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Kinemetrics Q330M+ Digitizer Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated a new digitizer, the Q330M+, manufactured by Quanterra, a division of Kinemetrics Inc. This digitizer is used to record sensor output for seismic and infrasound monitoring applications. The purpose of the digitizer evaluation was to measure the performance characteristics in such areas as sensitivity, input impedance, power consumption, self noise, dynamic range, system noise, relative transfer function, analog bandwidth, modified noise power ratio, harmonic distortion, common mode, cross talk, timing tag accuracy and timing drift. The Q330M+ provides six channels of 24 bit digitization, all of which may be transmitted utilizing CD1.1 protocol, at multiple sample rates.

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ACRONYMS AND DEFINITIONS

BB	Broadband
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
HNM	High Noise Model
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories
SP	Short-period

1 INTRODUCTION

Figure 1 Quanterra Q330M+ digitizer. Photo courtesy of Kinemetrics, Inc.

The evaluation of the digitizer, serial number 036000CACC6030CC, has identified that the unit's performance is consistent with the manufacturer's specifications.

QUANTERRA

A Division of Kinemetrics

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

USA - 2 Shaker Rd. Suite F200, Shirley, MA 01464
Tel (978) 425-2100 I www.kinemetrics.com

04-05-18

Figure 2 Q330M+ Manufacturer Specifications

2 TEST PLAN

2.1 Test Facility

Testing of the Q330M+ digitizer was performed at Sandia National Laboratories' Facility for Acceptance, Calibration and Testing (FACT) located near Albuquerque, New Mexico, USA. The FACT site is at approximately 1830 meters in elevation.

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

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

The majority of the Q330M+ testing were performed within the FACT sites underground bunker due to the bunker's stable temperature.

Figure 3 FACT Site Bunker

Figure 4 Q330M+ installed on the bunker pier.

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

Figure 5 Vaisala temperature monitor within the FACT bunker

A GPS re-broadcaster operates within the bunker to provide the necessary timing source for the Q330M+ digitizer and other recording equipment present.

Figure 6 GPS re-broadcaster

The Q330M+ digitizer was powered by a Protek 3003B DC Power Supply S/N H011919 laboratory power supply providing approximately 14.0 Volts.

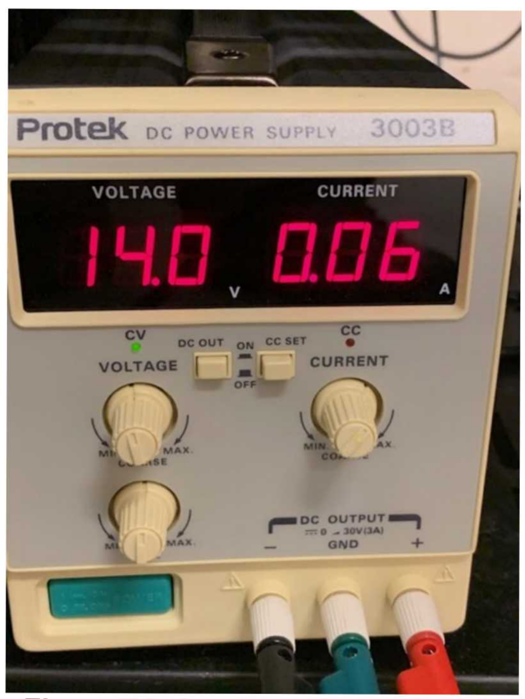


Figure 7 Laboratory Power Supply

2.2 Scope

The following table lists the tests and resulting evaluations that were performed at the various gain levels and sample rates of the Q330M+ digitizer.

Table 1 Tests performed

Test	Gain	Sample Rates (sps)
AC Accuracy	1x, 2, 4x, 8Lx*, 16x and 32x	100, 40 and 20
DC Accuracy	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
AC Full Scale	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
AC Over Scale	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Input Shorted Offset	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Self Noise	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Self Noise (-36°C through 50°C)	1x	100, 40 and 20
Dynamic Range	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
System Noise	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Response Verification	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Relative Transfer Function	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Analog Bandwidth	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Total Harmonic Distortion	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Common Mode	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Cross Talk	1x, 2, 4x, 8Lx, 16x and 32x	100, 40 and 20
Timing Accuracy (GPS-based)	1x	100, 40 and 20
Timing Drift (GPS-based)	1x	100, 40 and 20
Timing Accuracy (PTP-based)	1x	100, 40 and 20
Timing Drift (PTP-based)	1x	100, 40 and 20
Power Consumption	1x	100, 40 and 20

* low voltage input

The channel map utilized is based on the default convention provided the digitizer's configuration parameters and is as follows.

Table 2 Channel Naming Convention

Digitizer Channel	Channel Name		
	100 sps	40 sps	20 sps
1	HLZ	SLZ	BLZ
2	HLN	SLN	BLN
3	HLE	SLE	BLE
4	HHZ	SHZ	BHZ
5	HHN	SHN	BHN
6	HHE	SHE	BHE

This evaluation references data and analysis both by digitizer channel and channel name.

2.3 Timeline

Testing of the Q330M+ digitizer was performed at Sandia National Laboratories between March 6, 2019 and October 15, 2019.

3 TEST EVALUATION

3.1 Input Impedance

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

3.1.1 Measurand

The quantity being measured is ohms of impedance.

3.1.2 Configuration

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

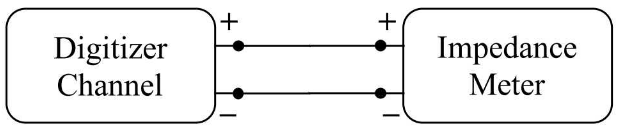


Figure 8 Input Impedance Configuration Diagram

Figure 9 Input Impedance Configuration Picture

Table 3 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Impedance Meter	Agilent 3458A	MY45048371	Ohms

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

3.1.3 Analysis

Measurements of the average impedance from each digitizer input channel are taken from the meter, preferably from a time-series recording:

3.1.4 Result

A representative waveform plot of impedance, acquired from the meter, is shown below. The measured impedance values for each of the digitizer channels are shown in the table below.

