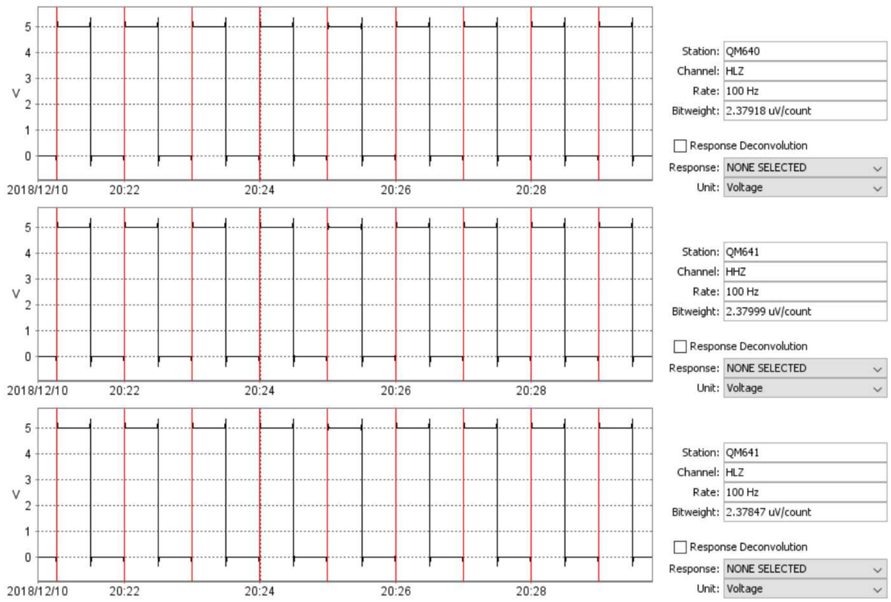


Figure 109 Time Tag Accuracy PPM Time Series

Prior to initiating the timing tests, the digitizer firmware revision v2.3 from Kinemetrics was applied to both digitizers. The GPS time tag accuracy was monitored using the recorded PPM signal from the time of reboot. The figure below shows the observed time tag error from just after the reboot until it had remained stable for at least 30 minutes.

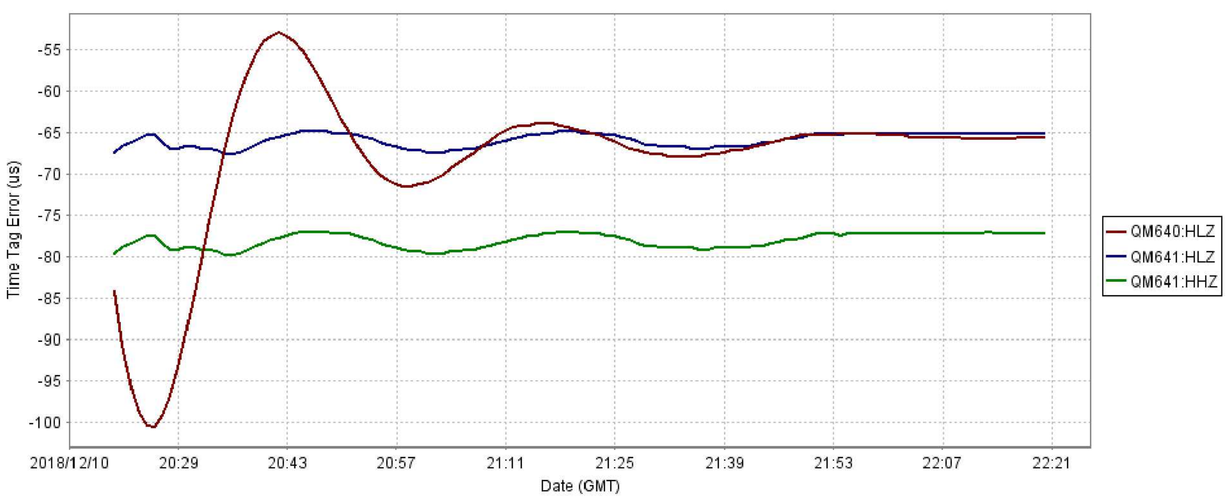


Figure 110 GPS Timing Lock and Stabilization

Similarly, both digitizers were configured for PTP and their PTP time tag accuracy was monitored using the recorded PPM signal from the time of reboot. The figure below shows the observed time tag error from just after the reboot until it had remained stable for at least 30 minutes.

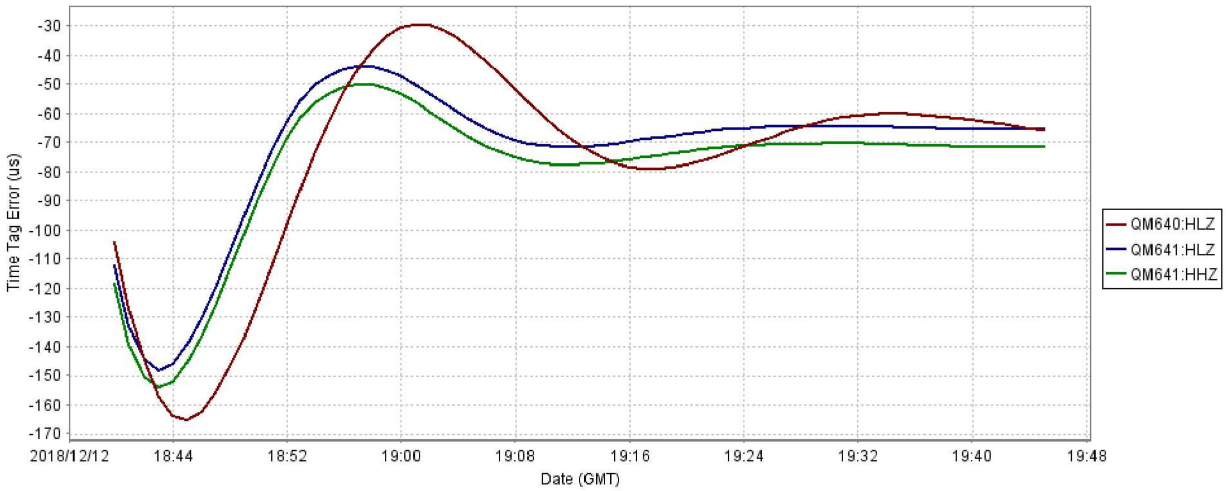


Figure 111 PTP Timing Lock and Stabilization

As may be seen in both the cases with the GPS and PTP timing lock, the timing accuracy was observed to oscillate for between an hour and 1.5 hours until stabilizing. The final 30 minutes of time tag data was used to compute the time tag accuracy.

The following table contains the computed timing accuracy results:

Table 83 Time Tag Accuracy (Stabilized)

	GPS		PTP	
Digitizer	Mean	Std	Mean	Std
Q330M+ 6640	-67.6 us	2.8 us	-67.4 us	6.7 us
Q330M+ 6641 Port A	-66.4 us	0.9 us	-65.6 us	1.4 us
Q330M+ 6641 Port B	-78.6 us	0.9 us	-71.8 us	1.5 us

3.20 Timing Drift

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

3.20.1 Measurand

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

3.20.2 Configuration

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

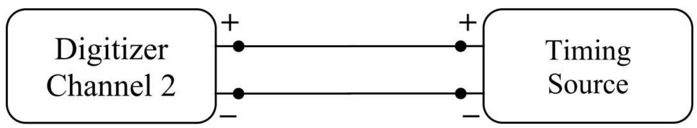


Figure 112 Timing Drift Configuration Diagram

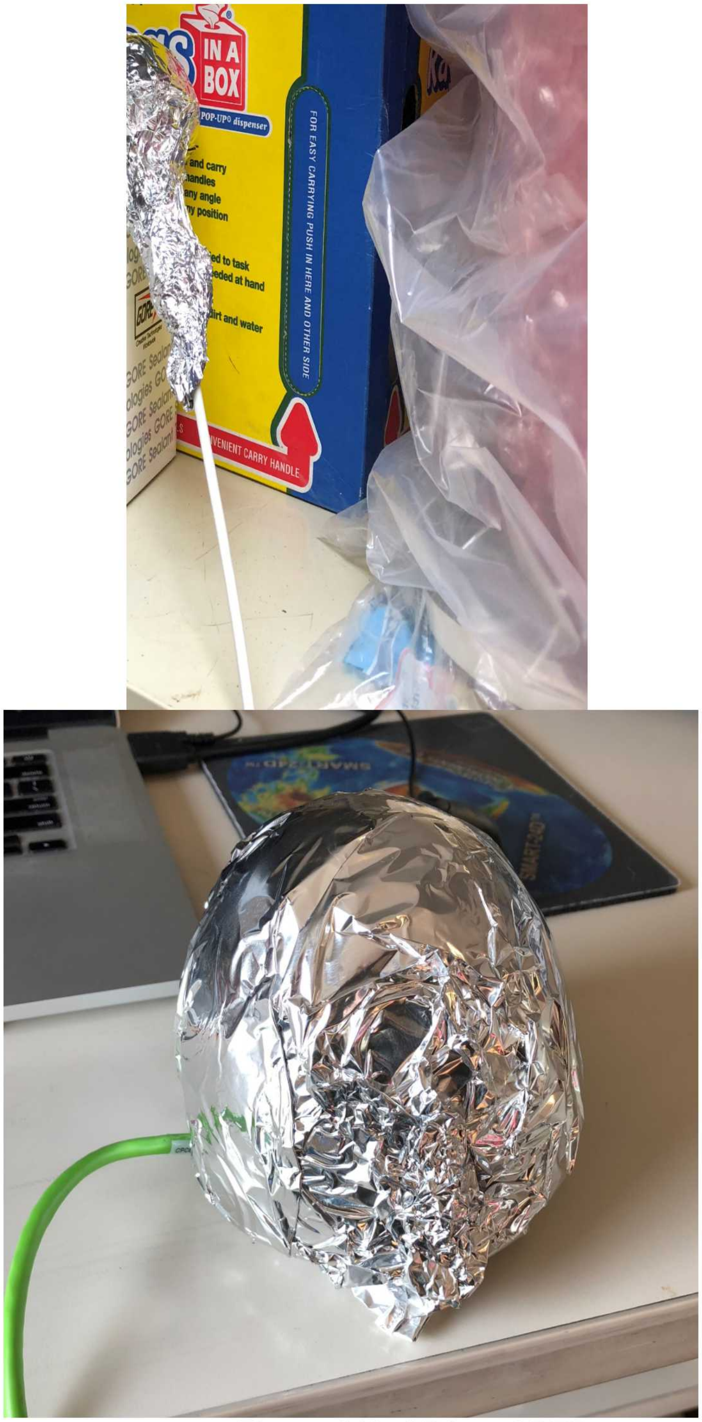


Figure 113 GPS and PTP antennas covered for drift test

Table 84 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

The digitizer clock is allowed to stabilize before the GPS antenna is shielded, resulting in the digitizer to lose timing lock. The digitizer is allowed to drift 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 when the digitizers were locked to the PTP Masterclock, the GPS antenna of the PTP server was covered.

3.20.3 Analysis

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

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

3.20.4 7Result

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

The GPS time tag drift was initiated on December 10, 2018 at 20:38 UTC by covering both the GPS antennas with metal foil and placing the antennas inside of a steel cabinet so that the digitizers would lose GPS lock.

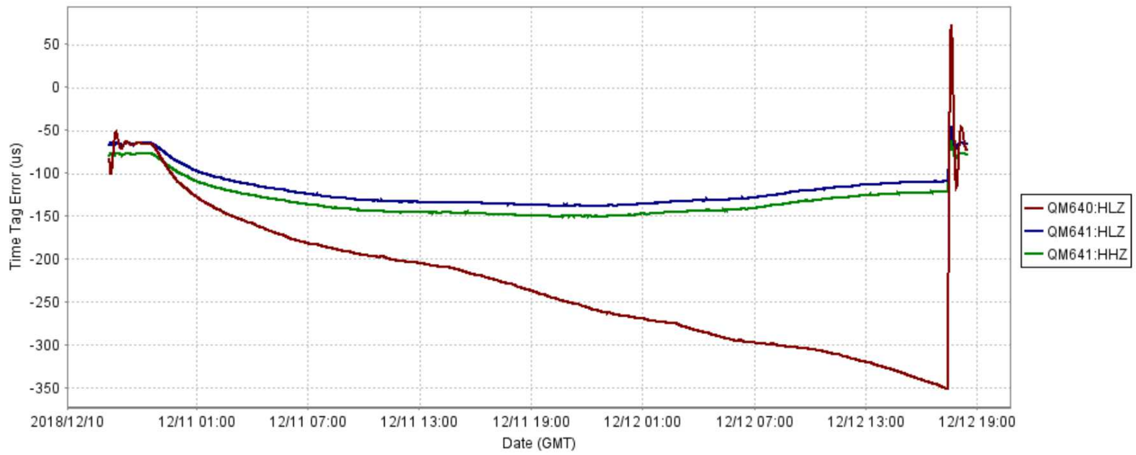


Figure 114 Time Tag Drift: GPS

The GPS time tag recovery was initiated on December 12, 2018 at 17:13 UTC by uncovering the both the GPS antennas, returning the antennas to their original location, and allowing the digitizers to regain GPS lock. The status on the digitizer webpage did not confirm that they had regained GPS lock until 17:27 UTC.

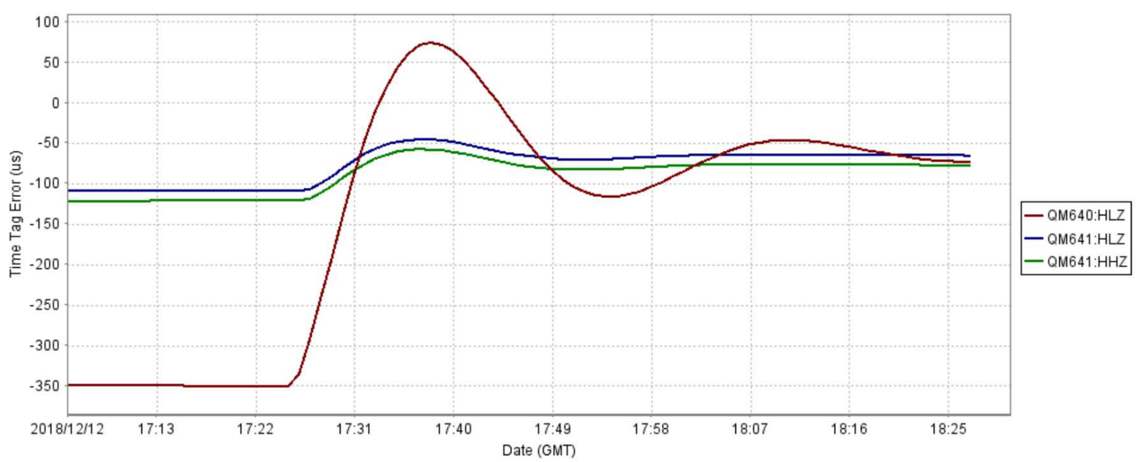


Figure 115 Time Tag Recovery: GPS

The time tag measurements shown in the figure above are consistent with the Q330M+ digitizers regaining timing lock at 17:27 UTC, approximately 14 minutes after the antennas were uncovered. During timing recovery, the timing corrections applied by the digitizer appear to be underdamped, oscillating past their stabilized point and taking approximately an hour to stabilize.

The PTP time tag drift was initiated on December 12, 2018 at 19:47 UTC by bringing the GPS antenna for the PTP master indoors, wrapping it in metal foil, and placing it inside of a steel cabinet. The PTP master immediately reported that it had lost GPS lock.

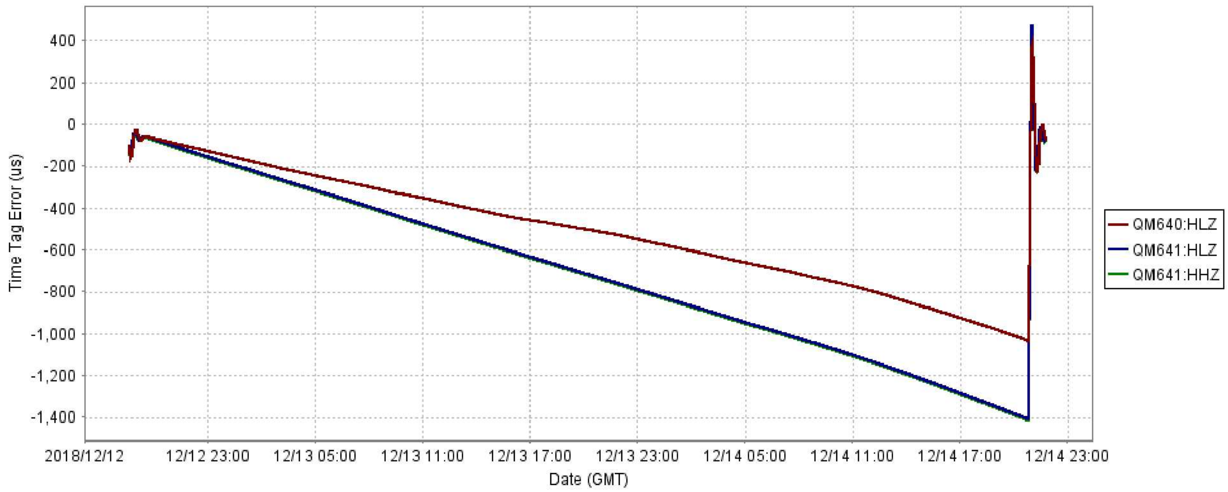


Figure 116 Time Tag Drift: PTP

Both digitizers timing appears to drift at different, although constant, linear rates during the 48 hours period that the PTP master was not locked.

The PTP time tag recovery was initiated on December 14, 2018 at 20:45 UTC by returning the GPS antenna for the PTP master outdoors where it could regain timing lock. The PTP master reported an initial satellite fix at 20:47 UTC and a time lock at 20:50 UTC.

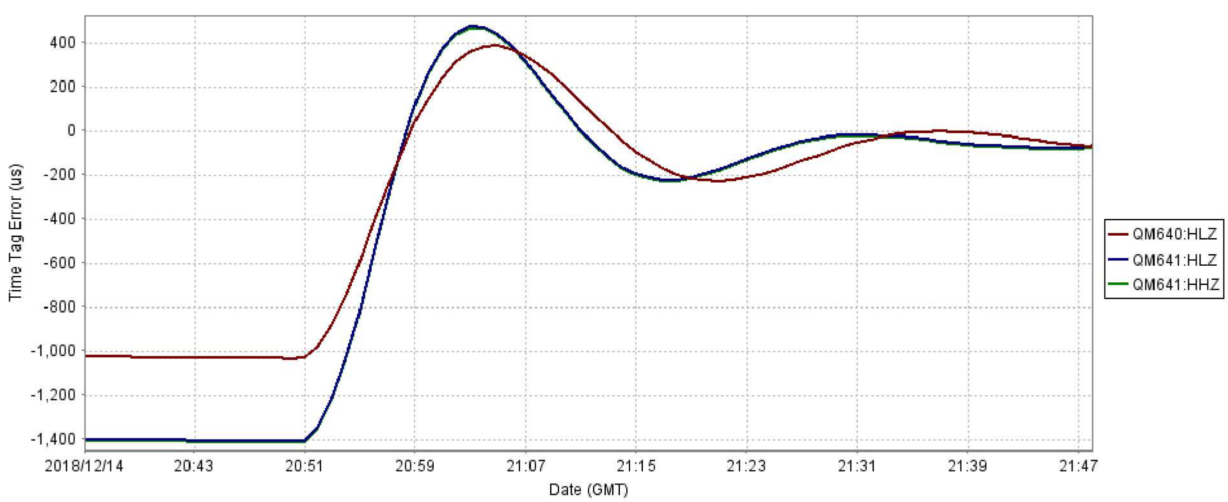


Figure 117 Time Tag Recovery: PTP

The timing accuracy measurements indicate that the digitizer immediately began to correct for the updated PTP timing fix. Similar to other results, the Q330M+ timing accuracy appears to oscillate for approximately 40 minutes before stabilizing.