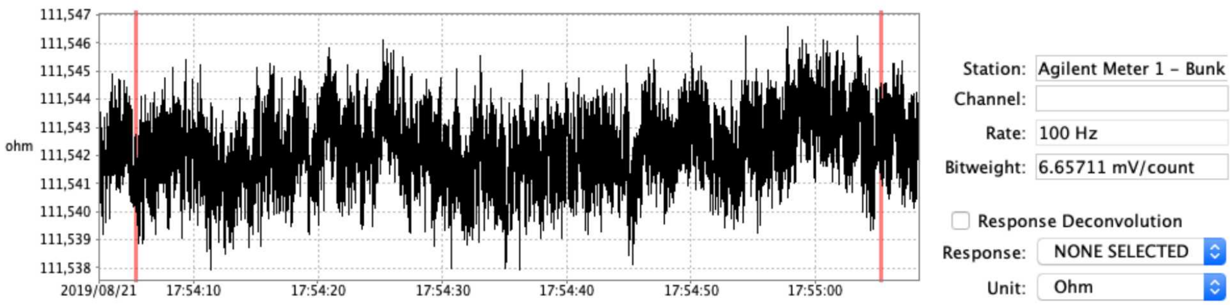


Figure 10 Impedance time series

Table 4 Impedance Results

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm
2x	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm
4x	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm	156.9 kohm

The measured input impedance of the Q330M+ digitizer channels were consistently 156.9 kohm, for settings of 1x through 4x.

3.2 Power Consumption

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

3.2.1 Measurand

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

3.2.2 Configuration

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

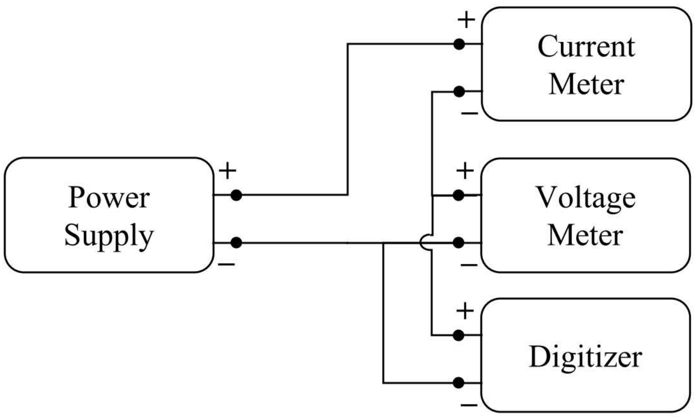


Figure 11 Power Consumption Configuration Diagram

Figure 12 Power Consumption Configuration Picture

Table 5 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
Power Supply	Protek 3003B	H011919	14.0 V
Current Meter	Agilent 3458A	MY45048371	Amps
Voltage Meter	Agilent 3458A	MY45048372	100 V full scale

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

3.2.3 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:

$$P = V * I$$

3.2.4 Result

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

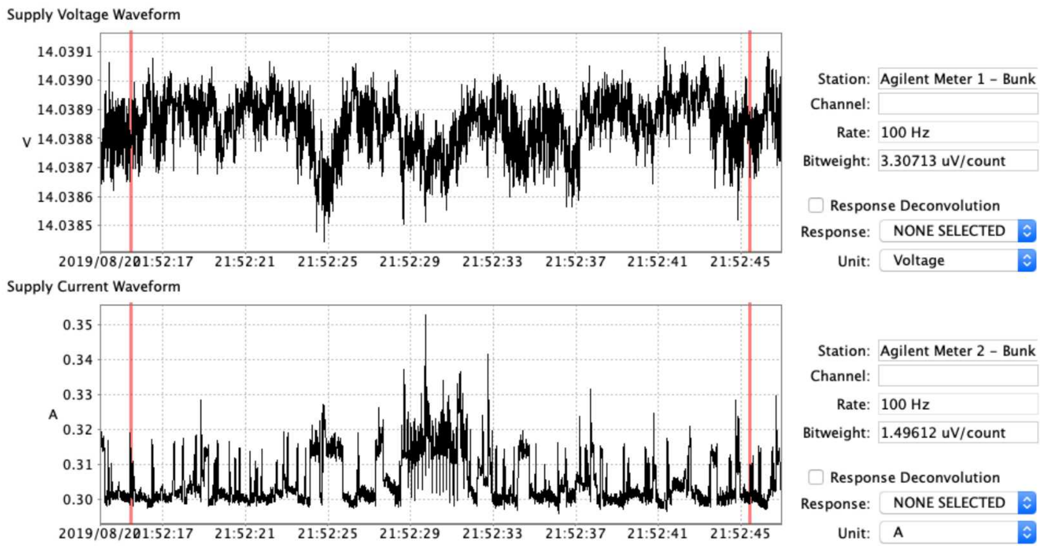


Figure 13 Voltage and Current Recorded Time Series

Table 6 Power Consumption Results

DWR	Supply Voltage	Supply Voltage SD	Supply Current	Supply Current SD	Power Consumption	Power Consumption SD
2453	14.04 V	100 uV	0.3053 A	27.397 mA	4.287 W	103.8 mW

The Q330M+ digitizer was observed to consume 4.287 watts of power while configured with a gain of 1x, recording data at 100 sps, 40 sps and 20 sps from the six digitizer channels and transmitting authenticated the six data channels at the aforementioned sample rates through its ethernet port. Power requirements may vary and perhaps increase momentarily beyond that shown depending on the specific configuration.

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 DC offset in volts and the bit weight in Volts/count.

3.3.2 Configuration

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

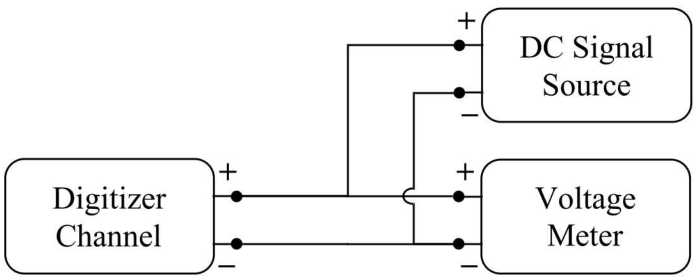


Figure 14 DC Accuracy Configuration Diagram

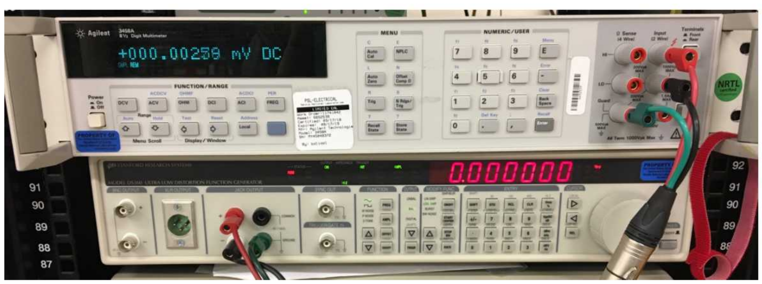


Figure 15 DC Accuracy Configuration Picture

Table 7 DC Accuracy Testbed Equipment

Type	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	Stanford Research Systems, DS3360	123762	+1V / - 1 V
Voltage Meter	Agilent 3458A	MY45048371	1 V full scale