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 85 Time Tag Drift and Recovery

	Q330M+ 6640		**Q330M+ 6641 Port A**		**Q330M+ 6641 Port B**	
	GPS	**PTP**	**GPS**	**PTP**	**GPS**	**PTP**
Lock Level	-65 us	-67 us	-65 us	-66 us	-77 us	-72 us
Initial Drift Rate (1 hr)	-32.9 us/hr	-19.6 us/hr	-14.3 us/hr	-29.1 us/hr	-15.7 us/hr	-29.3 us/hr
Final Drift Rate (1 hr)	-7.7 us/hr	-29.7 us/hr	+1.2 us/hr	-32 us/hr	+1.2 us/hr	-33 us/hr
Recovery Time	1+ hr	1 hr	1 hr	1 hr	1 hr	1 hr
Stabilized Recovery Level	-74 us	-74 us	-66 us	-76 us	-78 us	-82 us

The recovered timing accuracy was very close to the initial timing accuracy, indicating that after the approximately 1 hour stabilization the Q330M+ was able to regain a stable lock.

The drift rates were significantly higher with PTP; however, that is believed to be due to the PTP master being used and not the Q330M+.

3.21 Calibrator

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

3.21.1 Measurand

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

3.21.2 Configuration

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

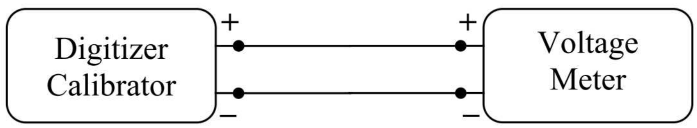


Figure 118 Calibrator Configuration Diagram

Table 86 Calibrator Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Voltage Meter	Agilent 3458A	MY45048371	10 V full scale

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

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

3.21.3 Analysis

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

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

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

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

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

3.21.4 Result

The figures and tables below show the reference meter recording of the calibrator output at a variety of sinusoid amplitudes and frequencies.

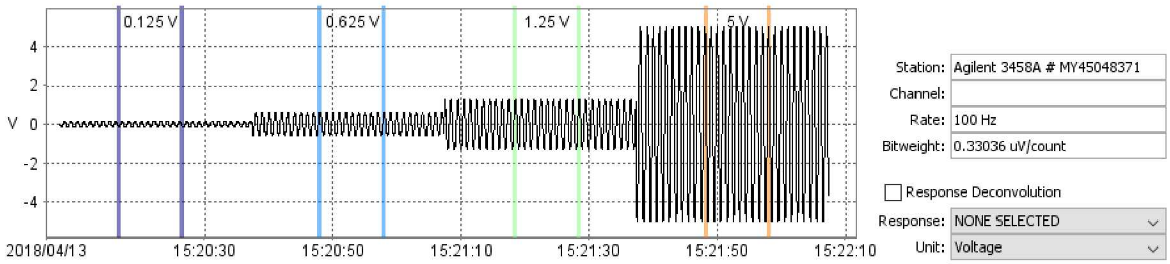


Figure 119 Calibrator Sine Amplitude at 1 Hz

Table 87 Calibrator Sine Amplitude at 1 Hz

Programmed Amplitude	Measured Amplitude
0.156 V	0.157337 V
0.625 V	0.629306 V
1.25 V	1.25862 V
5 V	5.03431 V

The calibrator amplitudes were all consistent with the programmed amplitudes to within 1%.

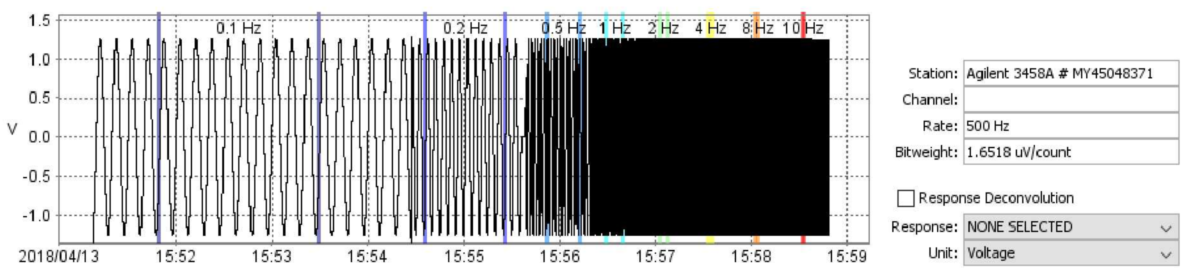


Figure 120 Calibrator Sine Frequency at 1.25 V

Table 88 Calibrator Sine Frequency at 1.25 V

Programmed Frequency	Measured Frequency
0.1 Hz	0.100001 Hz
0.2 Hz	0.200002 Hz
0.5 Hz	0.500006 Hz
1 Hz	1.00001 Hz
2 Hz	2.00002 Hz
4 Hz	4.00005 Hz
8 Hz	8.00009 Hz
10 Hz	10.0001 Hz

The calibrator frequencies were all consistent with the programmed frequencies to within 0.001%.

The figures below show the power spectra of the random white noise calibration signal generated by the Q330M+ digitizer with a bandwidth of 25 Hz and 125 Hz. In both cases, the output signal was recorded on the meter at 100 Hz.

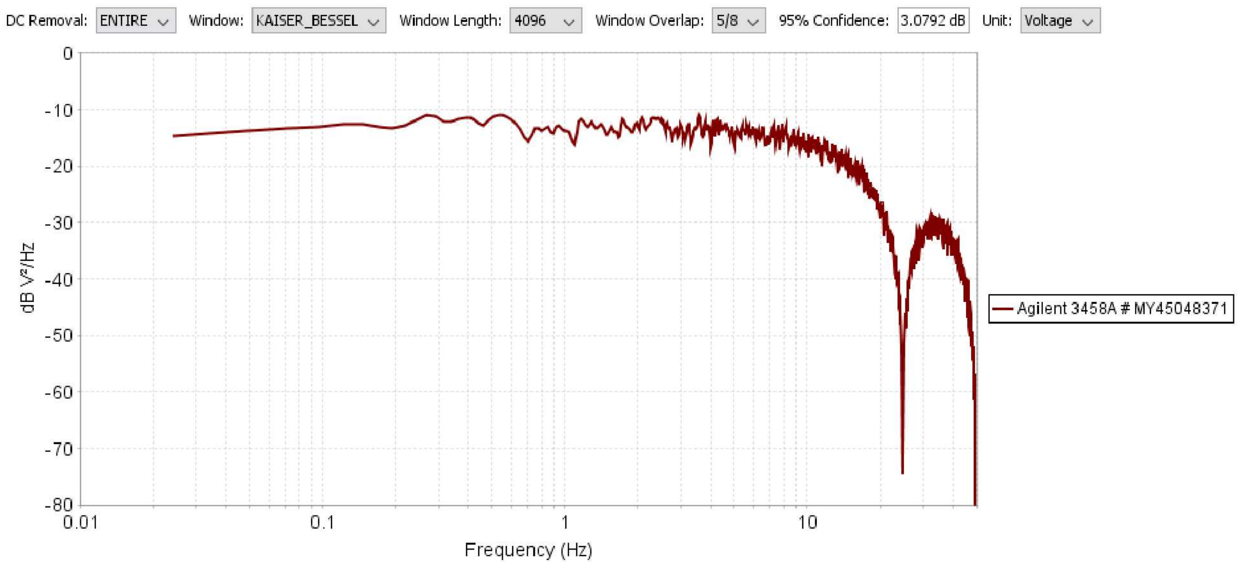


Figure 121 Calibrator White Noise, 25 Hz

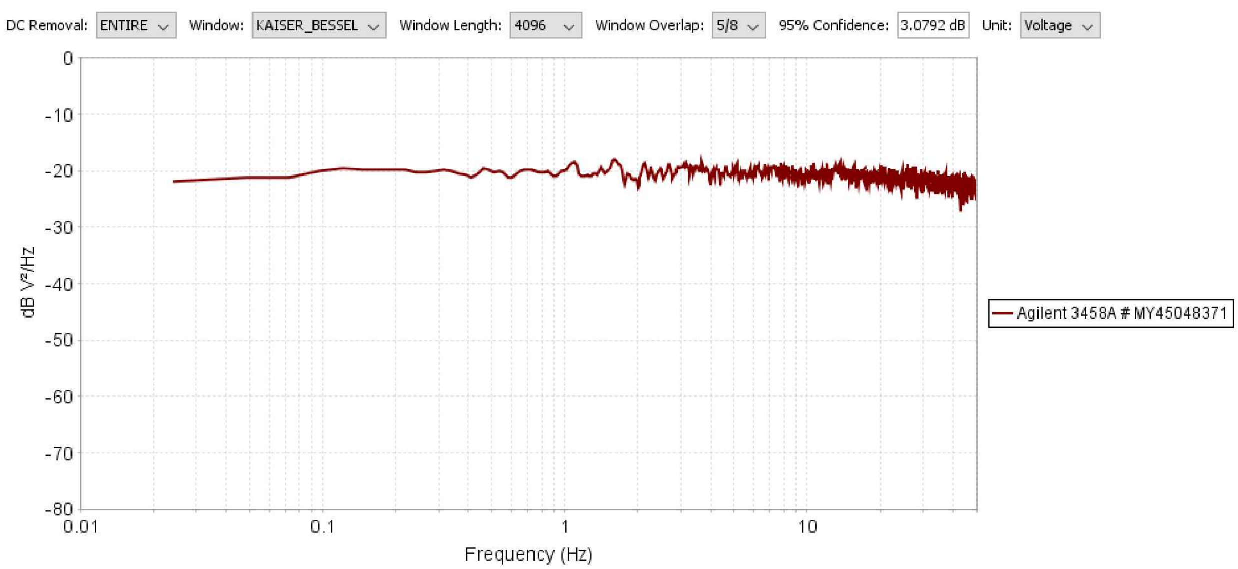


Figure 122 Calibrator White Noise, 125 Hz

The figure below shows the power spectra of the random binary calibration signal generated by the Q330M+ digitizer for a null point at 125 Hz.

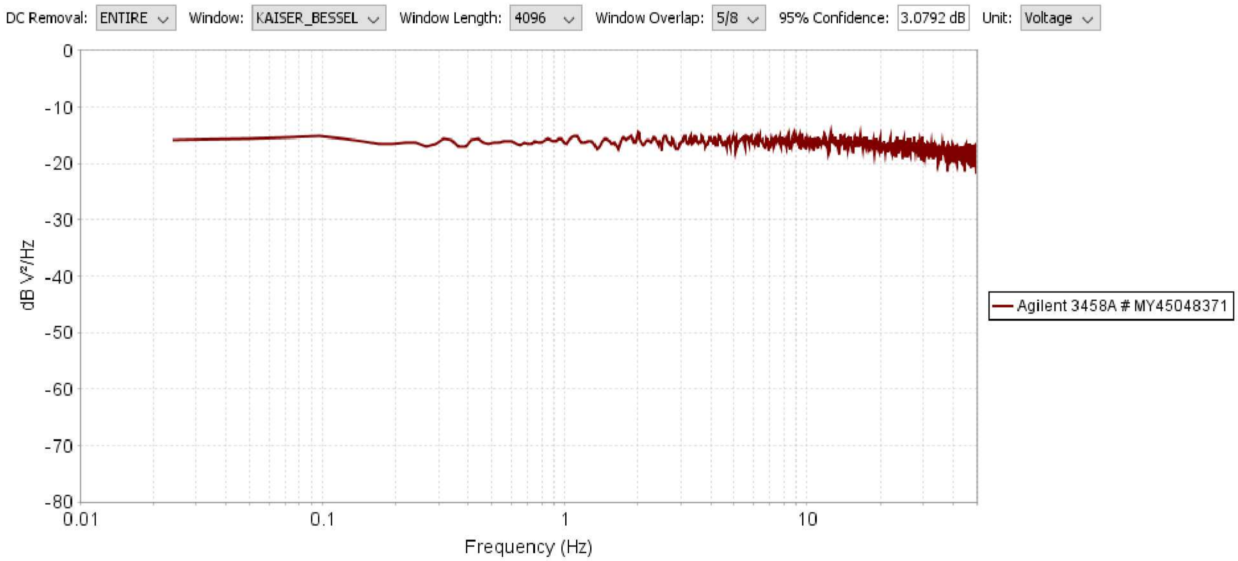


Figure 123 Calibrator Random Binary, 125 Hz

The figure below shows the power spectra of the red noise signal generated by the Q330M+ digitizer, which is intended for generating calibrations on an infrasound sensor.

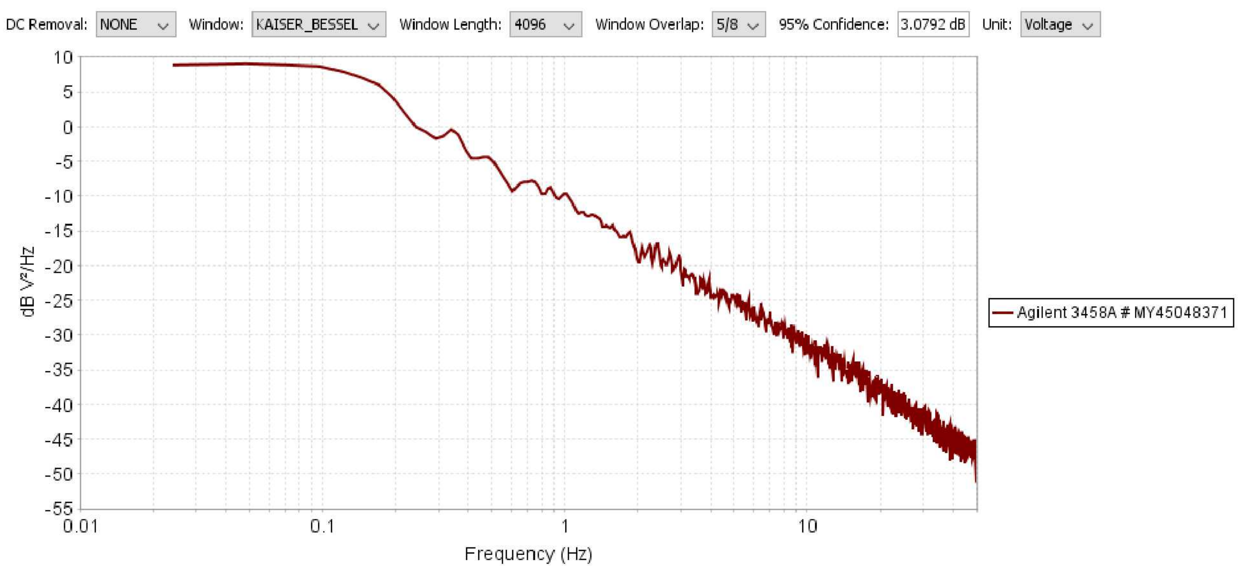


Figure 124 Calibrator Red Noise

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

Note that the Q330M+ allows for one of the input channels to be used as a monitor channel to internally record the calibrator output. It was confirmed that the channel used as the monitor channel automatically reverts to a gain of 1x for the duration of the calibration.

3.22 Sensor Compatibility Verification

The Q330M+ 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.

3.22.1 Geotech GS13

The Q330M+ #6640 was connected to a Geotech GS13 Seismometer, #614, and operated to collect site background noise as described in the following section. The digitizer channel was configured for a gain of 8xL, which sets the input impedance at a value of 2 Mohms and is appropriate for a passive sensor.

Figure 125 GS13 Seismometer #614

3.22.1.1 Site Background

The GS13 seismometer and Q330M+ digitizer collected background signal as shown in the power spectra plot below:

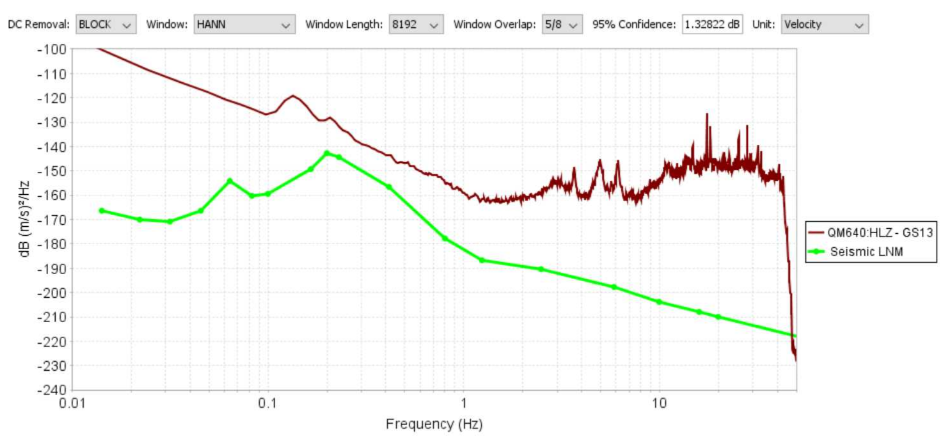


Figure 126 GS13 Background Power Spectra

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

3.22.2 Geotech GS21

The Q330M+ #6641 was connected to a Geotech GS21 Seismometer, #238, and operated to collect site background noise, a sine calibration, and a broadband calibration as described in the following sections. The digitizer channel was configured for a gain of 8xL, which sets the input impedance at a value of 2 Mohms and is appropriate for a passive sensor.

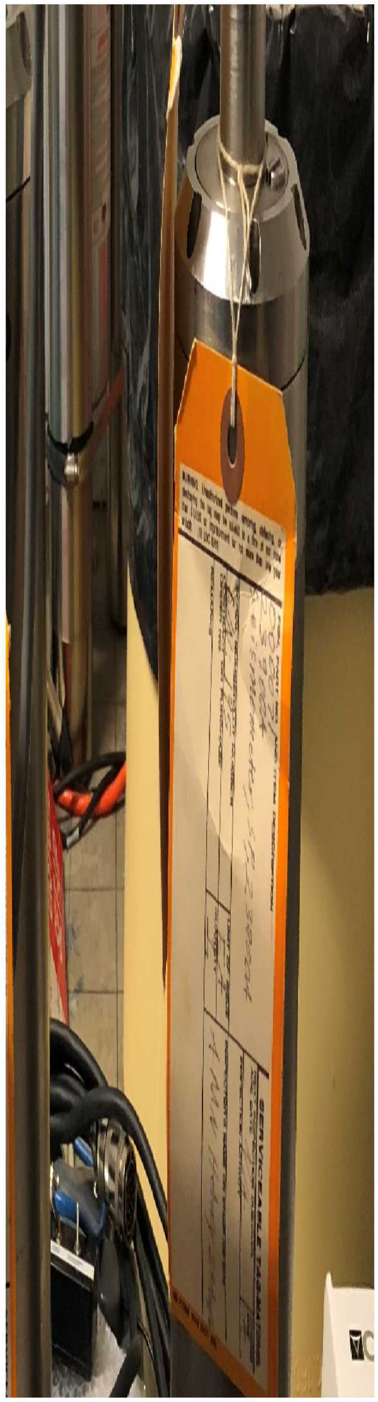


Figure 127 Geotech GS21 #238

3.22.2.1 Site Background

The GS21 seismometer and Q330M+ digitizer collected background signal as shown in the power spectra plot below:

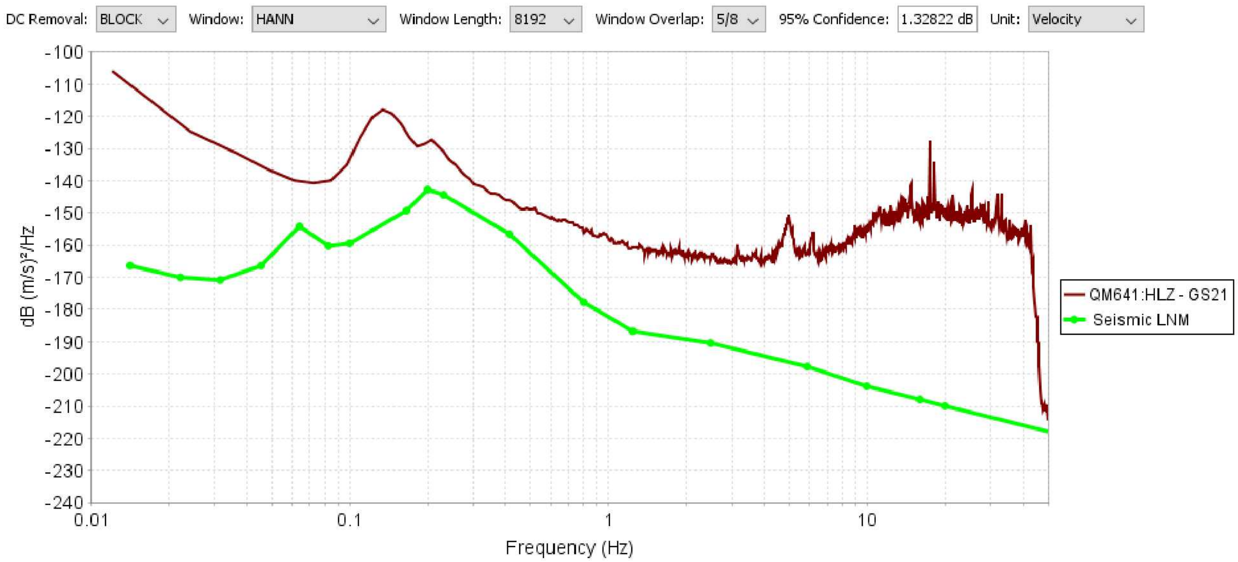


Figure 128 GS21 Background Power Spectra

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

3.22.2.2 Sinusoid Calibration

A sinusoid calibration was performed using the Q330M+ digitizer at 1 Hz and 0.3 V. The Q330M+ was configured to loopback the calibration on the N channel. The time series are shown in the figure below.

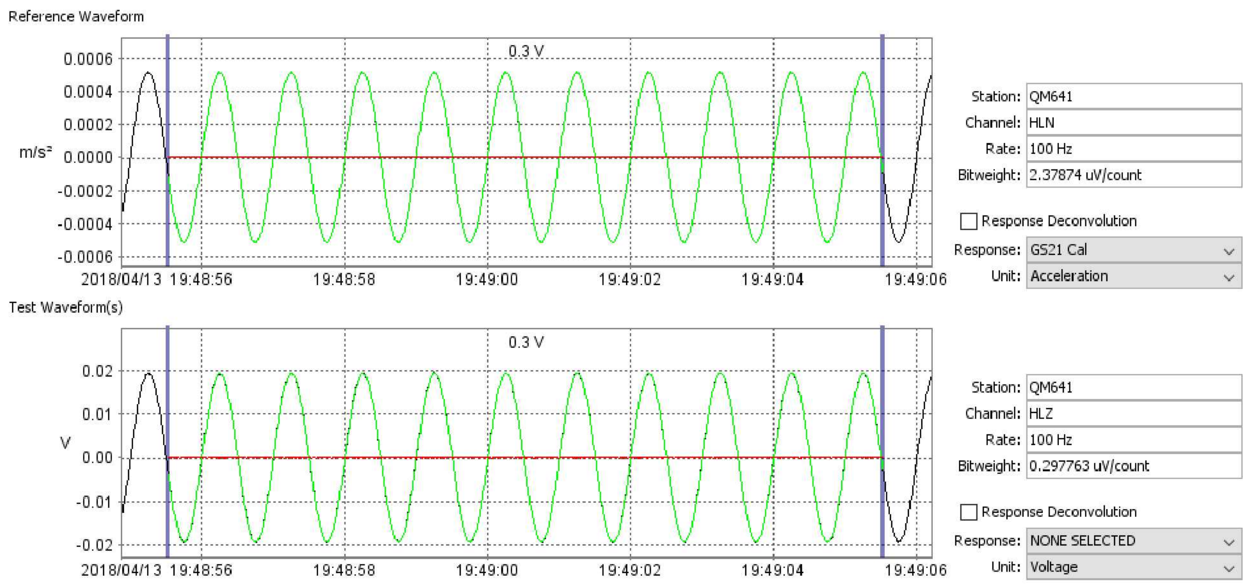


Figure 129 GS21 Sinusoid Calibration Time Series

The GS21 Seismometer has a nominal sensitivity of 418 V/(m/s) at 5 Hz, provided by the CTBTO. This is equivalent to 296 V/(m/s) at 1 Hz. The datasheet specifies these nominal values are accurate to within +/- 10%.

The GS21 also has a nominal calibration motor constant of 0.1975 N/A, calibration coil resistance of 24 ohms, and inertial mass of 5 kg. Note that the datasheet specifies that the coil impedance can vary by +/- 3 ohms, or +/- 12.5% and mass can vary by +/- 1%. Using these nominal values, a calibration sensitivity of 607.7 V/(m/s^2) is expected.

Using these nominal values for the calibration coil, the 0.3 V and 1 Hz sinusoidal signal input to the calibration coil resulted in a measured sensing coil sensitivity of 235.4 V/(m/s). This value is 20% less than what was expected from the nominal sensitivity, although not unrealistic given the uncertainties associated with using the nominal values.

3.22.2.3 Broadband Calibration

A white noise calibration was performed using the Q330M+ digitizer. The Q330M+ was configured to loopback the calibration on the N channel. The time series and power spectra are shown in the figures below.

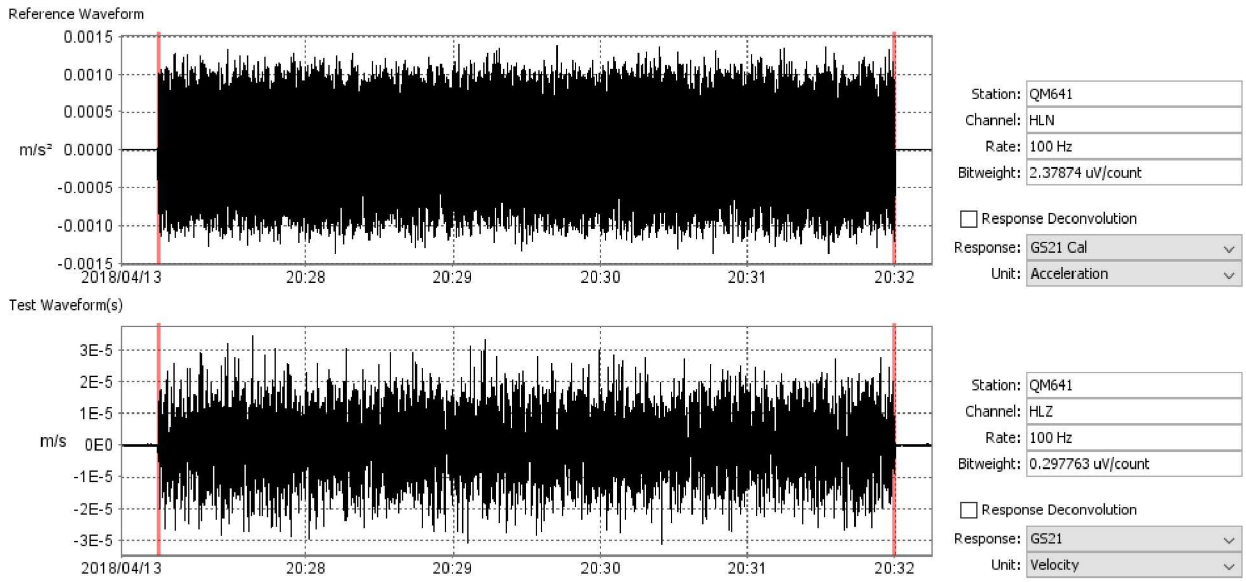


Figure 130 GS21 Broadband Calibration Time Series

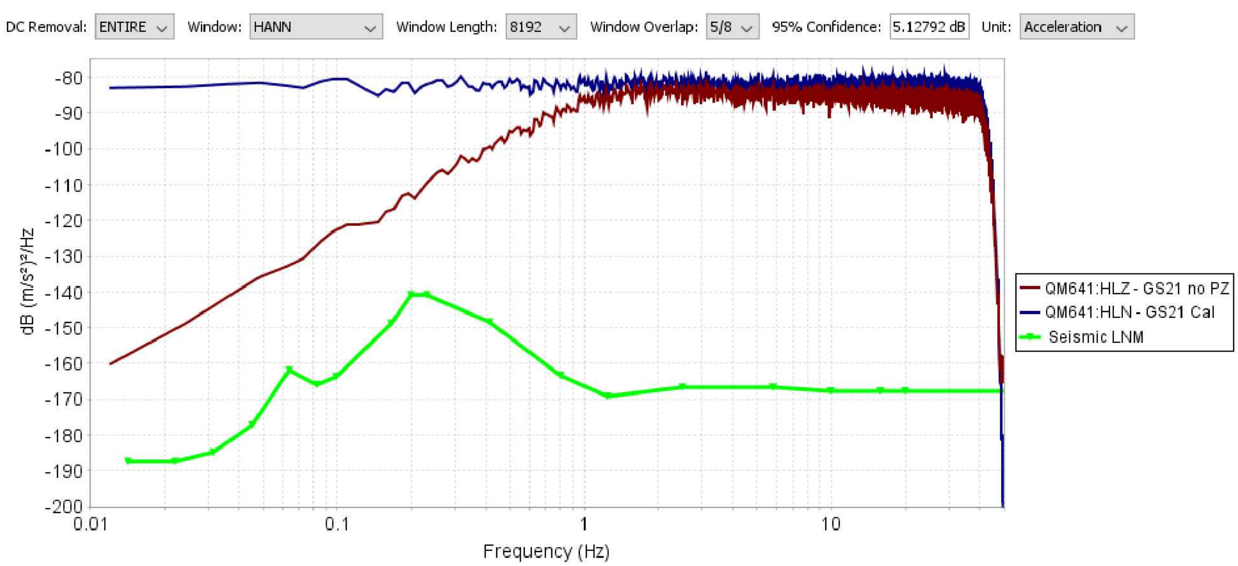


Figure 131 GS21 Calibration Power Spectra

The power spectra plot above shows the sensor output channels, corrected for the nominal sensitivities of the GS21 calibration and sensing coil, but not the full pole-zero response. The shape of the GS21 response curve with a corner at 1 Hz is readily visible. The coherence, relative amplitude, and relative phase plots are shown below along with the nominal amplitude and phase response in green.

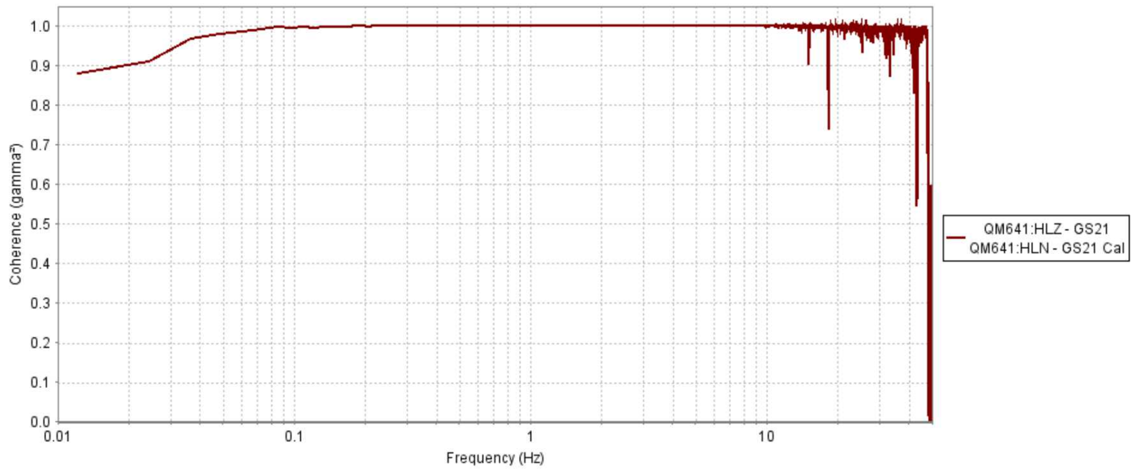


Figure 132 GS21 Calibration Coherence

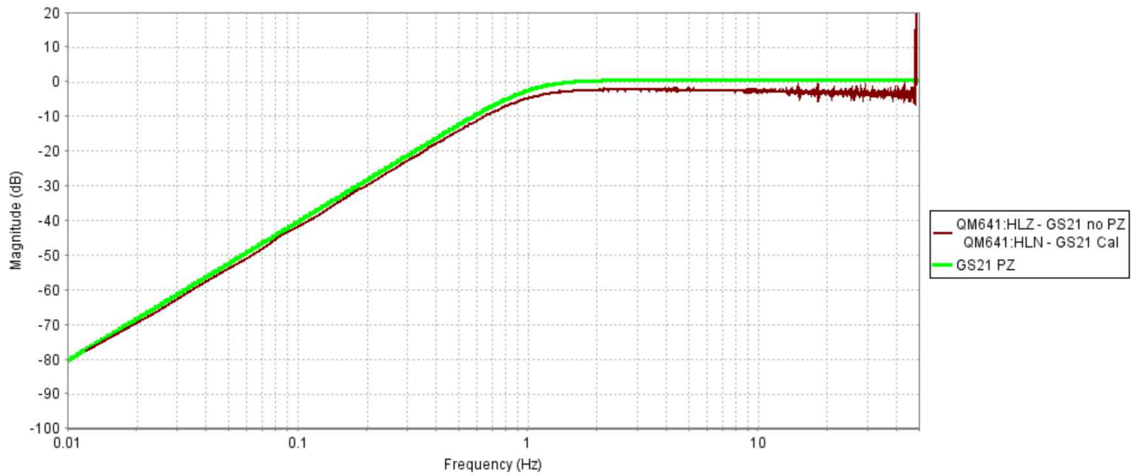


Figure 133 GS21 Calibration Relative Amplitude Response

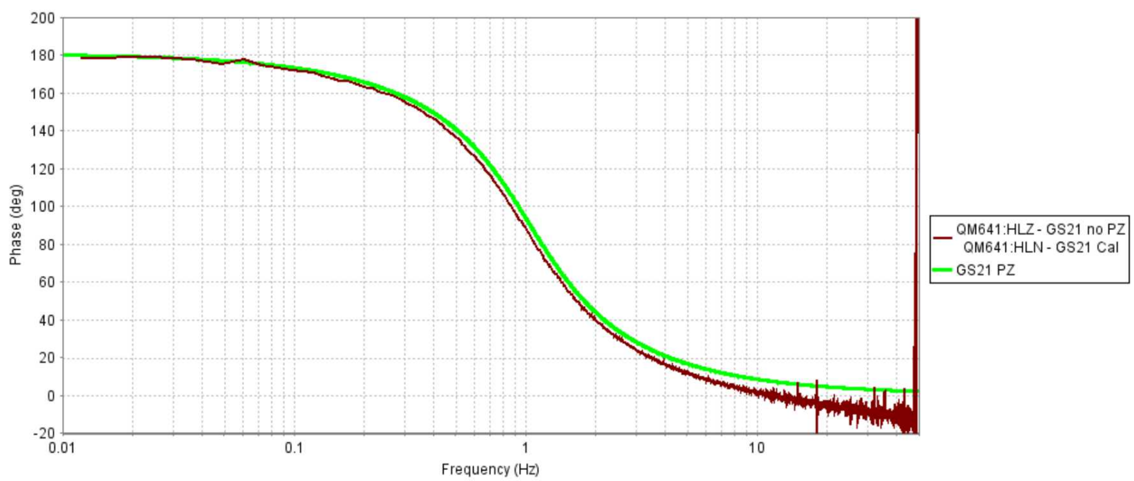


Figure 134 GS21 Calibration Relative Phase Response

The results of the broadband calibration demonstrate that there is good coherence across 0.1 to 1 Hz and both the relative amplitude and phase response are consistent with the nominal response.

3.22.3 Nanometrics Trillium 240

The Q330M+ #6640 was connected to a Nanometrics Trillium 240 Seismometer, #00934, and operated to collect site background noise and a sine calibration as described in the following sections. The digitizer channel was configured for a gain of 1x.

3.22.3.1 Site Background

The Trillium 240 seismometer and Q330M+ digitizer collected background signal as shown in the power spectra plot below:

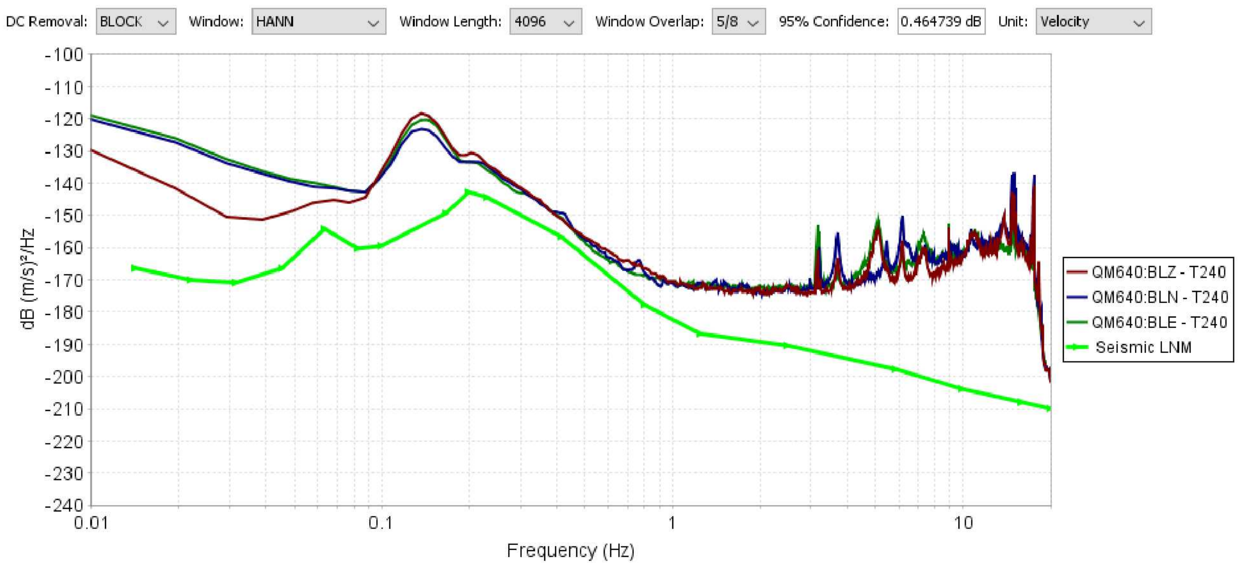


Figure 135 Trillium 240 Background Power Spectra

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

3.22.3.2 Sinusoid Calibration

A sinusoid calibration was performed using the Q330M+ digitizer at 1 Hz and 0.6 V on all legs of the Trillium 240. Since the Trillium 240 is a UVW instrument, this should result in only a signal on the vertical channel. The horizontal channels should not have any output. The Q330M+ was configured to loopback the calibration on the E channel. The time series are shown in the figure below.