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

The meter and the digitizer channel record the described DC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz. The meter used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.3.3 Analysis

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

The average of each of the positive and negative segments are computed from the reference meter in volts:

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

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

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

The digitizer bit weight in Volts / count is computed:

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

3.3.4 Result

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

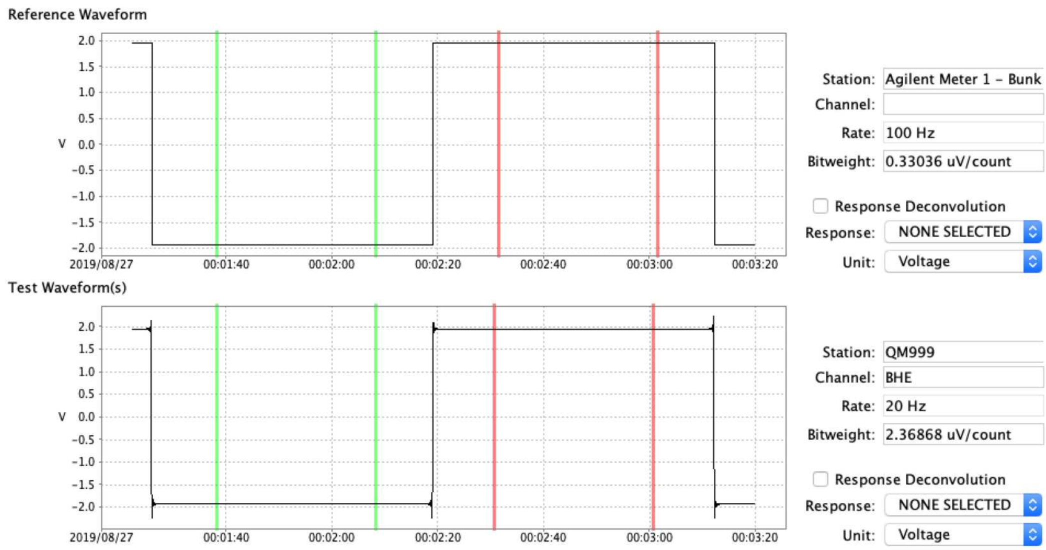


Figure 16 DC Accuracy Example Time Series

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

Table 8 DC Accuracy Bit Weight, 100 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	2.3823 uV/count	2.3817 uV/count	2.3817 uV/count	2.3795 uV/count	2.3795 uV/count	2.3833 uV/count
2x	1.1915 uV/count	1.1912 uV/count	1.1911 uV/count	1.1902 uV/count	1.1900 uV/count	1.1922 uV/count
4x	0.5959 uV/count	0.5958 uV/count	0.5958 uV/count	0.5955 uV/count	0.5953 uV/count	0.5963 uV/count
8Lx	0.2982 uV/count	0.2982 uV/count	0.2982 uV/count	0.2979 uV/count	0.2979 uV/count	0.2983 uV/count
16x	0.1491 uV/count	0.1491 uV/count	0.1491 uV/count	0.1490 uV/count	0.1490 uV/count	0.1492 uV/count
32x	74.594 nV/count	74.590 nV/count	74.600 nV/count	74.544 nV/count	74.517 nV/count	74.639 nV/count

Table 9 DC Accuracy Bit Weight, 40 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	2.3823 uV/count	2.3817 uV/count	2.3817 uV/count	2.3795 uV/count	2.3795 uV/count	2.3833 uV/count
2x	1.1915 uV/count	1.1912 uV/count	1.1911 uV/count	1.1902 uV/count	1.1900 uV/count	1.1922 uV/count
4x	0.5959 uV/count	0.5958 uV/count	0.5958 uV/count	0.5955 uV/count	0.5953 uV/count	0.5963 uV/count
8Lx	0.2982 uV/count	0.2982 uV/count	0.2982 uV/count	0.2979 uV/count	0.2979 uV/count	0.2983 uV/count
16x	0.1491 uV/count	0.1491 uV/count	0.1491 uV/count	0.1490 uV/count	0.1490 uV/count	0.1492 uV/count
32x	74.594 nV/count	74.590 nV/count	74.600 nV/count	74.544 nV/count	74.517 nV/count	74.639 nV/count

Table 10 DC Accuracy Bit Weight, 20 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	2.3823 uV/count	2.3817 uV/count	2.3817 uV/count	2.3795 uV/count	2.3795 uV/count	2.3833 uV/count
2x	1.1915 uV/count	1.1912 uV/count	1.1911 uV/count	1.1902 uV/count	1.1900 uV/count	1.1922 uV/count
4x	0.5959 uV/count	0.5958 uV/count	0.5958 uV/count	0.5955 uV/count	0.5953 uV/count	0.5963 uV/count
8Lx	0.2982 uV/count	0.2982 uV/count	0.2982 uV/count	0.2979 uV/count	0.2979 uV/count	0.2983 uV/count
16x	0.1491 uV/count	0.1491 uV/count	0.1491 uV/count	0.1490 uV/count	0.1490 uV/count	0.1492 uV/count
32x	74.594 nV/count	74.590 nV/count	74.600 nV/count	74.544 nV/count	74.517 nV/count	74.639 nV/count

Table 11 Nominal Bit Weights

Gain	Bit Weight
1x	2.3840 uV/count
2x	1.1920 uV/count
4x	0.5960 uV/count
8Lx	0.2980 uV/count
16x	0.149 uV/count
32x	74.5 nV/count

The bit weights provided by Quanterra for this serial number unit were specified to be: 2.384 uV/count at a gain of 1. Nominal bit weights for the other gain settings of interest are calculated from this manufacturer-provided bit weight.