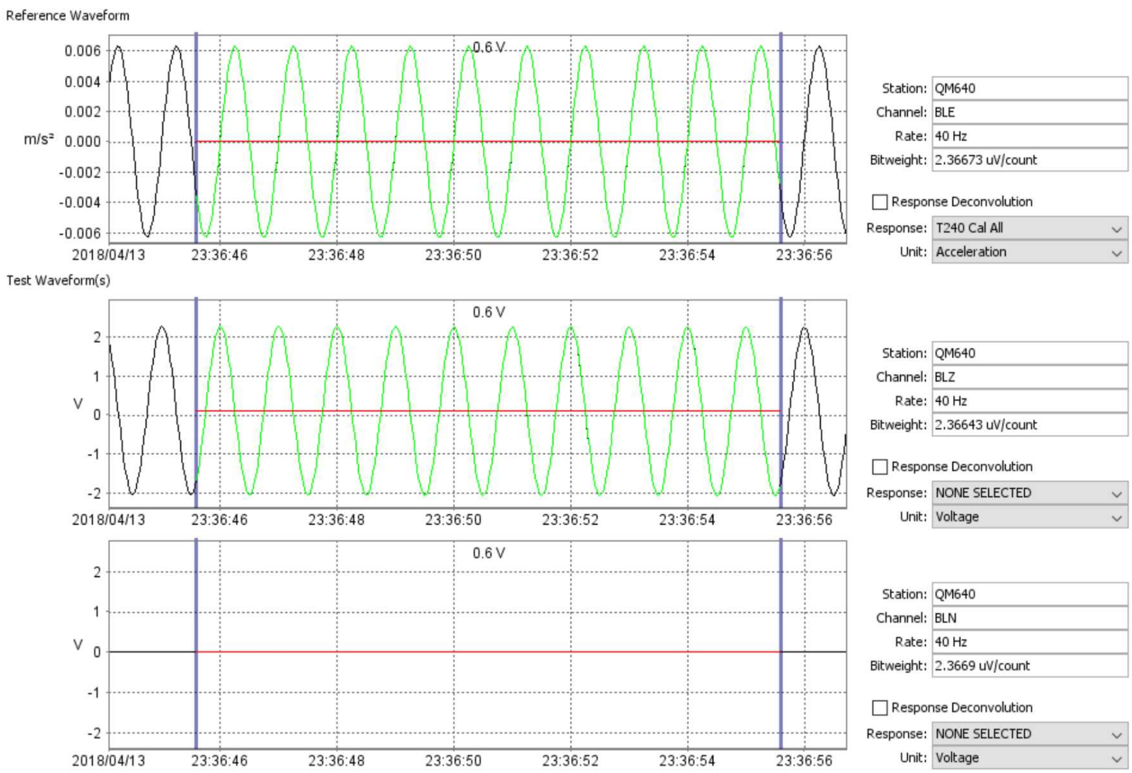


Figure 136 Trillium 240 Sinusoid Calibration Time Series

The Trillium 240 seismometer has a nominal sensitivity of 1200 V/(m/s) and a calibration sensitivity of 0.01 (m/s^2)/V or 100 V/(m/s^2) on each of the UVW legs.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{\sqrt{6}} \cdot \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

Figure 137 Trillium 240 UVW – XYZ Conversion

Since all three UVW legs combine to form the Z output, a calibration on all legs will result in a combined calibration sensitivity of 3 * √2 / √6 * 0.01 (m/s^2)/V or 0.0173 (m/s^2)/V or 57.735 V/(m/s^2).

Using these nominal values for the calibration coil, the 0.6 V and 1 Hz sinusoidal signal input to the calibration coil resulted in a measured sensing coil sensitivity of 1240 V/(m/s). This value is within 3.3% of the nominal sensitivity.

3.22.4 Kinematrics STS-2

The Q330M+ #6641 was connected to a Kinemetrics STS-2 seismometer and operated to collect site background noise and a sine calibration as described in the following sections. The digitizer channel was configured for a gain of 1x.

3.22.4.1 Site Background

The STS-2 seismometer and Q330M+ digitizer collected background signal as shown in the power spectra plot below:

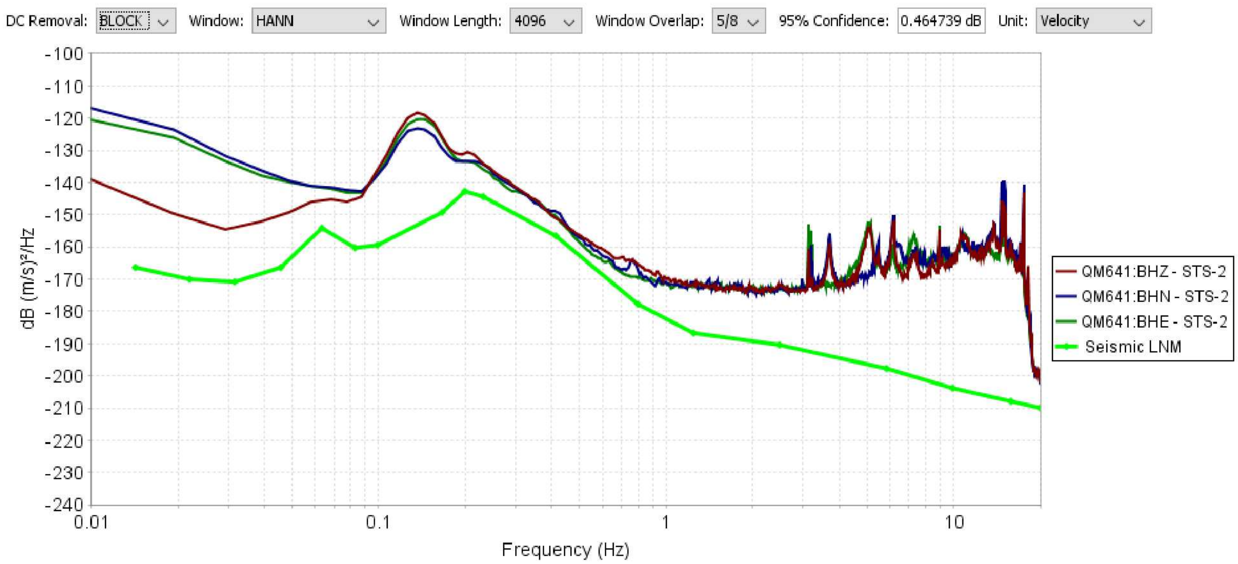


Figure 138 STS-2 Background Power Spectra

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

3.22.4.2 Sinusoid Calibration

A sinusoid calibration was performed using the Q330M+ digitizer at 1 Hz and 1.25 V on all of legs of the STS-2. Since the STS-2 is a UVW instrument, this should result in only a signal on the vertical channel. The horizontal channels should not have any output. The Q330M+ was configured to loopback the calibration on the Z channel of port B. The time series are shown in the figure below.

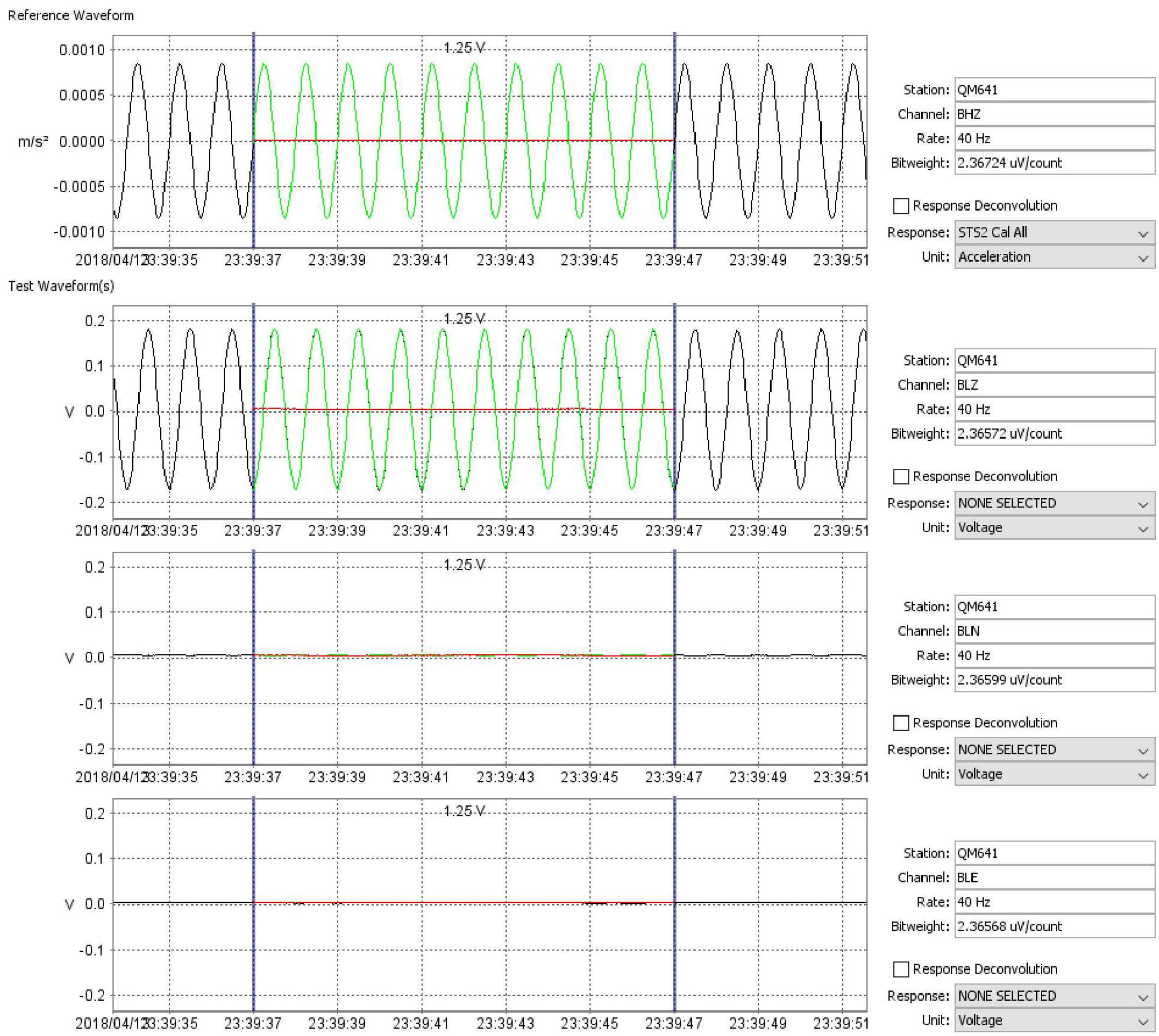


Figure 139 GS21 Sinusoid Calibration Time Series

The STS-2 seismometer has a nominal sensitivity of 1500 V/(m/s) and a calibration sensitivity of 0.002 g/mA on each of the UVW legs, which has a calibration coil resistance of 30 ohms each.

$$X = -\sqrt{(2/3)}\,U + \sqrt{(1/6)}\,V + \sqrt{(1/6)}\,W$$
$$Y = \sqrt{(1/2)}\,V - \sqrt{(1/2)}\,W$$
$$Z = \sqrt{(1/3)}\,U + \sqrt{(1/3)}\,V + \sqrt{(1/3)}\,W$$

Figure 140 STS-2 UVW – XYZ Conversion

In addition, the STS-2 cable provided by Kinemetrics includes a 49.9 kohm resistor in series with each of the seismometer calibration inputs. Since all three UVW legs combine to form the Z output, a calibration on all legs will result in a combined calibration sensitivity of $\sqrt{3}$ * 0.002 g/mA. This is equivalent to a calibration sensitivity of 1470 V/(m/s^2).

Using these nominal values for the calibration coil, the 1.25 V and 1 Hz sinusoidal signal input to the calibration coil resulted in a measured sensing coil sensitivity of 1301 V/(m/s). This value is within 15% of the nominal sensitivity.

3.22.5 Guralp CMG-3T

The Q330M+ #6641 was connected to a Guralp CMG-3T Seismometer, T39680, and operated to collect site background noise and a sine calibration as described in the following sections. The digitizer channel was configured for a gain of 1xL. The calibration sheet for T39680 provided by Guralp is shown below.

CMG-3T CALIBRATION SHEET

WORKS ORDER:	F036286	DATE:	21-Mar-2017
SERIAL NUMBER:	T39680	TESTED BY:	S. Goddard

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 745	2581	0.02581
NORTH/SOUTH	2 x 750	615	0.02276
EAST/WEST	2 x 747	621	0.02299

Power Consumption: 65mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.

Figure 141 Guralp CMG-3T #T39680 Calibration Sheet

3.22.5.1 Site Background

The CMG-3T seismometer and Q330M+ digitizer collected background signal as shown in the power spectra plot below:

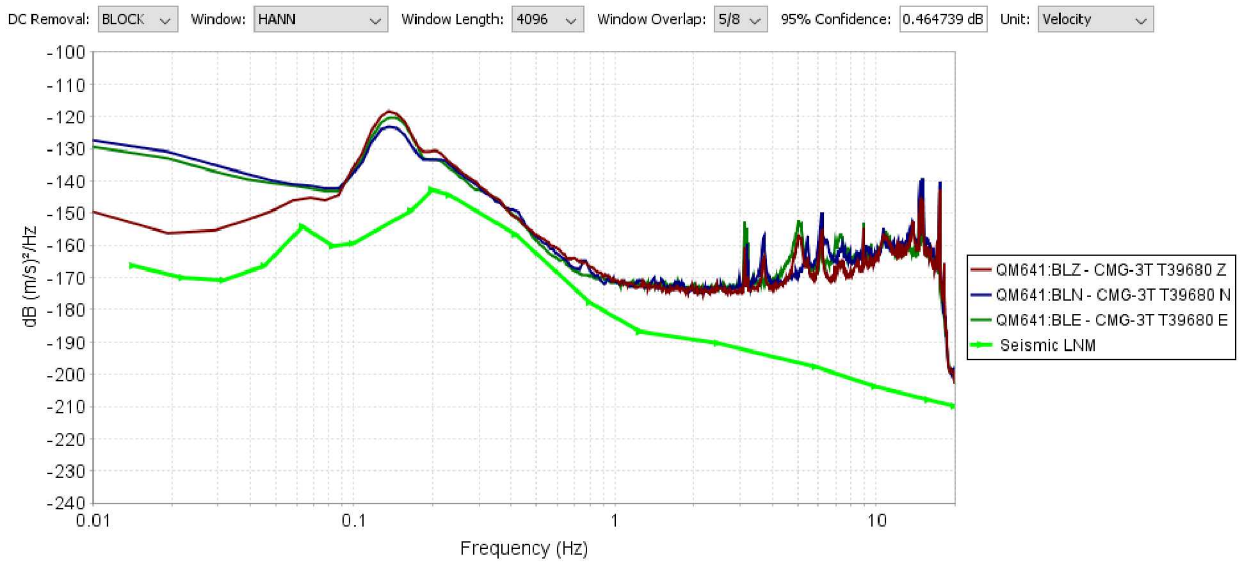


Figure 142 STS-2 Background Power Spectra

The power spectra has been scaled by sensitivities in the calibration sheet, nominally 1500 V/(m/s), and properly represents the local site noise, indicating that the seismometer and digitizer are collecting valid signals.

3.22.5.2 Sinusoid Calibration

A sinusoid calibration was performed using the Q330M+ digitizer at 1 Hz and 0.3125 V on all axes of the CMG-3T. The Q330M+ was configured to loopback the calibration on the E channel of port B. The time series are shown in the figure below.

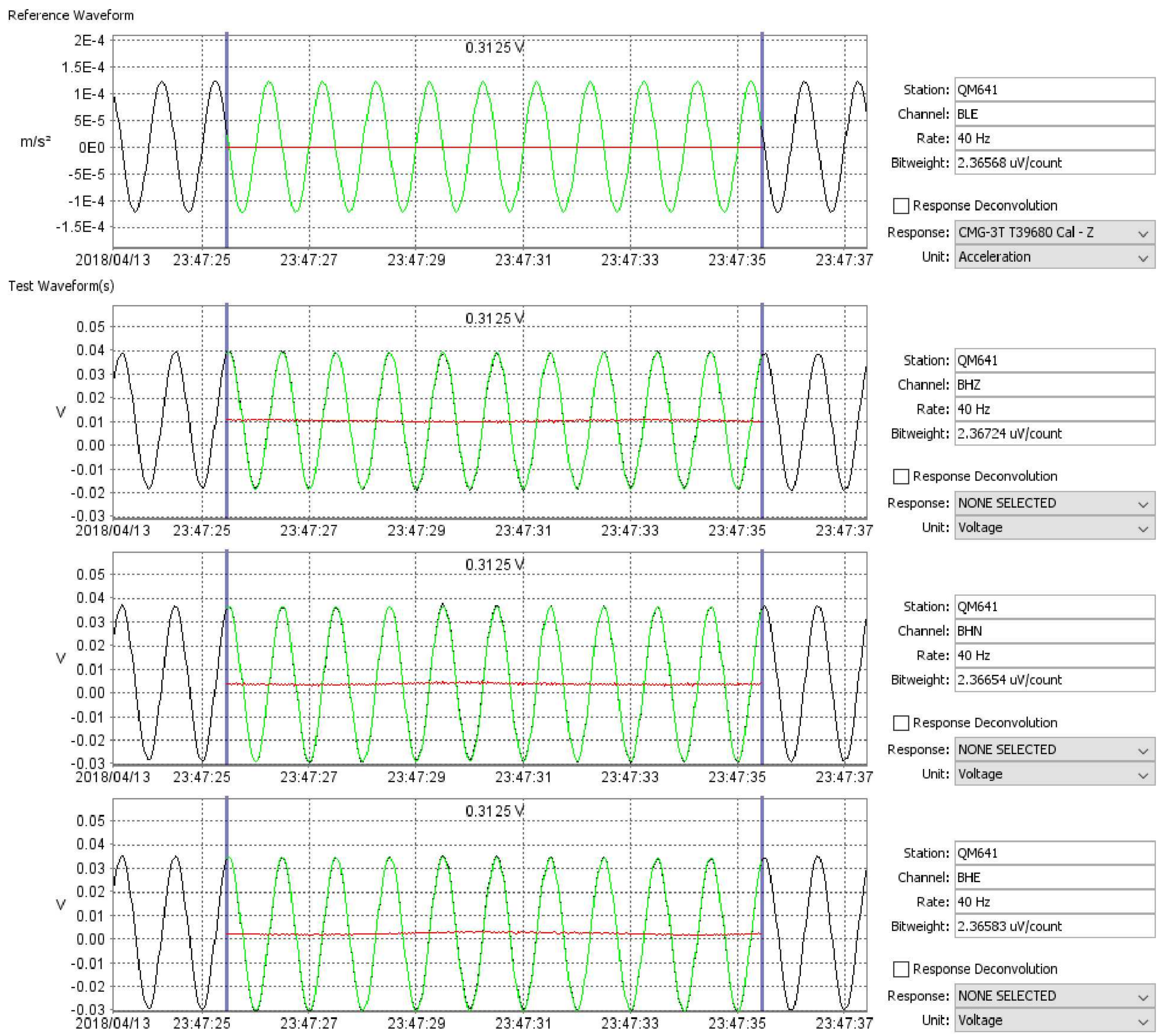


Figure 143 GS21 Sinusoid Calibration Time Series

The CMG-3T seismometer has a nominal sensitivity of 1500 V/(m/s) and a feedback coil constant of 0.02581 A/(m/s^2), 0.02276 A/(m/s^2), and 0.02299 A/(m/s^2) for each of the vertical, north, and east axes, respectively. Each coil has a calibration resistance of 51 kohms. In addition, the Q330M+ to CMG-3T cable provided by Kinemetrics has a series resistor in line with the incoming calibration signal of 16.2 kohms. This incoming calibration signal is split within the sensor between the three axes when performing a calibration on all of them simultaneously.

These calibration constants and resistor impedances result in a calibration sensitivities of 2570 V/(m/s^2), 2267 V/(m/s^2), and 2290 V/(m/s^2) for each of the vertical, north, and east axes, respectively when performing a calibration on all axes simultaneously.

Using these nominal values for the calibration coil, the 1 Hz and 0.3125 V sinusoidal signal input to the calibration coil resulted in a measured sensing coil sensitivity of 1482.5 V/(m/s), 1490.5 V/(m/s), and 1481.4 V/(m/s) for each of the vertical, north, and east axes, respectively. These values are all within 1% of the sensitivities in the calibration sheet for this seismometer.

3.22.6 MB2005

The Q330M+ #6640 was connected to an MB2005 #5107 infrasound sensor on channel 2, as shown in the figure below. The digitizer channel was configured for a gain of 1x

Figure 144 MB2005 infrasound sensor

The MB2005 was operated to collect site background noise and compared against a co-located MB3a. The collected background signals for a 10 hours period with the sensor ports open are shown in the plots below:

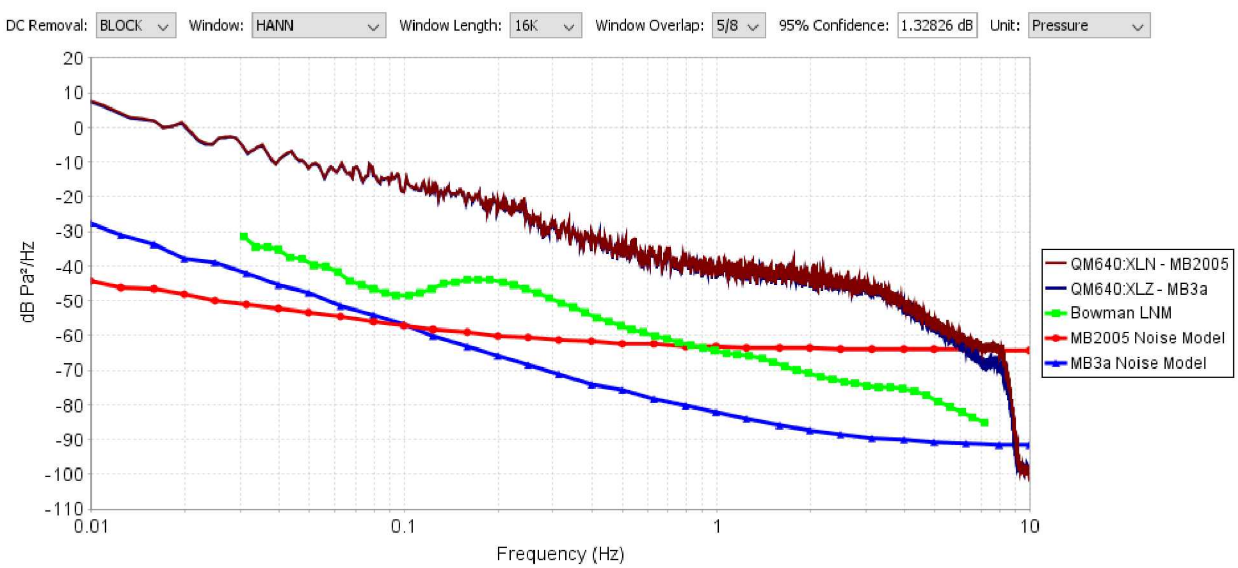


Figure 145 MB3a and MB2005 Open Background Power Spectra

The data collected for 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 with the exception of the MB2005 elevated noise floor at higher frequencies.

3.22.7 MB3a

The Q330M+ #6640 was connected to an MB3a #00117 infrasound sensor on channel 1, as shown in the figure below. The digitizer channel was configured for a gain of 1x.

Figure 146 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.

3.22.7.1 Site Background

The MB3a was operated to collect site background noise and compared against a co-located MB2005. The collected background signals for a 10 hours period with the sensor ports open are shown in the plots below:

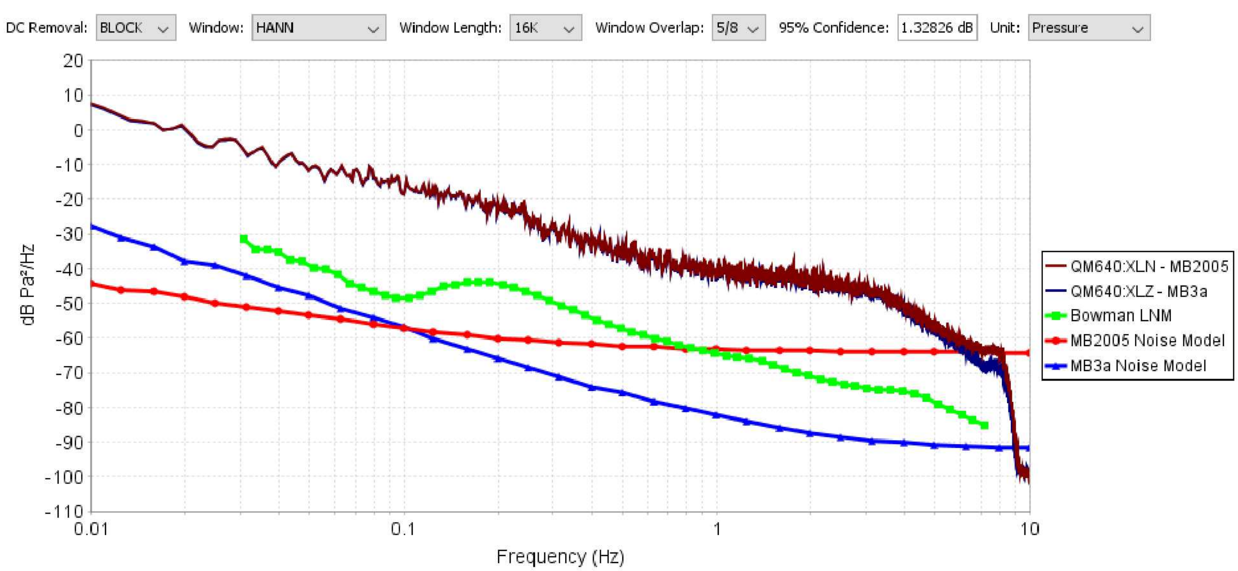


Figure 147 MB3a and MB2005 Open Background Power Spectra

The data was collected for 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 with the exception of the MB2005 elevated noise floor at higher frequencies.

3.22.7.2 Sine Calibration

A sine calibration was performed using the Q330M+ #6640 digitizer to generate a 1 Hz sinusoid at output amplitudes of 0.313 V. The Q330M+ supports a maximum of 5 V amplitude from the calibrator output. Note that the Q330M+ calibrator output is differential and the MB3a calibrator input is single ended, therefore the response was adjusted accordingly.

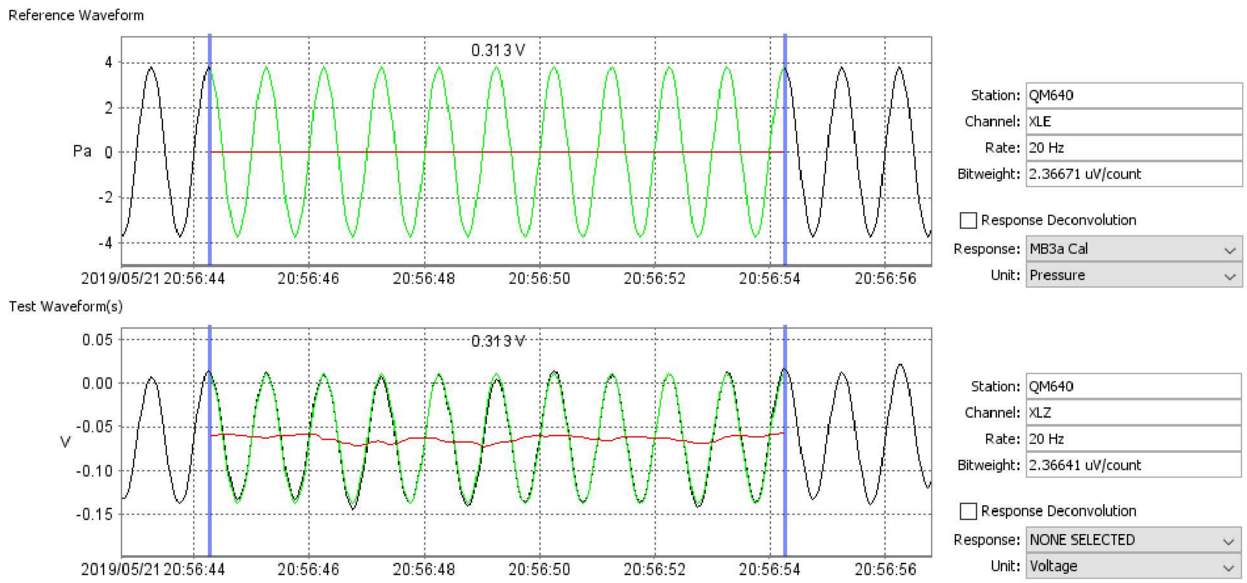


Figure 148 MB3a Sine Calibration Time Series

Computing the ratio of the sensor voltage output and the calibration pressure results in an observed MB3a sensitivity at 1 Hz of 19.78 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 Q330M+ was able to generate a calibration signal that matched very closely with the theoretical MB3a response at 1 Hz.

3.22.7.3 White Noise Calibration

A broadband calibration was performed using the Q330M+ 6640 digitizer to generate a white noise signal with an amplitude of 5 V and a corner frequency of 20.833 Hz. The coherence between a separate recording of the calibration signal and the sensor output was calculated to determine the relative amplitude response.

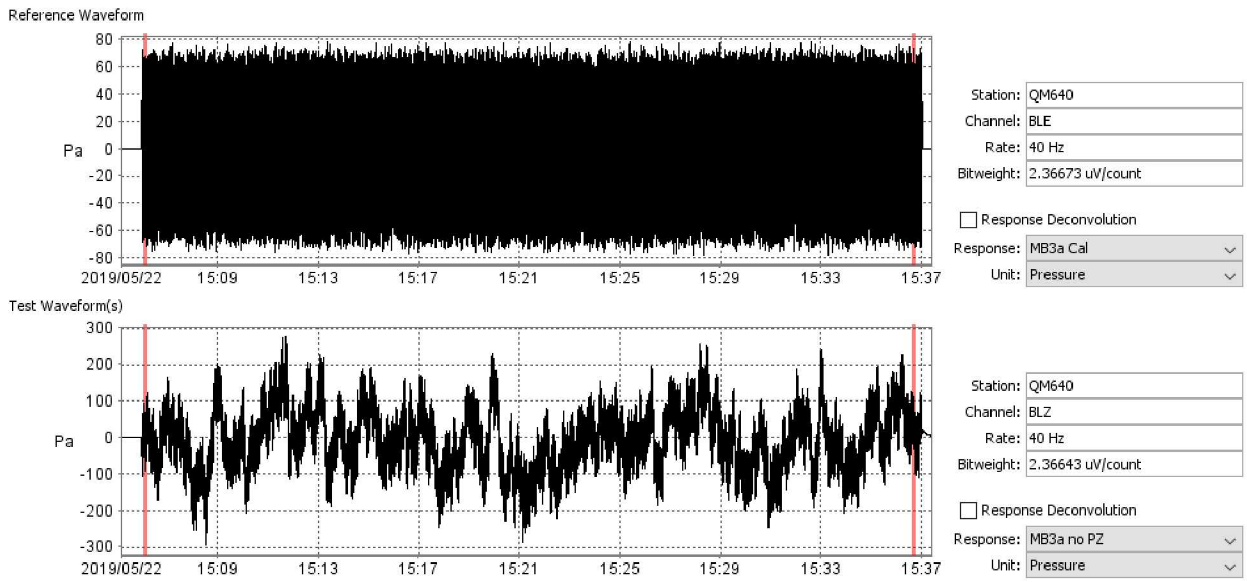


Figure 149 MB3a White Noise Calibration Time Series

The MB3a calibrator sensitivity was applied to the input calibration signal to convert it from voltage to pressure, accounting for the single ended versus differential signal. Computing the power spectra of both the calibration signal and the sensor output, there is good agreement between the two except for signals below 1 Hz where the background noise is above the calibration signal.

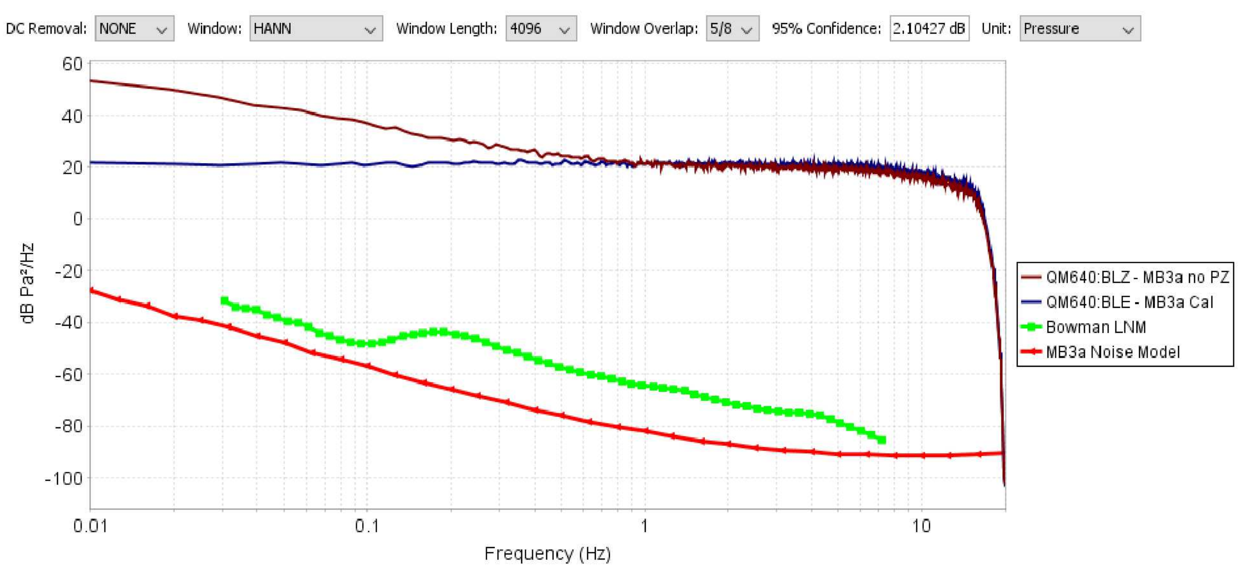


Figure 150 MB3a White Noise Calibration Power Spectra

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

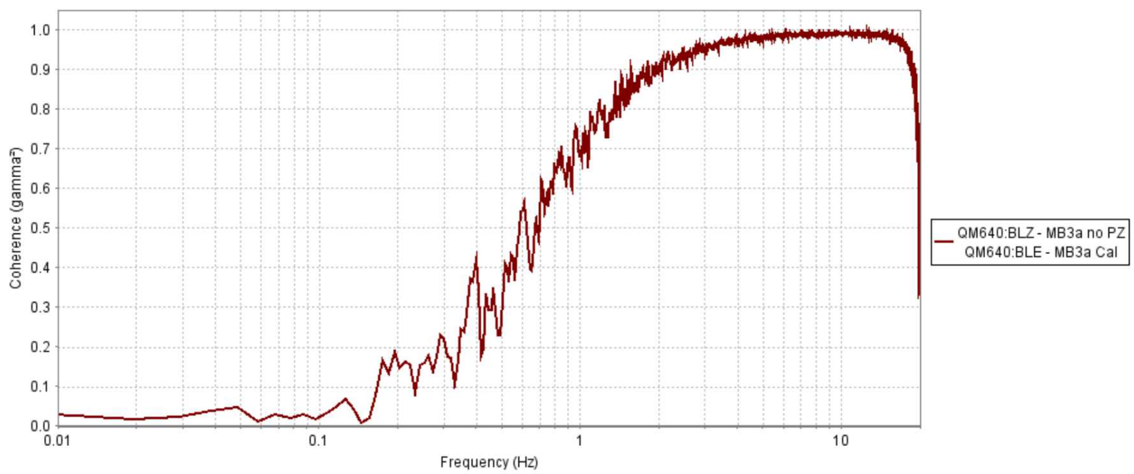


Figure 151 MB3a White Noise Calibration Coherence

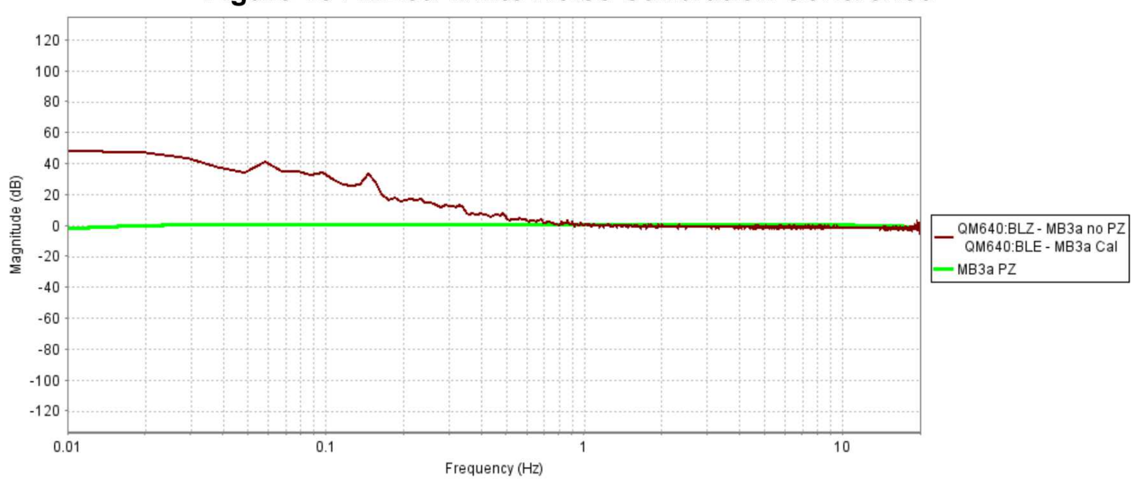


Figure 152 MB3a White Noise Calibration Relative Amplitude

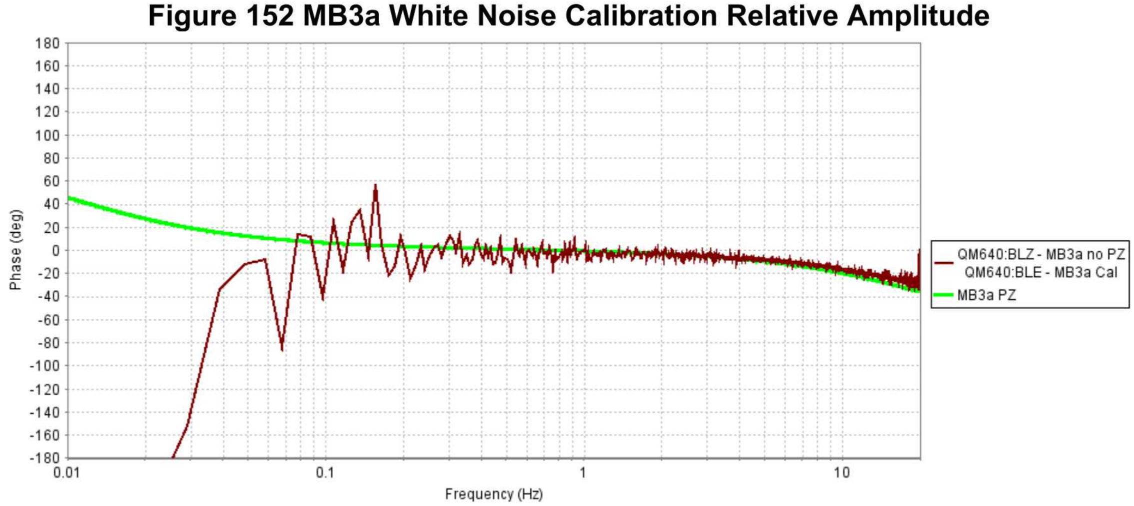


Figure 153 MB3a White Noise Calibration Relative Phase

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, discounting the frequency region where the coherence is reduced due to background noise.

The reduced signal coherence at low frequencies is evidence that a spectrally flat white noise is not an optimal broadband signal for calibrating an infrasound sensor in the presence of background noise.

3.22.7.4 Red Noise Calibration

A broadband calibration was performed using the Q330M+ 6640 digitizer to generate a red noise signal with an amplitude of 5 V and a corner frequency of 20.833 Hz. The coherence between a separate recording of the calibration signal and the sensor output was calculated to determine the relative amplitude response.