Observed bit weights varied no more than 0.19% from nominal, at a gain of 1x. A gain of 8Lx provided the lowest maximum variation in gain from nominal across all channels.

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 and DC offset in volts.

3.4.2 Configuration

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

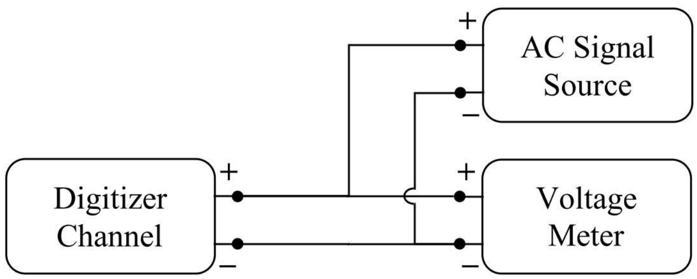


Figure 17 AC Accuracy Configuration Diagram

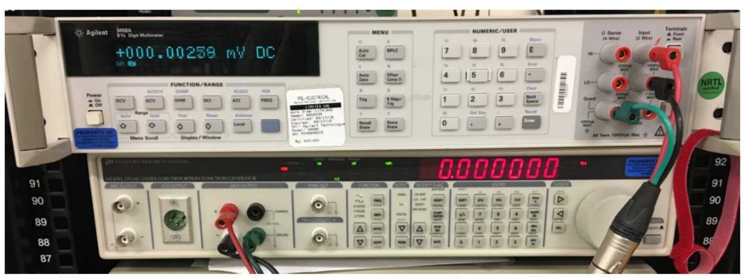


Figure 18 AC Accuracy Configuration Picture

Table 12 AC Accuracy Testbed Equipment

Type	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	Stanford Research Systems, DS3360	123762	+1V / - 1 V
Voltage Meter	Agilent 3458A	MY45048371	1 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 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment.

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

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

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

The digitizer bit weight in Volts / count is computed:

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

3.4.4 Result

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

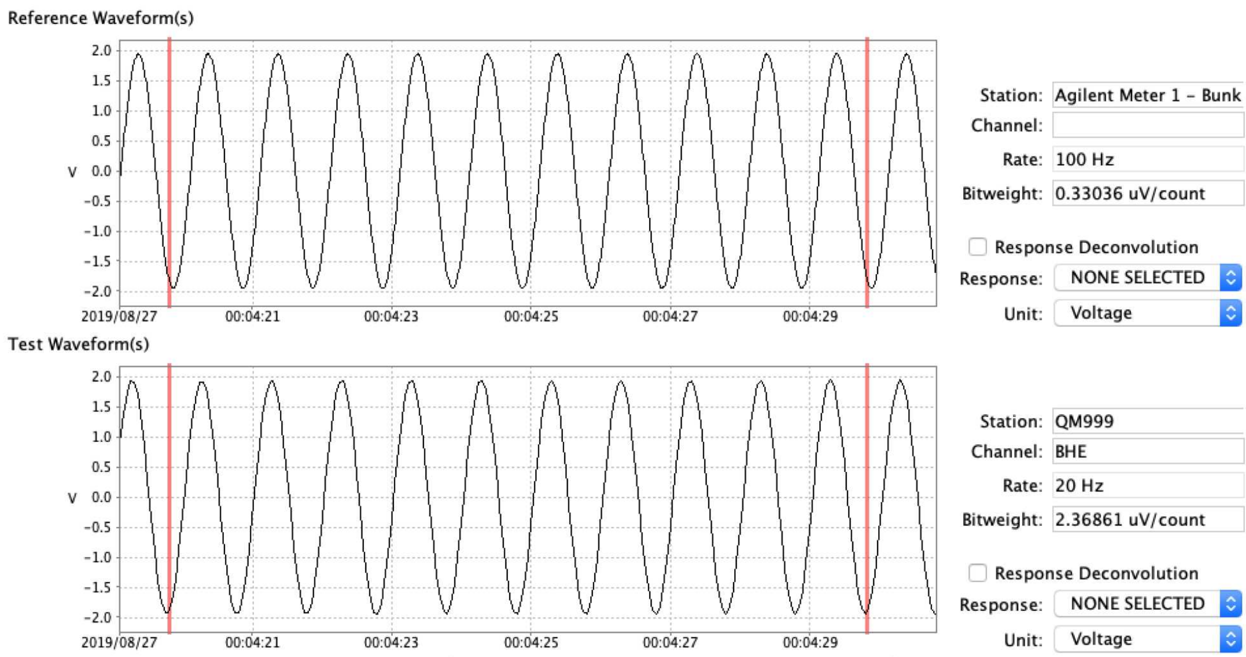


Figure 19 AC Accuracy Test Example Time Series

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

Table 13 AC Accuracy Bit weight, 100 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	2.3806 uV/count	2.3799 uV/count	2.3799 uV/count	2.3777 uV/count	2.3777 uV/count	2.3815 uV/count
2x	1.1906 uV/count	1.1903 uV/count	1.1902 uV/count	1.1893 uV/count	1.1892 uV/count	1.1913 uV/count
4x	0.5955 uV/count	0.5954 uV/count	0.5954 uV/count	0.5950 uV/count	0.5948 uV/count	0.5959 uV/count
8Lx	0.2980 uV/count	0.2979 uV/count	0.2980 uV/count	0.2977 uV/count	0.2977 uV/count	0.2981 uV/count
16x	0.1490 uV/count	0.1490 uV/count	0.1490 uV/count	0.1489 uV/count	0.1489 uV/count	0.1491 uV/count
32x	74.539 nV/count	74.535 nV/count	74.544 nV/count	74.489 nV/count	74.462 nV/count	74.583 nV/count

Table 14 AC Accuracy Bit weight, 40 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	2.3678 uV/count	2.3671 uV/count	2.3672 uV/count	2.3650 uV/count	2.3650 uV/count	2.3687 uV/count
2x	1.1842 uV/count	1.1840 uV/count	1.1839 uV/count	1.1829 uV/count	1.1828 uV/count	1.1849 uV/count
4x	0.5923 uV/count	0.5922 uV/count	0.5922 uV/count	0.5918 uV/count	0.5916 uV/count	0.5927 uV/count
8Lx	0.2964 uV/count	0.2963 uV/count	0.2964 uV/count	0.2961 uV/count	0.2961 uV/count	0.2965 uV/count
16x	0.1482 uV/count	0.1482 uV/count	0.1482 uV/count	0.1481 uV/count	0.1481 uV/count	0.1483 uV/count
32x	74.139 nV/count	74.135 nV/count	74.145 nV/count	74.090 nV/count	74.063 nV/count	74.184 nV/count