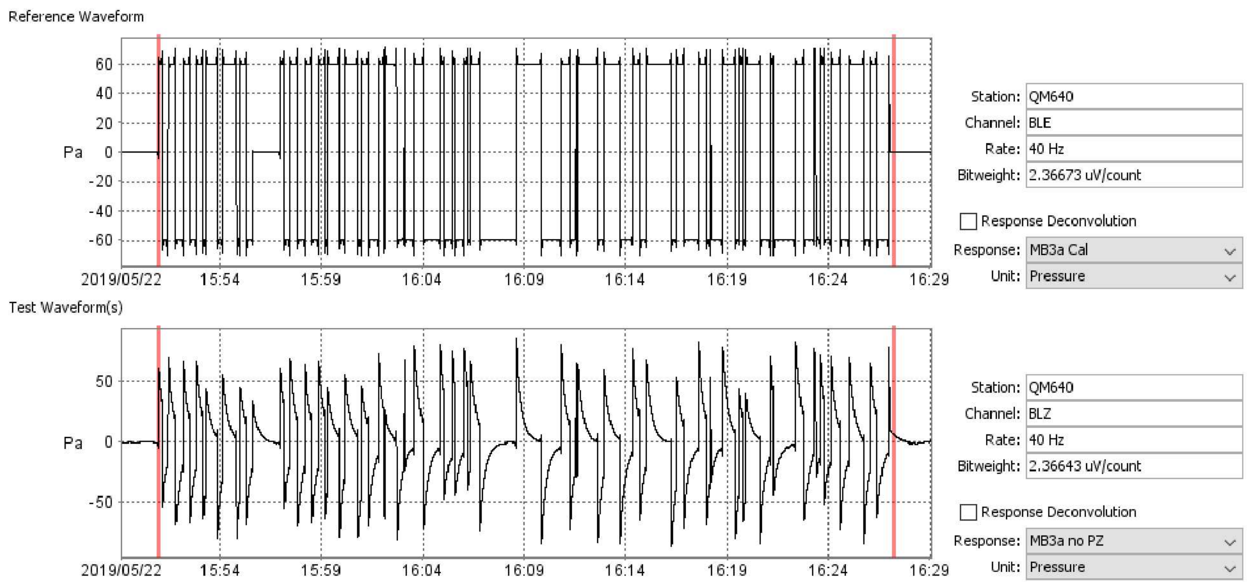


Figure 154 MB3a Red Noise Calibration Time Series

Examining the time series from the Q330M+ calibrator, it is apparent that the implemented red noise calibration signal uses a type of random binary signal generation. The MB3a calibrator sensitivity was applied to the input calibration signal to convert it from voltage to pressure, accounting for the single ended versus differential signal.

Computing the power spectra of both the calibration signal and the sensor output, there is good agreement between the two except for a shift in amplitude that was not apparent in the white noise signal.

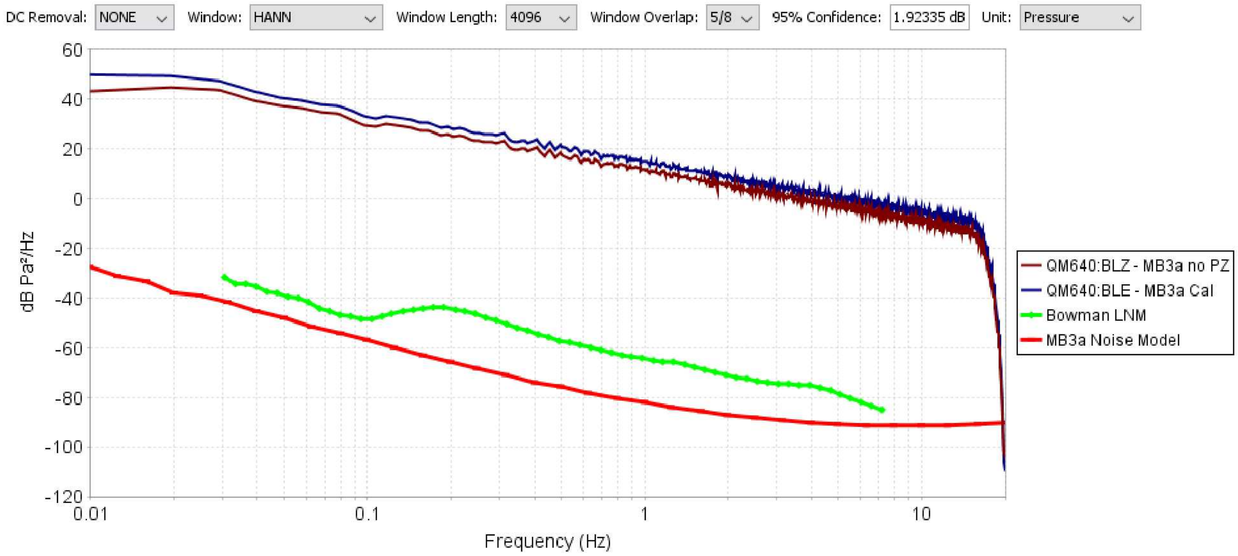


Figure 155 MB3a Red Noise Calibration Power Spectra

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

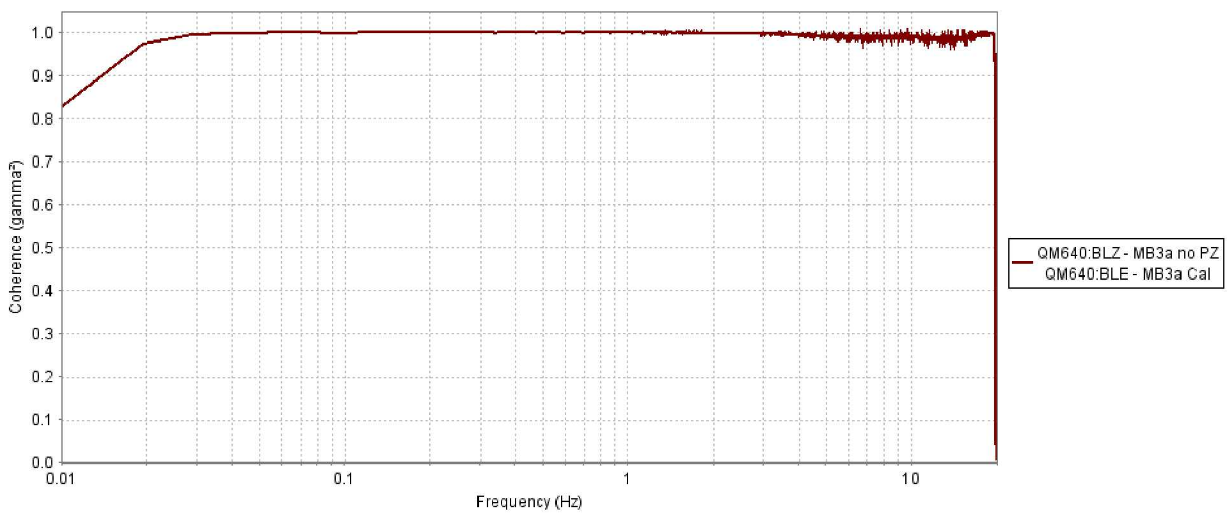


Figure 156 MB3a Red Noise Calibration Coherence

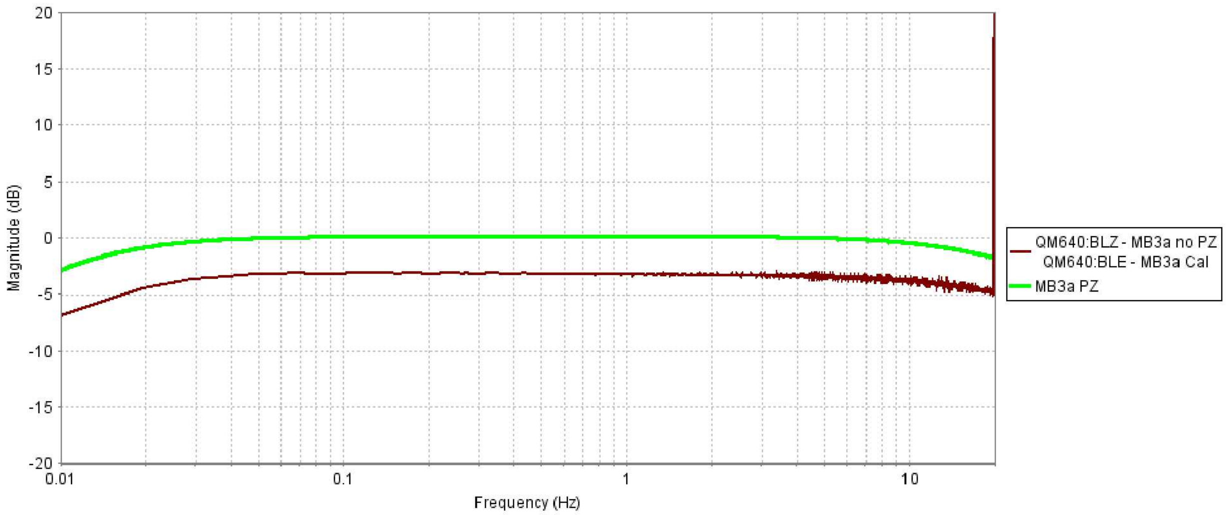


Figure 157 MB3a Red Noise Calibration Relative Amplitude

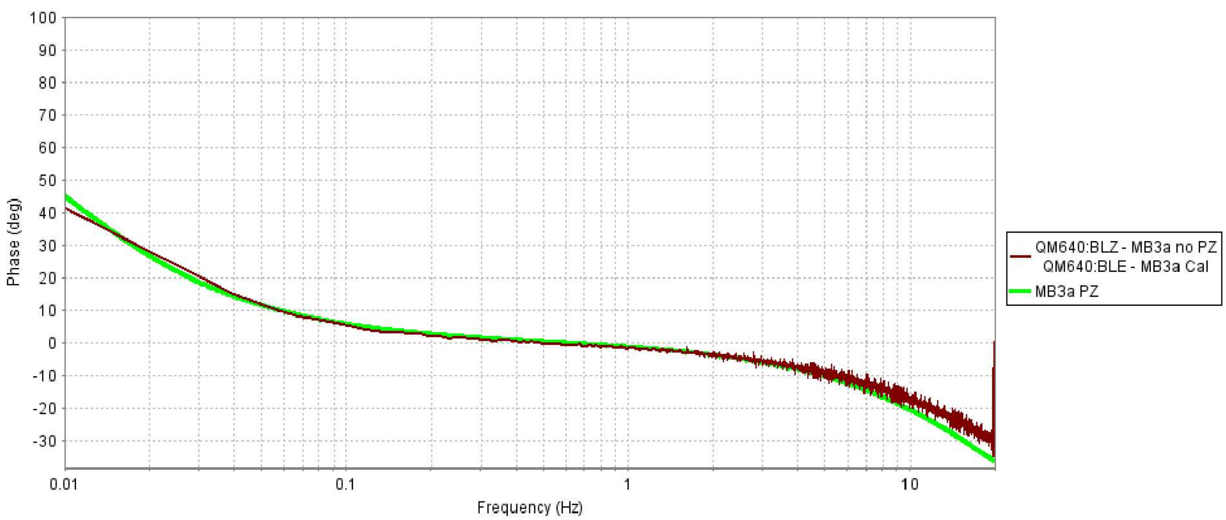


Figure 158 MB3a Red Noise Calibration Relative Phase

Unlike with the white noise signal, the red noise signal contains more power at lower frequency and is able to generate sufficient signal amplitude above the background noise for the calibration signal to be visible across the frequency passband.

The relative amplitude response between calibration signal and the MB3a output matches the expected shape of the MB3a response except that it is offset by approximately 3 dB across the passband. It is unknown why there was a difference in the relative amplitude results between the white noise and red noise calibrations.

3.22.8 Weather Station

The Q330M+ digitizer supports acquisition of data from a weather station through the Auxiliary Channel Processor (ACP) module. The ACP module was connected to Q330M+ #6640 for this evaluation. Both analog and digital weather stations are supported.

Figure 159 Q330M+ Auxiliary Channel Processor

As shown in the figure above, the ACP provides an external interface box with connections for a digital weather station and connections for discrete analog weather sensors, including barometric pressure, temperature, and wind speed and direction.

Both a digital and analog weather stations were connected to the ACP, as shown in the figures below.

Figure 160 Digital Weather Station, Vaisala WXT536

The digital weather station, a Vaisala WXT536 is a compact, multi-parameter weather sensor that provides measurements of air temperature, humidity, pressure, rainfall rate, and wind speed and direction. The Q330M+ is able to read the weather data directly from the sensor and integrate the data into the CD1.1 data feed.

Figure 161 Analog Weather Stations Components: Gil 1390 Wind Speed/Direction, Vaisala PTB101B Barometer, and Vaisala HMP45AC Temperature/Humidity Sensors

The analog weather station components, a Gil 1390 Wind Speed/Direction, Vaisala PTB101B Barometer, and Vaisala HMP45AC, are connected to analog inputs on the ACP. The Q330M+ is able to read the analog inputs and integrate the data into the CD1.1 data feed.

The outputs from the two weather stations are shown in the plots below. The weather stations were both installed within the underground bunker, so they were exposed to minimal environmental variations.

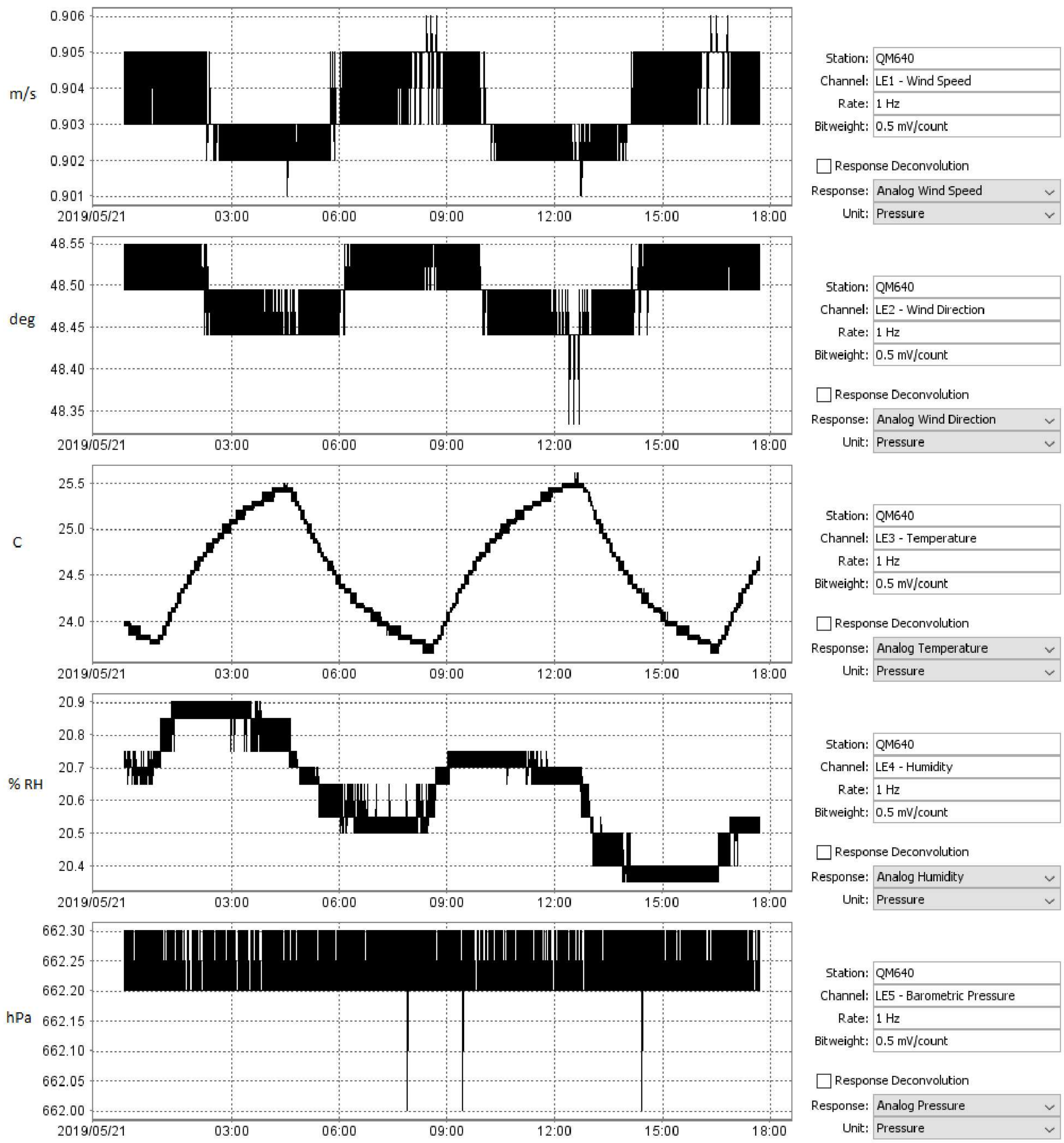


Figure 162 Analog Weather Station

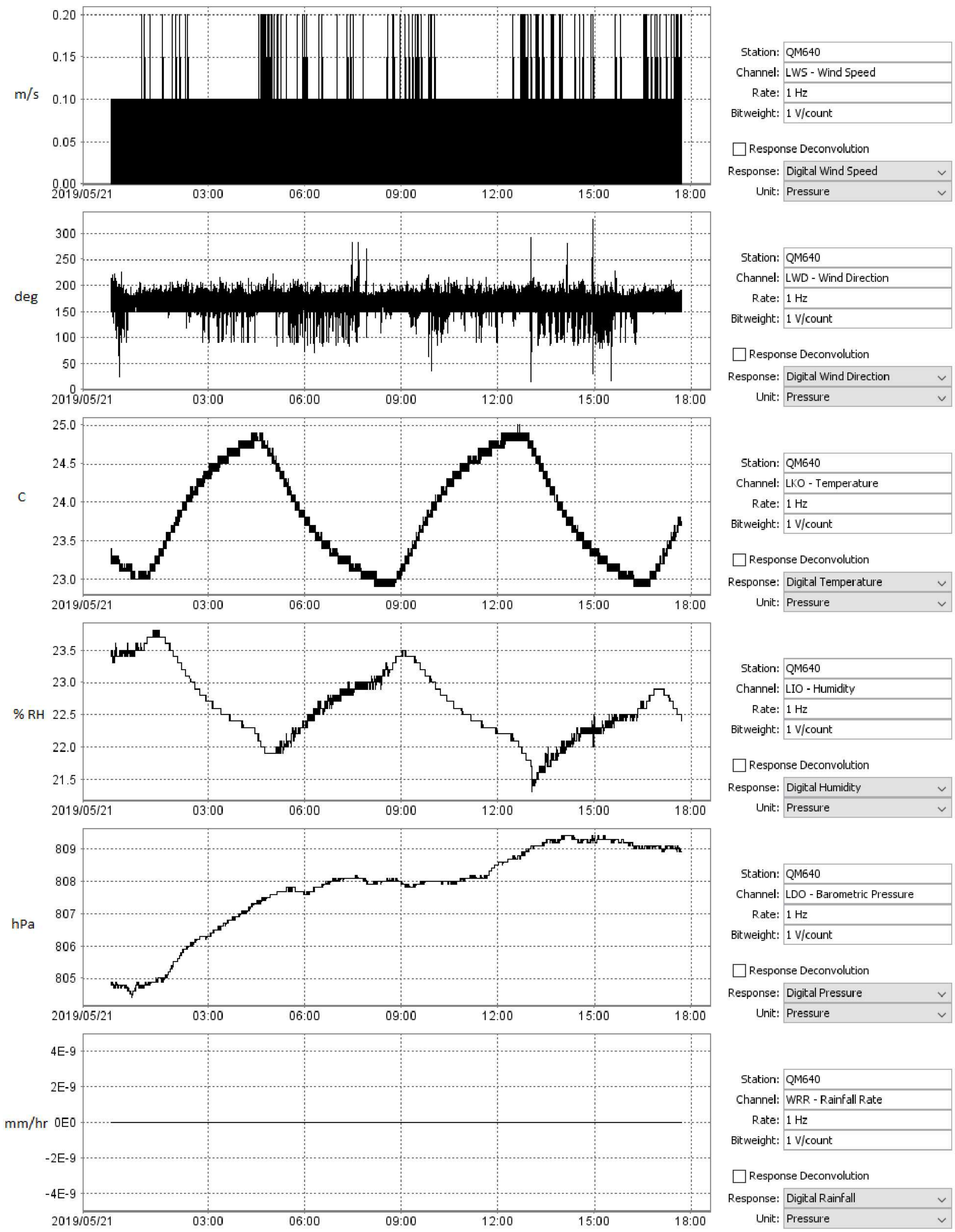


Figure 163 Digital Weather Station

3.23 CD1.1 Status Flag Verification

During the evaluation of the Q330M+ digitizers, the status flags on the CD1.1 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 CD1.1 status flags was performed using both Q330M+ 6640 and 6641. As a baseline, the CD1.1 status flags being reported during normal operation were observed to be:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [1984]
    Packet length (bytes): 404
    Number of samples: 400
    Time stamp: "2018096 18:20:50.000" [1523038850.000000 2018/04/06 18:20:50.000000]
    Authentication offset (bytes): 360
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/
    Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x00 0x00 0x00 "2018096 18:21:19.000" 0
        vault door opened
    Data format: i4
    Data size (bytes): 254
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2084]
    Signature check: [Unknown]
```

The CD1.1 status flags indicate that the relay for the vault door was not connected to anything and that the GPS was locked with 0 micro-seconds of offset. There were no relays connected to the vault door pins; therefore, that flag was being reported.

3.23.1 Calibration underway

A calibration was initiated from the webpage of the Q330M+ 6640 on April 13, 2018 at 15:14 (UTC) to generate a sine calibration signal for several minutes. The following was observed on the CD1.1 status:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2048]
    Packet length (bytes): 396
    Number of samples: 400
    Time stamp: "2018103 15:14:40.000" [1523632480.000000 2018/04/13 15:14:40.000000]
    Authentication offset (bytes): 352
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x08 0x04 0x00 0x00 0x00 0x00 0x00 "2018103 15:15:10.000" 0
        calibration underway
        vault door opened
    Data format: i4
    Data size (bytes): 245
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2148]
    Signature check: [Unknown]
```