Table 15 AC Accuracy Bit weight, 20 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	2.3678 uV/count	2.3671 uV/count	2.3671 uV/count	2.3650 uV/count	2.3649 uV/count	2.3687 uV/count
2x	1.1842 uV/count	1.1839 uV/count	1.1839 uV/count	1.1829 uV/count	1.1828 uV/count	1.1849 uV/count
4x	0.5923 uV/count	0.5922 uV/count	0.5922 uV/count	0.5918 uV/count	0.5916 uV/count	0.5927 uV/count
8Lx	0.2964 uV/count	0.2963 uV/count	0.2964 uV/count	0.2961 uV/count	0.2961 uV/count	0.2965 uV/count
16x	0.1482 uV/count	0.1482 uV/count	0.1482 uV/count	0.1481 uV/count	0.1481 uV/count	0.1483 uV/count
32x	74.139 nV/count	74.135 nV/count	74.144 nV/count	74.089 nV/count	74.062 nV/count	74.183 nV/count

The bit weights provided by Kinemetrics are as provided in Table 11 Nominal Bit Weights.

Maximum deviation from nominal bit weights across all gain settings was 0.800% for the 20 sps data at a gain of 1x. A gain of 16x provided the lowest maximum variation in gain from nominal across all channels, 0.093% for 100 sps data. Maximum deviation from nominal bit weights of all sample rates decreased with increase in gain, with the exception of the 100 sps channels at a gain of 32x.

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

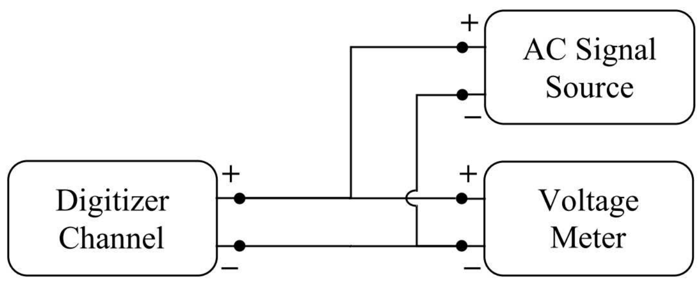


Figure 20 AC Full Scale Configuration Diagram

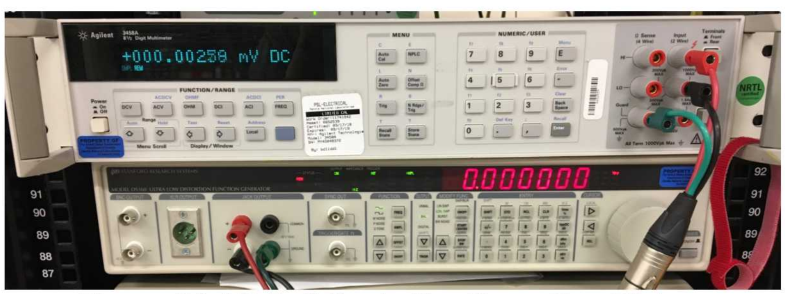


Figure 21 AC Full Scale Configuration Picture

Table 16 AC Full Scale Testbed Equipment

Type	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	Stanford Research Systems, DS3360	123762	+20V / -20 V
Voltage Meter	Agilent 3458A	MY45048371	100 V full scale

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

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

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

3.5.3 Analysis

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

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

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

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

3.5.4 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.

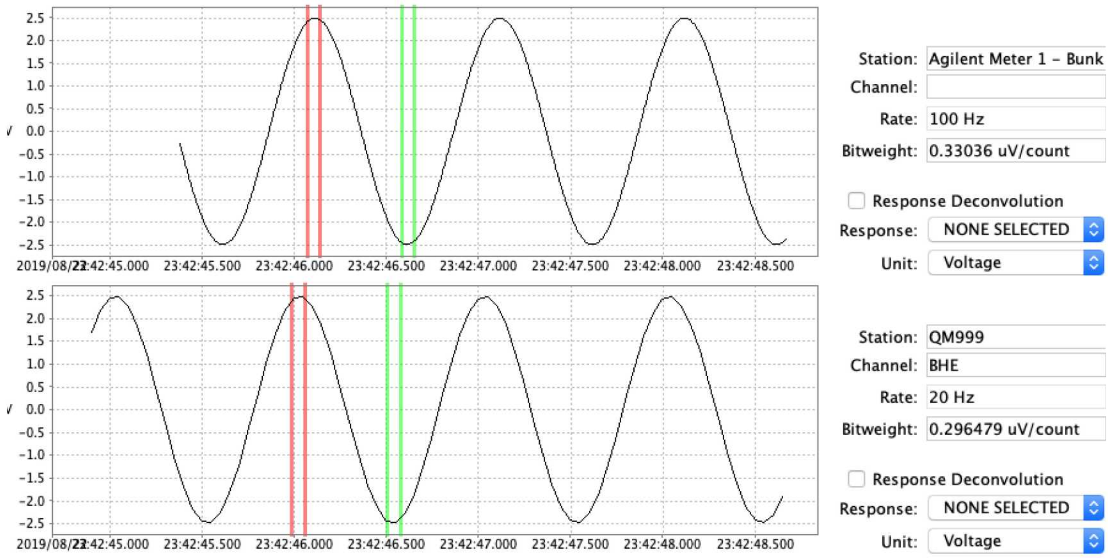


Figure 22 AC Full Scale Time Series

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 17 AC Full Scale Positive Peak, 100 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	19.7050 V	19.7000 V	19.7000 V	19.7000 V	19.7000 V	19.7000 V	19.7000 V
2x	9.8496 V	9.8522 V	9.8522 V	9.8522 V	9.8522 V	9.8522 V	9.8522 V
4x	4.9264 V	4.9305 V	4.9305 V	4.9305 V	4.9305 V	4.9305 V	4.9305 V
8Lx	2.4871 V	2.4880 V	2.4880 V	2.4880 V	2.4880 V	2.4880 V	2.4880 V
16x	1.2432 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V
32x	0.6215 V	0.6216 V	0.6216 V	0.6216 V	0.6216 V	0.6216 V	0.6216 V

Table 18 AC Full Scale Positive Peak, 40 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	19.7050 V	19.6590 V	19.6590 V	19.6590 V	19.6590 V	19.6590 V	19.6590 V
2x	9.8496 V	9.8523 V	9.8523 V	9.8523 V	9.8523 V	9.8523 V	9.8523 V
4x	4.9264 V	4.9443 V	4.9443 V	4.9443 V	4.9443 V	4.9443 V	4.9443 V
8Lx	2.4871 V	2.4856 V	2.4856 V	2.4856 V	2.4856 V	2.4856 V	2.4856 V
16x	1.2432 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V
32x	0.6215 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V

Table 19 AC Full Scale Positive Peak, 20 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	19.7050 V	19.6310 V	19.6310 V	19.6310 V	19.6310 V	19.6310 V	19.6310 V
2x	9.8496 V	9.8522 V	9.8522 V	9.8522 V	9.8522 V	9.8522 V	9.8522 V
4x	4.9264 V	4.9443 V	4.9443 V	4.9443 V	4.9443 V	4.9443 V	4.9443 V
8Lx	2.4871 V	2.4731 V	2.4731 V	2.4731 V	2.4731 V	2.4731 V	2.4731 V
16x	1.2432 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V	1.2434 V
32x	0.6215 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V

Table 20 AC Full Scale Negative Peak, 100 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-19.7570 V	-19.7480 V	-19.7480 V	-19.7480 V	-19.7480 V	-19.7480 V	-19.7480 V
2x	-9.8768 V	-9.8785 V	-9.8785 V	-9.8785 V	-9.8785 V	-9.8785 V	-9.8785 V
4x	-4.9402 V	-4.9440 V	-4.9440 V	-4.9440 V	-4.9440 V	-4.9440 V	-4.9440 V
8Lx	-2.4950 V	-2.4951 V	-2.4951 V	-2.4951 V	-2.4951 V	-2.4951 V	-2.4951 V
16x	-1.2459 V	-1.2462 V	-1.2462 V	-1.2462 V	-1.2462 V	-1.2462 V	-1.2462 V
32x	-0.6231 V	-0.6233 V	-0.6233 V	-0.6233 V	-0.6233 V	-0.6233 V	-0.6233 V

Table 21 AC Full Scale Negative Peak, 40 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-19.7570 V	-19.7190 V	-19.7190 V	-19.7190 V	-19.7190 V	-19.7190 V	-19.7190 V
2x	--9.8768 V	-9.8784 V	-9.8784 V	-9.8784 V	-9.8784 V	-9.8784 V	-9.8784 V
4x	-4.9402 V	-4.9602 V	-4.9602 V	-4.9602 V	-4.9602 V	-4.9602 V	-4.9602 V
8Lx	-2.4950 V	-2.4921 V	-2.4921 V	-2.4921 V	-2.4921 V	-2.4921 V	-2.4921 V
16x	-1.2459 V	-1.2461 V	-1.2461 V	-1.2461 V	-1.2461 V	-1.2461 V	-1.2461 V
32x	-0.6231 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V	0.6217 V

Table 22 AC Full Scale Negative Peak, 20 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-19.7570 V	-19.6690 V	-19.6690 V	-19.6690 V	-19.6690 V	-19.6690 V	-19.6690 V
2x	--9.8768 V	-9.8783 V	-9.8783 V	-9.8783 V	-9.8783 V	-9.8783 V	-9.8783 V
4x	-4.9402 V	-4.9602 V	-4.9602 V	-4.9602 V	-4.9602 V	-4.9602 V	-4.9602 V
8Lx	-2.4950 V	-2.4825 V	-2.4825 V	-2.4825 V	-2.4825 V	-2.4825 V	-2.4825 V
16x	-1.2459 V	-1.2461 V	-1.2461 V	-1.2461 V	-1.2461 V	-1.2461 V	-1.2461 V
32x	-0.6231 V	-0.6233 V	-0.6233 V	-0.6233 V	-0.6233 V	-0.6233 V	-0.6233 V

For all sample rates and gain levels, the primary and auxiliary 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 exceeding 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 a AC signal source and a meter configured to measure voltage as shown in the diagram below.

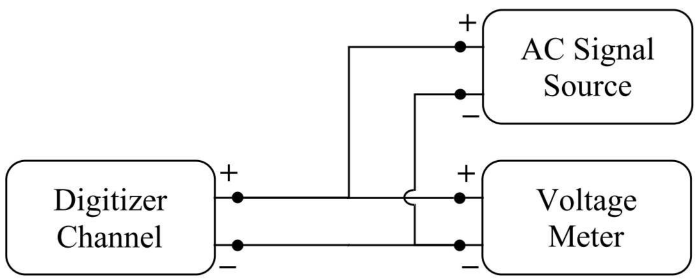


Figure 23 AC Full Scale Configuration Diagram

Figure 24 AC Full Scale Configuration Picture

Table 23 AC Over Scale Testbed Equipment

Type	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	Stanford Research Systems, DS3360	123762	+20V / - 20 V
Voltage Meter	Agilent 3458A	MY45048371	100 V full scale

The AC Signal Source is configured to generate an AC voltage with an amplitude of approximately 110% 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.

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 in order to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.01 %.