The proper *calibration underway* flag was set. At the completion of the calibration signal, the CD1.1 status flags reverted to the baseline condition:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2048]
    Packet length (bytes): 396
    Number of samples: 400
    Time stamp: "2018103 15:22:50.000" [1523632970.000000 2018/04/13 15:22:50.000000]
    Authentication offset (bytes): 352
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x00 0x00 0x00 "2018103 15:23:25.000" 0
        vault door opened
    Data format: i4
    Data size (bytes): 245
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2148]
    Signature check: [Unknown]
```

3.23.2 GPS Unlocked

Both the Q330M+ 6640 and 6641 GPS antennas were covered with metal foil and placed within a steel cabinet, without disconnecting the antennas from the digitizers, to recreate conditions in which the GPS antenna did not have reception. The drift test was initiated on December 10, 2018 at 22:37 UTC. At 22:37 UTC, Q330M+ 6640 reported that its GPS receiver was unlocked with a last lock time of 22:35 UTC.

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2508]
    Packet length (bytes): 680
    Number of samples: 800
    Time stamp: "2018344 22:37:00.000" [1544481420.000000 2018/12/10 22:37:00.000000]
    Authentication offset (bytes): 636
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x00 0x00 0x00 "2018344 22:35:00.000" 4
        vault door opened
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 530
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2608]
    Signature check: [Unknown]
```

Similarly, at 22:37 UTC, Q330M+ 6641 reported that its GPS receiver was unlocked with a last lock time of 22:35 UTC

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2624]
    Packet length (bytes): 680
    Number of samples: 800
    Time stamp: "2018344 22:37:00.000" [1544481420.000000 2018/12/10 22:37:00.000000]
    Authentication offset (bytes): 636
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x00 0x00 0x00 "2018344 22:35:00.000" 4
        vault door opened
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 531
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2724]
    Signature check: [Unknown]
```

3.23.3 GPS Unlocked (PTP)

Both the Q330M+ 6640 and 6641 were configured for PTP time synchronization and the PTP master's GPS antenna was covered with metal foil and placed within a steel cabinet, without disconnecting the antenna, to recreate conditions in which the GPS antenna did not have reception. The drift test was initiated on December 12, 2018 at 19:46 UTC. At 19:47 UTC, Q330M+ 6640 reported that its GPS receiver was unlocked with a last fix time of 19:46 UTC.

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2544]
    Packet length (bytes): 704
    Number of samples: 800
    Time stamp: "2018346 19:47:20.000" [1544644040.000000 2018/12/12 19:47:20.000000]
    Authentication offset (bytes): 660
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x00 0x00 0x00 "2018346 19:46:00.000" 5
        vault door opened
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 555
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2644]
    Signature check: [Unknown]
```

Similarly, at 19:47 UTC, Q330M+ 6641 reported that its GPS receiver was unlocked with a last fix time of 19:45 UTC.

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2660]
    Packet length (bytes): 704
    Number of samples: 800
    Time stamp: "2018346 19:47:20.000" [1544644040.000000 2018/12/12 19:47:20.000000]
    Authentication offset (bytes): 660
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x00 0x00 0x00 "2018346 19:45:00.000" 5
        vault door opened
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 555
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2760]
    Signature check: [Unknown]
```

3.23.4 GPS Drift

Both the Q330M+ 6640 and 6641 were time synchronized to GPS and allowed to drift from December 10, 2018 at 22:37 UTC until December 12, 2018 at 17:00 UTC. The digitizers correctly reported during the entire drift test that its last lock time occurred at 22:37 UTC on December 10, 2018 and the estimate of the timing offset increased throughout the drift period.

The clock differential too large flag was first set on Q330M+ 6640 and 6641 at December 11, 2018 at 03:34:20 UTC when the estimate of clock offset transitioned to 500 microseconds.

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2540]
    Packet length (bytes): 704
    Number of samples: 800
    Time stamp: "2018345 03:34:20.000" [1544499260.000000 2018/12/11 03:34:20.000000]
    Authentication offset (bytes): 660
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x05 0x00 0x00 0x00 0x00 "2018344 22:36:00.000" 500
        vault door opened
        clock differential too large
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 555
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2640]
    Signature check: [Unknown]
```

At the end of the drift period, the CD1.1 status flags were reporting a timing offset of 4,242 microseconds, indicating a presumed drift rate of 100 microseconds per hour.

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2516]
    Packet length (bytes): 680
    Number of samples: 800
    Time stamp: "2018346 17:00:00.000" [1544634000.000000 2018/12/12 17:00:00.000000]
    Authentication offset (bytes): 636
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x05 0x00 0x00 0x00 0x00 "2018344 22:36:00.000" 4242
        vault door opened
        clock differential too large
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 530
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2616]
    Signature check: [Unknown]
```

The GPS antennas were uncovered, allowing the Q330M+ digitizers GPS receivers to regain lock, on December 12, 2018 at 17:13 UTC. It was not until 17:24:20 UTC that the CD1.1 status flags indicated the time offset had returned to 0 microseconds and not until 17:25:00 UTC that the GPS receiver was no longer unlocked:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2544]
    Packet length (bytes): 704
    Number of samples: 800
    Time stamp: "2018346 17:24:20.000" [1544635460.000000 2018/12/12 17:24:20.000000]
    Authentication offset (bytes): 660
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x00 0x00 0x00 "2018346 17:23:00.000" 0
        vault door opened
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 554
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2644]
    Signature check: [Unknown]
```

3.23.5 GPS Drift (PTP)

Both the Q330M+ 6640 and 6641 were time synchronized to a PTP master and allowed to drift from December 12, 2018 at 19:47 UTC until December 14, 2018 at 20:45 UTC. The digitizers correctly reported during the entire drift test that its last lock time occurred at 19:47 UTC on December 12, 2018 and the estimate of the timing offset increased throughout the drift period.

The clock differential too large flag was first set on Q330M+ 6640 and 6641 at December 11, 2018 at 03:34:20 UTC when the estimate of clock offset transitioned to 500 microseconds:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2544]
    Packet length (bytes): 704
    Number of samples: 800
    Time stamp: "2018347 00:44:20.000" [1544661860.000000 2018/12/13 00:44:20.000000]
    Authentication offset (bytes): 660
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x05 0x00 0x00 0x00 0x00 "2018346 19:46:00.000" 500
        vault door opened
        clock differential too large
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 555
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2644]
    Signature check: [Unknown]
```

At the end of the drift period, the CD1.1 status flags were reporting a timing offset of 4,909 microseconds, indicating a presumed drift rate of 100 microseconds per hour:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2512]
    Packet length (bytes): 680
    Number of samples: 800
    Time stamp: "2018348 20:50:00.000" [1544820600.000000 2018/12/14 20:50:00.000000]
    Authentication offset (bytes): 636
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x05 0x00 0x00 0x00 0x00 "2018346 19:46:00.000" 4909
        vault door opened
        clock differential too large
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 530
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2612]
    Signature check: [Unknown]
```

The GPS antenna on the PTP master was uncovered, allowing the Q330M+ digitizers to regain lock, on December 14, 2018 at 20:45 UTC. It was not until 20:50:20 UTC that the CD1.1 status flags indicated the time offset had returned to 0 microseconds:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2668]
    Packet length (bytes): 704
    Number of samples: 800
    Time stamp: "2018348 20:50:20.000" [1544820620.000000 2018/12/14 20:50:20.000000]
    Authentication offset (bytes): 660
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x04 0x04 0x00 0x00 0x00 0x00 "2018348 20:48:00.000" 0
        vault door opened
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 555
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2768]
    Signature check: [Unknown]
```

It was not until 20:51:00 UTC that the status flag indicated that the GPS receiver was no longer unlocked:

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2624]
    Packet length (bytes): 680
    Number of samples: 800
    Time stamp: "2018348 20:51:00.000" [1544820660.000000 2018/12/14 20:51:00.000000]
    Authentication offset (bytes): 636
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x00 0x00 0x00 "2018348 20:49:00.000" 0
        vault door opened
    Data format: i4
    Data size (bytes): 530
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2724]
    Signature check: [Unknown]
```

3.23.6 GPS Off

To evaluate the GPS Off status flag, the GPS antenna on Q330M+ 6640, which was synchronized to GPS, was physically disconnected on December 12, 2018 at 18:26 UTC. The CD1.1 status flags updated to reflect that the GPS was off and that the GPS receiver was unlocked.

```
Channel # [7]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [2508]
    Packet length (bytes): 680
    Number of samples: 800
    Time stamp: "2018346 18:26:00.000" [1544639160.000000 2018/12/12 18:26:00.000000]
    Authentication offset (bytes): 636
    Subframe Time Length (mS): 20000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM640/BLZ/00
    Channel status: 32/0x01 0x00 0x04 0x06 0x00 0x00 0x00 0x00 "2018346 18:24:00.000" 4
        vault door opened
        GPS receiver off
        GPS receiver unlocked
    Data format: i4
    Data size (bytes): 530
    Subframe count: 0
    Authentication Key ID: 137
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.000000]
    Data offset (bytes): [2608]
    Signature check: [Unknown]
```

3.23.7 Tamper Switches

In order to test the CD1.1 status flags for the tampering, tamper switches were installed on Q330M+ 6641 on April 12, 2018.

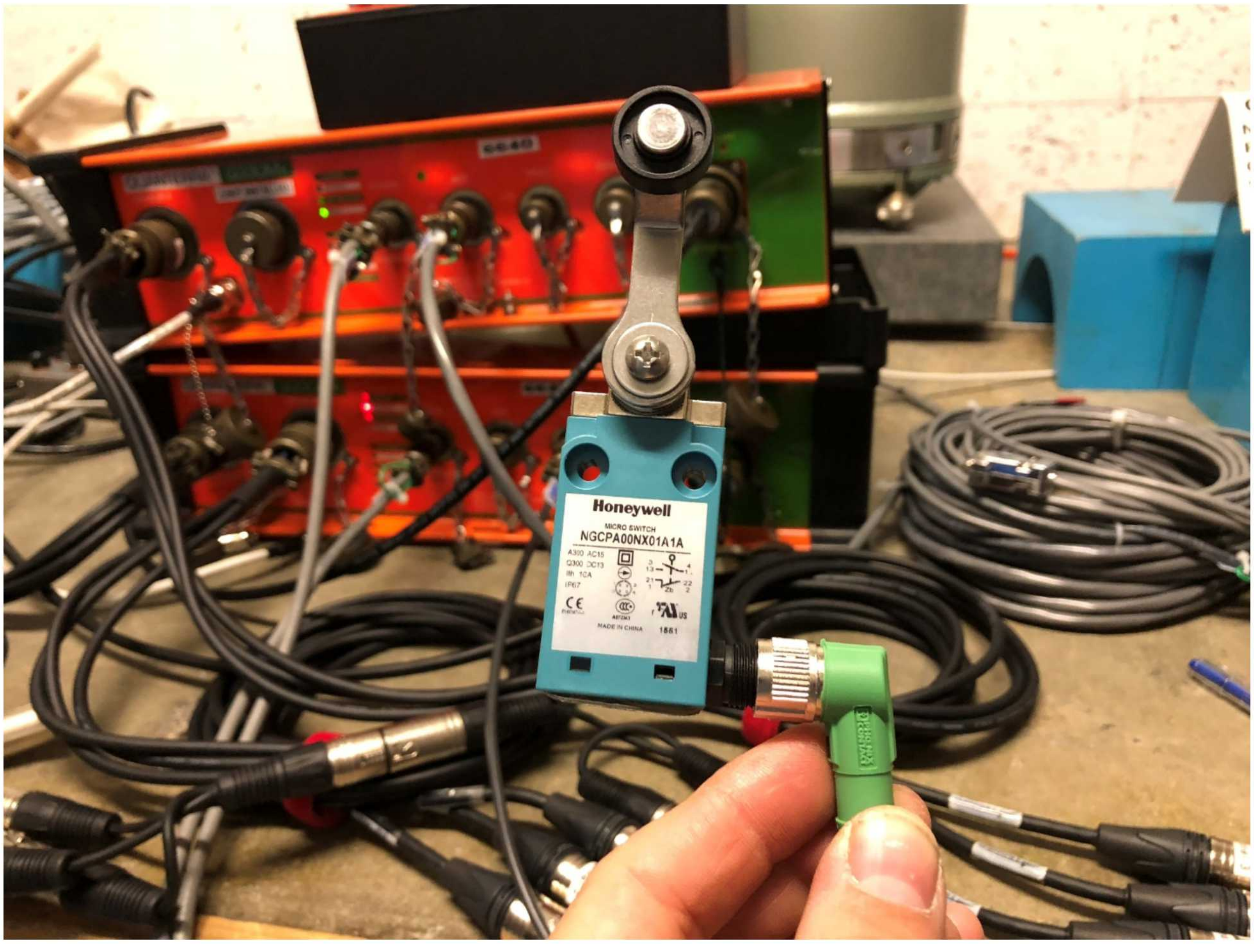


Figure 164 Q330M+ Tamper Switch

Note that just prior to testing the tamper switches, the GPS antenna had been disconnected, so the CD1.1 flag GPS receiver off was also being reported during some of the tamper tests.

At 16:38:30 UTC, the vault door switch was installed on the Q330M+ and closed, resulting in the clearing of the Vault Door Opened flag:

```
Channel # [2]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [1080]
    Packet length (bytes): 396
    Number of samples: 400
    Time stamp: "2018102 16:38:50.024" [1523551130.024000 2018/04/12 16:38:50.023999]
    Authentication offset (bytes): 352
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x00 0x02 0x00 0x00 0x00 0x00 "2018102 16:35:10.000" 0
        GPS receiver off
    Data format: i4
    Data size (bytes): 248
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.015000]
    Data offset (bytes): [1180]
    Signature check: [Unknown]
```

At 16:40:50 UTC the vault door switch was opened, resulting in the setting of the Vault Door Opened flag:

```
Channel # [2]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [1092]
    Packet length (bytes): 396
    Number of samples: 400
    Time stamp: "2018102 16:40:50.024" [1523551250.024000 2018/04/12 16:40:50.023999]
    Authentication offset (bytes): 352
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x04 0x02 0x00 0x00 0x00 0x00 "2018102 16:35:11.000" 0
        vault door opened
        GPS receiver off
    Data format: i4
    Data size (bytes): 248
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.015000]
    Data offset (bytes): [1192]
    Signature check: [Unknown]
```

At 16:43:20 UTC, the Q330M+ equipment case was opened, resulting in the setting of the Digitizing Equipment Open flag. Note that the vault door switch was left opened as well:

```
Channel # [2]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [1084]
    Packet length (bytes): 400
    Number of samples: 400
    Time stamp: "2018102 16:43:20.024" [1523551400.024000 2018/04/12 16:43:20.023999]
    Authentication offset (bytes): 356
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x06 0x00 0x00 0x00 0x00 0x00 "2018102 16:43:34.000" 0
        digitizing equipment open
        vault door opened
    Data format: i4
    Data size (bytes): 251
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.015000]
    Data offset (bytes): [1184]
    Signature check: [Unknown]
```

At 16:45:50 UTC, the Q330M+ equipment case was closed, resulting in a clearing of the Digitizer Equipment Open flag:

```
Channel # [2]:
    Channel parsing code: [0x0]
    Channel offset (bytes): [1084]
    Packet length (bytes): 396
    Number of samples: 400
    Time stamp: "2018102 16:45:50.024" [1523551550.024000 2018/04/12 16:45:50.023999]
    Authentication offset (bytes): 352
    Subframe Time Length (mS): 10000
    Nominal sample rate (s/sec): [40.000000]
    Authentication switch: 1 [on]
    Compression: 1 [Canadian before signing]
    Sensor type: 0 [Seismic]
    Calibration factor (nm/count): 1
    Calibration period (sec): 1.000000
    Site/Channel/Location names: QM641/BHZ/00
    Channel status: 32/0x01 0x00 0x04 0x00 0x00 0x00 0x00 0x00 "2018102 16:46:08.000" 0
        vault door opened
    Data format: i4
    Data size (bytes): 247
    Subframe count: 0
    Authentication Key ID: 135
    Authentication size (bytes): 40
    Diff from nominal time (sec): [0.015000]
    Data offset (bytes): [1184]
    Signature check: [Unknown]
```

In this examination of the CD1.1 tamper flags, both of the Vault Door Opened and Digitizing Equipment Open flags appear to be reported properly.

4 SUMMARY

Power Consumption
The Q330M+ digitizer was found to consume between 3.27 and 3.31 watts of power for a 3-channel configuration and between 3.61 and 3.67 watts of power for a 6-channel configuration. These power consumption levels were measured while simultaneous recording of 20 Hz, 40 Hz, and 100 Hz sample rates, internal recording, network data streaming, enabled authentication card, and continuous GPS operation.

Input Impedance
The Q330M+ digitizer channels were found to have an input impedance that were all consistently at 156.9 kOhms for gains of 1x, 2x, 4x, and 8xH, which is 4.6% higher than the nominal 150 kOhms. The input impedance for gains of 8xL, 16x, and 32x were all consistently at 1.998 Mohms, which is 0.10% lower than the nominal 2.0 Mohms.

DC Accuracy
The Q330M+ digitizer channels were found to have bit-weights that were consistent with the nominal values to within 0.23% of the nominal values across the 20 Hz, 40 Hz, and 100 Hz sample rates and gains of 1x, 2x, 4x, 8xH, 8xL, 16x, and 32x

AC Accuracy
The Q330M+ digitizer channels were found to have bit-weights that were consistent with the nominal values to within 0.84% of the nominal values across the 20 Hz, 40 Hz, and 100 Hz sample rates and gains of 1x, 2x, 4x, 8xH, 8xL, 16x, and 32x.

AC Full Scale
The Q330M+ digitizer channels could fully resolve peak-to-peak amplitudes at or about their full scale of +/- 20 V, +/- 10 V, +/- 5 V, +/- 2.5 V, +/- 2.5 V, +/- 1.25 V, and +/- 0.625 V at gains of 1x, 2x, 4x, 8xH, 8xL, 16x, and 32x, respectively, across the 20 Hz, 40 Hz, and 100 Hz sample rates and.

AC Over Scale
The Q330M+ digitizer channels all were determined to have a full-scale amplitude that exceeded the nominally specified full scale across the 20 Hz, 40 Hz, and 100 Hz sample rates by 7% at gains of 1x, 2x, 4x, and 8xH and 0.5% at gains of 8xL, 16x, and 32x.

Input Shorted Offset
The Q330M+ digitizer channels were observed to have a small offset that was largely driven by ambient temperature. Changes in terminating resistor, sample rate, and gain were not observed to impact the offset measured in counts.