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

3.6.3 Analysis

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

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

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

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

3.6.4 Result

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

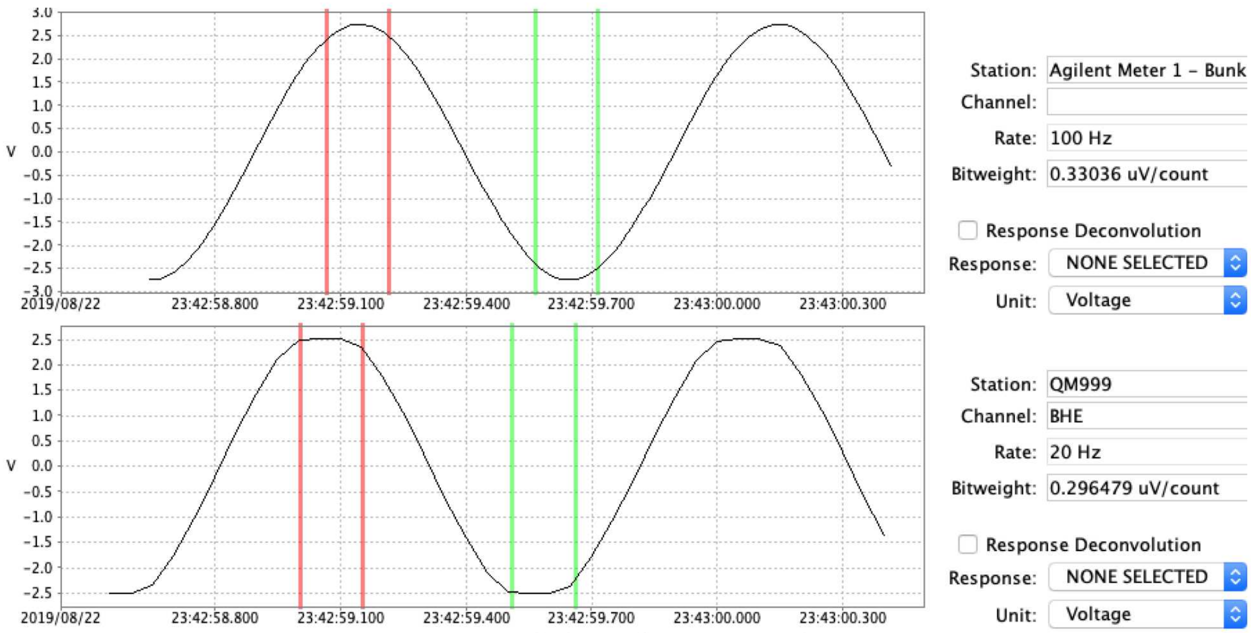


Figure 25 AC Over Scale Time Series

Table 24 AC Over Scale Positive Peak, 100 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	21.6790 V	21.3970 V	21.3910 V	21.3910 V	21.3710 V	21.3710 V	21.4060 V
2x	10.8370 V	10.7020 V	10.6990 V	10.6980 V	10.6890 V	10.6880 V	10.7080 V
4x	5.4195 V	5.3568 V	5.3557 V	5.3558 V	5.3524 V	5.3504 V	5.3604 V
8Lx	2.7382 V	2.5162 V	2.5158 V	2.5162 V	2.5134 V	2.5133 V	2.5170 V
16x	1.3695 V	1.2584 V	1.2583 V	1.2583 V	1.2572 V	1.2570 V	1.2590 V
32x	0.6839 V	0.6293 V	0.6293 V	0.6293 V	0.6289 V	0.6287 V	0.6296 V

Table 25 AC Over Scale Positive Peak, 40 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	21.6790 V	21.4140 V	21.4070 V	21.4080 V	21.3860 V	21.3860 V	21.4220 V
2x	10.8370 V	10.7120 V	10.7090 V	10.7080 V	10.6990 V	10.6970 V	10.7190 V
4x	5.4195 V	5.3908 V	5.3895 V	5.3896 V	5.3860 V	5.3838 V	5.3947 V
8Lx	2.7382 V	2.5158 V	2.5154 V	2.5158 V	2.5128 V	2.5128 V	2.5167 V
16x	1.3695 V	1.2586 V	1.2584 V	1.2585 V	1.2572 V	1.2570 V	1.2593 V
32x	0.6839 V	0.6302 V	0.6302 V	0.6303 V	0.6298 V	0.6295 V	0.6306 V

Table 26 AC Over Scale Positive Peak, 20 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	21.4320 V	21.4260 V	21.4220 V	21.4220 V	21.4080 V	21.4080 V	21.4320 V
2x	10.8370 V	10.6620 V	10.6600 V	10.6600 V	10.6540 V	10.6540 V	10.6650 V
4x	5.4195 V	5.4166 V	5.4158 V	5.4159 V	5.4134 V	5.4119 V	5.4192 V
8Lx	2.7382 V	2.5220 V	2.5217 V	2.5219 V	2.5196 V	2.5195 V	2.5227 V
16x	1.3695 V	1.2611 V	1.2610 V	1.2610 V	1.2600 V	1.2598 V	1.2616 V
32x	0.6839 V	0.6309 V	0.6308 V	0.6309 V	0.6305 V	0.6303 V	0.6312 V

Table 27 AC Over Scale Negative Peak, 100 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-21.7280 V	-21.3970 V	-21.3920 V	-21.3920 V	-21.3760 V	-21.3760 V	-21.4030 V
2x	-10.8650 V	-10.7000 V	-10.6980 V	-10.6980 V	-10.6910 V	-10.6900 V	-10.7050 V
4x	-5.4348 V	-5.3565 V	-5.3557 V	-5.3557 V	-5.3531 V	-5.3515 V	-5.3592 V
8Lx	-2.7465 V	-2.5152 V	-2.5148 V	-2.5151 V	-2.5122 V	-2.5122 V	-2.5161 V
16x	-1.3745 V	-1.2585 V	-1.2584 V	-1.2584 V	-1.2573 V	-1.2571 V	-1.2591 V
32x	-0.6855 V	-0.6294 V	-0.6294 V	-0.6295 V	-0.6290 V	-0.6288 V	-0.6298 V

Table 28 AC Over Scale Negative Peak, 40 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-21.4180 V	-21.4090 V	-21.4030 V	-21.4030 V	-21.3820 V	-21.3820 V	-21.4180 V
2x	10.8650 V	-10.7080 V	-10.7050 V	-10.7040 V	-10.6940 V	-10.6920 V	-10.7150 V
4x	-5.4348 V	-5.3885 V	-5.3872 V	-5.3873 V	-5.3836 V	-5.3814 V	-5.3925 V
8Lx	-2.7465 V	-2.5158 V	-2.5154 V	-2.5157 V	-2.5128 V	-2.5128 V	-2.5167 V
16x	-1.3745 V	-1.2586 V	-1.2584 V	-1.2585 V	-1.2572 V	-1.2570 V	-1.2593 V
32x	-0.6855 V	-0.6300 V	-0.6300 V	0.6187 V	-0.6296 V	-0.6293 V	-0.6304 V