Self-Noise
The Q330M+ digitizers were observed to have noise free bits at a gain of 1x of 23.05 bits, 22.66 bits, and 22.04 bits at sample rates of 20 Hz, 40 Hz, and 100 Hz, respectively. There does not appear to be any observed change in self-noise levels by adjusting the terminating resistor from 50 ohms to 9.4 kohm, with the exception of at a gain of 32x which may be due to a difference in

the digitizer channels and not due to the terminator. Increasing gains levels from 1x to 2x, 4x, 8xL, 16x, and 32x resulted in reductions in noise levels by 4.92 dB, 8.22 dB, 18.78 dB, 23.81 dB, and 29.94 dB. Interestingly, there is slightly elevated noise levels at a gain of 4x, relative to 1x, than would be expected. However, noise levels at gains above 4x are in-line with theoretical expectations. In addition, PSD levels are quite flat across the frequency passband, with minimal increase at low frequencies.

Dynamic Range
At 100 Hz sampling rate the dynamic ranges varied from as low as 128.8 dB at a gain of 4x up to 132.6 dB at other gain levels. At 40 Hz, dynamic ranges varied from as low as 132.7 dB at a gain of 4 x up to 136.4 dB at other gain levels. At 20 Hz, dynamic ranges varied from as low as 135.5 dB at a gain of 4x up to 139.5 dB at other gain levels. The quoted dynamic ranges are computed using the self-noise measured across the entire frequency passband up to the Nyquist rate.

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 Q330M+ digitizer channels exhibited no observable change in self-noise power spectra levels at temperatures between -10 C and 40 C. There was a predictable change in DC offset as a function of temperature of approximately 16 to 17 counts per degree Celsius. Otherwise, the digitizers continued to operate as expected at these temperature extremes.

Response Verification
The Q330M+ 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 between channels.

Relative Transfer Function
The Q330M+ digitizer channels exhibited less than +/- 5 microsecond of timing skew from channel to channel.

Analog Bandwidth
The Q330M+ digitizer channels exhibited a bandwidth of between 80.5% and 82.8% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, and 100 Hz. Bandwidth was not observed to vary with gain level.

Total Harmonic Distortion
The observed harmonic distortion ranged between a high level of -114.5 dB to -118.8 dB at gains of 1x and 2x to as low as -118 to -128 dB at higher gain levels. The observed THD at gains of 1x and 2x appear to be limited by the signal quality of the reference signal.

Modified Noise Power Ratio

The Q330M+ digitizer channels exhibited a modified noise power ratio, measured at a sample rate of 100 Hz and gains of 1x and 8xL, indicating that both digitizers perform consistently with just under 22 bits of linear performance across the range of amplitudes.

Common Mode Rejection

The Q330M+ digitizer channels exhibited common mode rejection ratios of between 80 and 114.5 dB. As expected, the common mode levels were unchanged for each unique physical digitizer channel and did not vary with sample rate or gain.

Crosstalk

The Q330M+ digitizer channels exhibited crosstalk that was measured to be better than between -157 dB and -146.85 dB. The measurement was limited due to there being minimal observable crosstalk present on the channel self-noise.

Timing Accuracy

The Q330M+ digitizers were measured to have time tag accuracy values with between -67 and -78 microseconds, with similar results for both GPS and PTP time synchronization. Note that it took approximately 1 hour for the time tag accuracy to stabilize after a change in timing was made.

Timing Drift

The Q330M+ digitizers observed drift using GPS appeared to be limited to within -350 microseconds over the 2-day period, likely due to the thermal stability of the testing environment the digitizers were in. In contrast, when synchronized to PTP, the digitizers followed the PTP master drift to within -1400 microseconds over the same 2 day period, likely due to the PTP master being located in a less thermally stable environment. Note that although the digitizers began correcting for timing drift soon after the timing source recovered lock, it took approximately 1 hour for the time tag accuracy to fully stabilize.

Calibrator Demonstration

The Q330M+ digitizer demonstrated the ability to accurately generate sinusoids at amplitudes of between 0.156 V and 5.0 V with an amplitude accuracy of better than 1%. Sinusoids with frequencies between 0.1 Hz and 10 Hz were generated with a frequency accuracy of approximately 0.001%. The Q330M+ was confirmed to be able to generate random white noise, red noise, and Pseudo Random Binary with selectable amplitude, pulse width and duration.

Sensor Compatibility Verification

The Q330M+ has been demonstrated to operate with a variety of sensors including a Geotech GS13, Geotech GS21, Nanometrics Trillium 240, Kinemetrics STS-2, Guralp CMG-3T, MB2005, MB3a, and both analog and digital weather stations.

CD1.1 Status Flag Verification

The Q330M+ digitizer successfully demonstrated the transmission of CD1.1 status flags for a calibration underway, GPS receiver unlocked, GPS off, clock differential too large, and the various tamper flags.

REFERENCES

1. Holcomb, Gary L. (1989), *A Direct Method for calculating Instrument Noise Levels in Side-by-Side Seismometer Evaluations*, DOI USGS Open-File Report 89-214.

2. IEEE Standard for Digitizing Waveform Recorders, IEEE Std. 1057-1994.

3. IEEE Standard for Analog to Digital Converters, IEEE Std. 1241-2010.

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

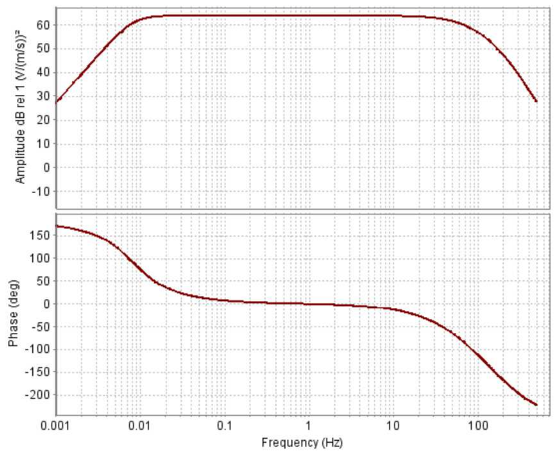
5. McDonald, Timothy S. (1994), *Modified Noise Power Ratio Testing of High Resolution digitizers*, SAND94-0221.

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

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

APPENDIX A: RESPONSE MODELS

Guralp CMG-3T Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

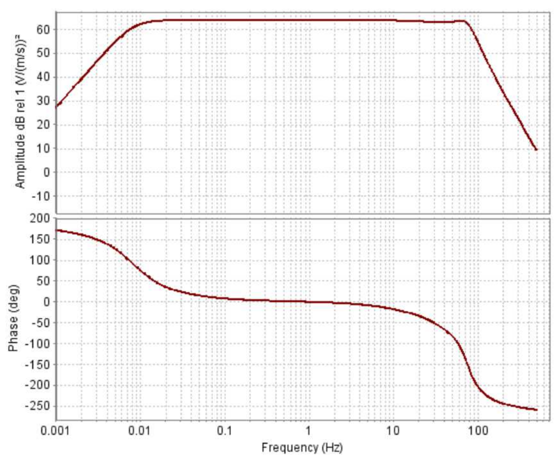
-1130.0	0.0
-1010.0	0.0
-503.0	0.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
861,208.00814 MV·s/m

Kinemetrics STS-2 Low Gain Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

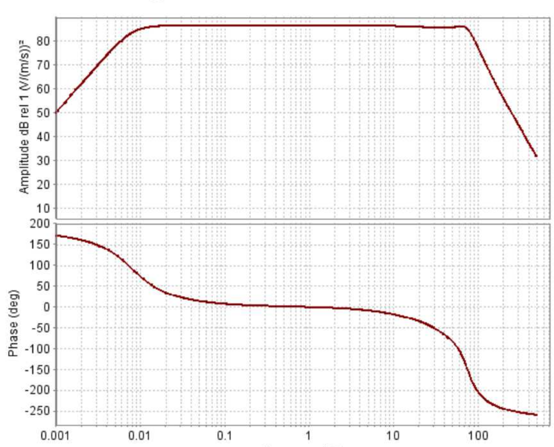
-251.0	0.0
-131.0	467.0
-131.0	-467.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
88,586.67303 MV·s/m

Kinemetrics STS-2 High Gain Seismometer



Sensitivity:
20 kV·s/m at 1.0 Hz

Poles:

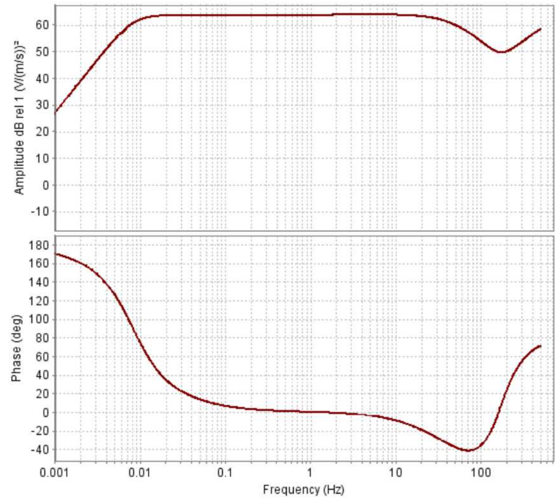
-251.33	0.0
-131.04	467.29
-131.04	-467.29
-0.035647	0.036879
-0.035647	-0.036879

Zeros:

0.0	0.0
0.0	0.0

A:
1.1841199E6 MV·s/m

Kinematics STS-5A Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

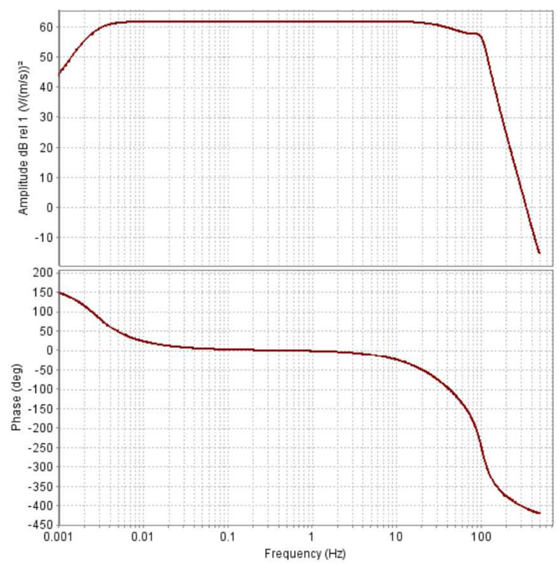
-961.0	0.0
-339.0	116.0
-339.0	-116.0
-16.0	0.0
-16.0	0.0
-0.037	-0.037
-0.037	0.037

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

Kinematics STS-6A Seismometer



Sensitivity:
1,200 V·s/m at 1.0 Hz

Poles:

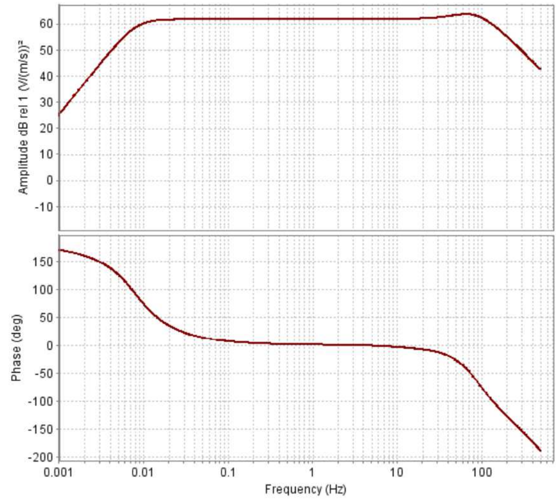
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-351.858	0.0
-121.58	647.231
-121.58	-647.231
-22.3068	0.0
-22.3068	0.0
-0.01231	0.01206
-0.01231	-0.01206

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 240 Seismometer



Sensitivity:
1,200 V·s/m at 1.0 Hz

Poles:

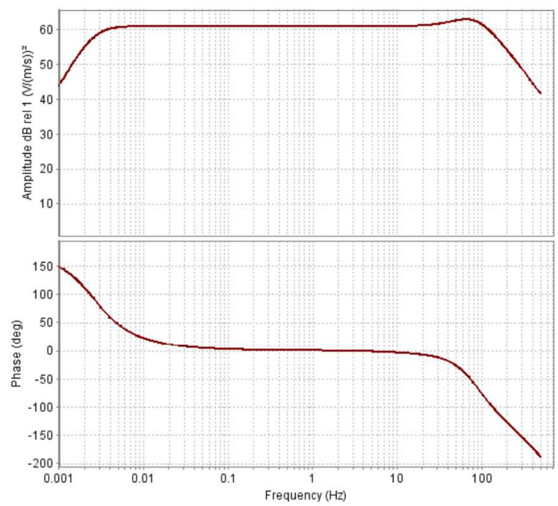
-7100.0	1700.0
-7100.0	-1700.0
-4900.0	5204.0
-4900.0	-5204.0
-1260.0	0.0
-364.0	404.0
-364.0	-404.0
-142.0	0.0
-32.55	0.0
-0.036614	0.037059
-0.036614	-0.037059

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:

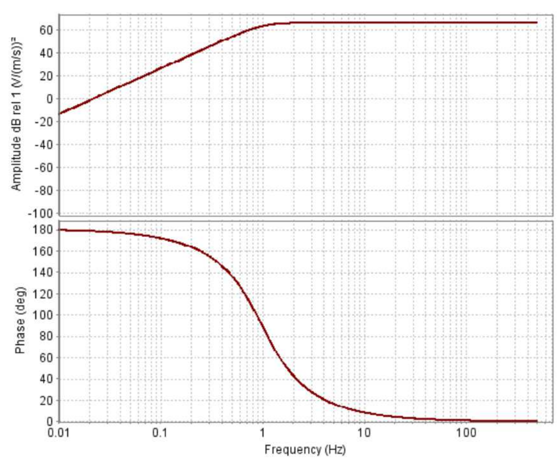
-7200.0	1700.0
-7200.0	-1700.0
-4900.0	5200.0
-4900.0	-5200.0
-1234.0	0.0
-360.0	405.0
-360.0	-405.0
-146.0	0.0
-0.01189	0.01189
-0.01189	-0.01189

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:

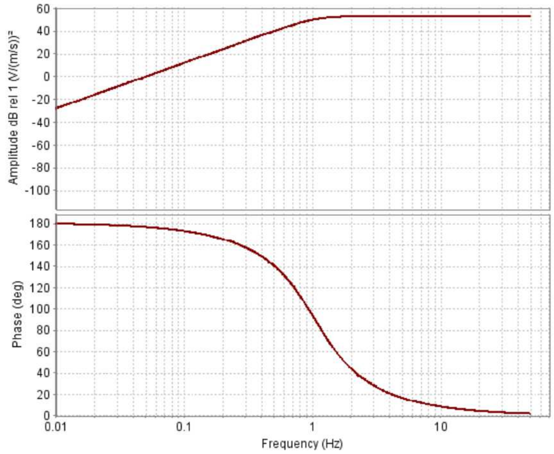
-4.443	4.443
-4.443	-4.443

Zeros:

0.0	0.0
0.0	0.0

A:
2,001.59953 V·s/m

Geotech GS21 Seismometer



Sensitivity:
418 V·s/m at 5.0 Hz

Poles:

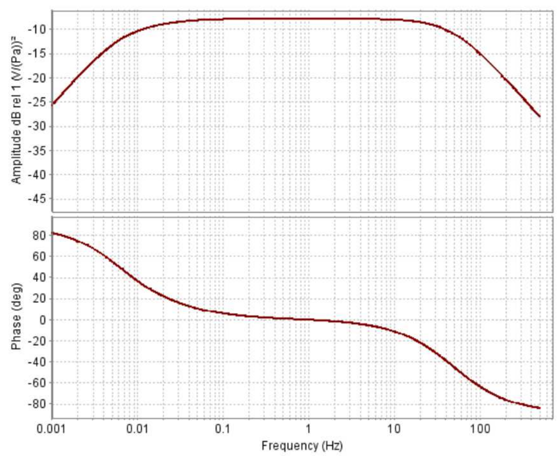
-4.4138	4.9251
-4.4138	-4.9251

Zeros:

0.0	0.0
0.0	0.0

A:
416.38503 V·s/m

Chaparral 50A Infrasound Sensor



Sensitivity:
0.4 V/Pa at 1.0 Hz

Poles:

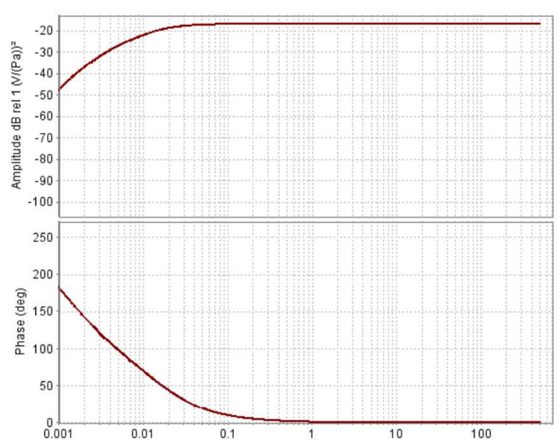
-314.0	0.0
-0.188	0.0
-0.044	0.0
0.0	0.0

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:

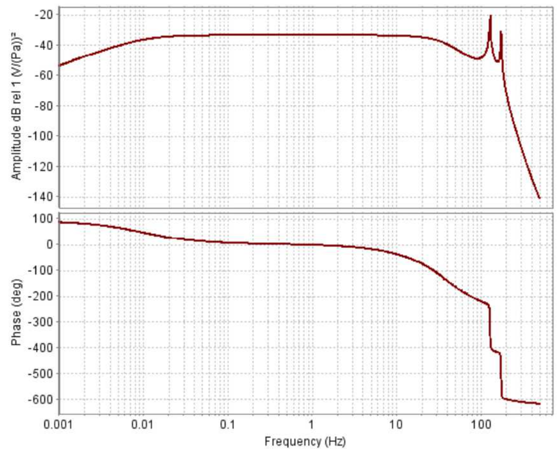
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

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:

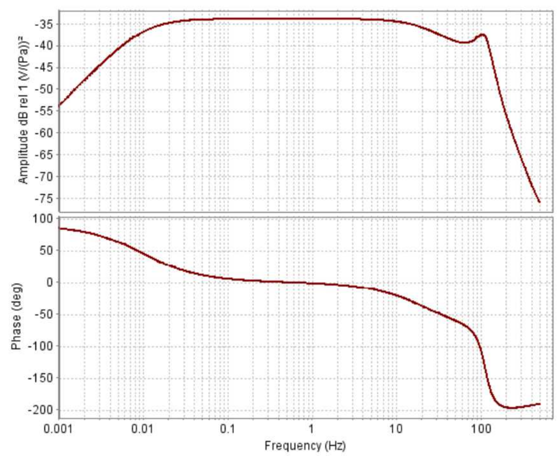
-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.06283	0.0

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

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

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

Page 1 of 8
6652541_11726859

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

AC Current:

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

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

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

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

Calibration Data Report

Primary Electrical Lab

Unit Under Test: Agilent 3458A Digital Multimeter	Test Result: **PASS**
Asset Number: 6652541	Test Type: FOUND-LEFT
Serial Number: MY45048371	Calibration Date: 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

```
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.

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	

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	9.99399	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 *****

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

PRIMARY STANDARDS
LABORATORY
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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:

Chance, Jason
Metrologist

Approved By:

Johnson, Raegan Lynn
QA Representative

End-of-Document

Agilent 3458A # MY45048372

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LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

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

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

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

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

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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	0.9999860	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	0.9999606	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	9.999900	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	1.000487	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	

PRIMARY STANDARDS LABORATORY

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	10.000221	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 *****

Limitations

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

Equipment (Standard) Used

Asset #	Description	Model	Expires
6668991	Standard,Measurement	5790B	June 29, 2017
6664631	Calibrator,Multifunction	5730A	April 25, 2018
6651332	Generator,Function	33250A	February 16, 2018
20174	Amplifier	5725A	August 10, 2017
11123	Resistor,Standard	5155-9	May 10, 2018

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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;
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