Table 29 AC Over Scale Negative Peak, 20 sps

Gain	Reference	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-21.7280 V	-21.4520 V	-21.4480 V	-21.4480 V	-21.4330 V	-21.4330 V	-21.4580 V
2x	-10.8650 V	-10.6620 V	-10.6600 V	-10.6600 V	-10.6540 V	-10.6530 V	-10.6660 V
4x	-5.4348 V	-5.4184 V	-5.4175 V	-5.4176 V	-5.4149 V	-5.4134 V	-5.4212 V
8Lx	-2.7465 V	-2.5228 V	-2.5225 V	-2.5228 V	-2.5204 V	-2.5203 V	-2.5236 V
16x	-1.3745 V	-1.2615 V	-1.2614 V	-1.2614 V	-1.2604 V	-1.2603 V	-1.2620 V
32x	-0.6855 V	-0.6310 V	-0.6309 V	-0.6310 V	-0.6306 V	-0.6303 V	-0.6313 V

At all sample rates, applied voltages greater than full scale were observed across all channels with obvious clipping visible in the timeseries, similar to that illustrated in Figure 25 AC Over Scale Time Series

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

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

Figure 26 Input Shorted Offset Configuration Diagram

Figure 27 Input Shorted Offset Termination Resistors

Table 30 Input Shorted Offset Termination Resistors

Channels	Termination Resistor
Primary	200 ohm (100 x 2 ohm)

One hour of data are recorded.

3.7.3 Analysis

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

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

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.

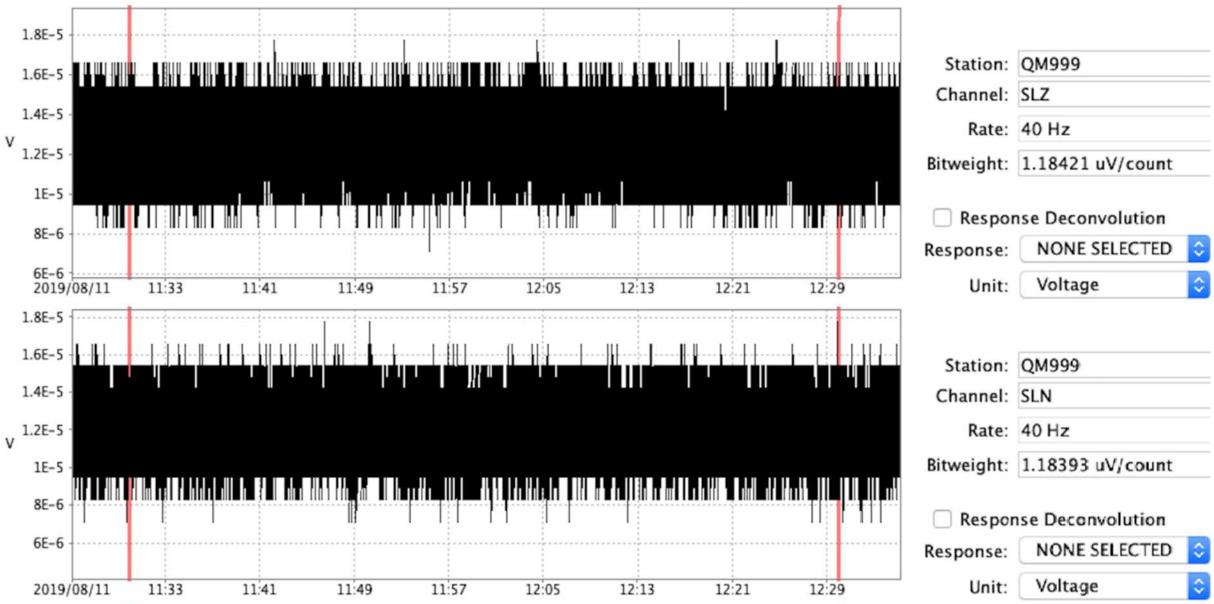


Figure 28 Input Shorted Offset Time Series

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

Table 31 Input Shorted Offset, 100 sps

Gain	Channel 1	Channel 2	Channel 3	Gain	Channel 4	Channel 5	Channel 6
1x	119.3 uV	127.5 uV	126.1 uV	8x	14.19 uV	13.65 uV	13.70 uV
2x	12.71 uV	12.15 uV	11.00 uV	16x	2.01 uV	1.59 uV	2.17 uV
4x	4.52 uV	1.55 uV	5.04 uV	32x	1.30 uV	0.84 uV	1.34 uV

Table 32 Input Shorted Offset, 40 sps

Gain	Channel 1	Channel 2	Channel 3	Gain	Channel 4	Channel 5	Channel 6
1x	118.6 uV	126.8 uV	125.4 uV	8x	14.19 uV	13.65 uV	13.70 uV
2x	12.64 uV	12.09 uV	10.94 uV	16x	2.00 uV	1.59 uV	2.15 uV
4x	4.50 uV	1.54 uV	5.01 uV	32x	1.30 uV	0.84 uV	1.34 uV

Table 33 Input Shorted Offset, 20 sps

Gain	Channel 1	Channel 2	Channel 3	Gain	Channel 4	Channel 5	Channel 6
1x	118.5 uV	126.8 uV	125.3 uV	8x	14.11 uV	13.57 uV	13.62 uV
2x	12.61 uV	12.05 uV	10.90 uV	16x	1.99 uV	1.58 uV	2.15 uV
4x	4.48 uV	1.52 uV	4.99 uV	32x	1.30 uV	0.84 uV	1.33 uV

The maximum observed input shorted offsets across all gains, with respect to nominal full scale, ranged from a maximum of 0.0001% at gains 2x and 4x (all sample rates) to a maximum of 0.0006% at gains of 1x and 8x (all sample rates).

3.8 Self Noise

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

3.8.1 Measurand

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

3.8.2 Configuration

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

Figure 29 Self Noise Configuration Diagram

Figure 30 Input Shorted Offset Termination Resistors

Table 34 Input Terminated Noise Termination Resistors

Channels	Termination Resistor
Primary	200 ohm (2 x 100 ohm)

A minimum of 12 hours of data is recorded.

3.8.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using between a 16k-sample to 4K-sample Hann window, depending on the sample rate of data. The window length and data duration were chosen such that there were a few points below the lower limit of the evaluation pass-band of 0.02 Hz and resulting 90% confidence interval was determined to be between 0.54 dB and 0.60 dB.

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

Over frequencies (in Hertz):

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

In addition, the total RMS noise over the application pass-band of 0.02 to 4.0 Hz 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 figures below show the waveform time series and power spectra for the recording made on a digitizer channel under test. The window regions bounded by the red lines indicate the segment of data used for analysis.

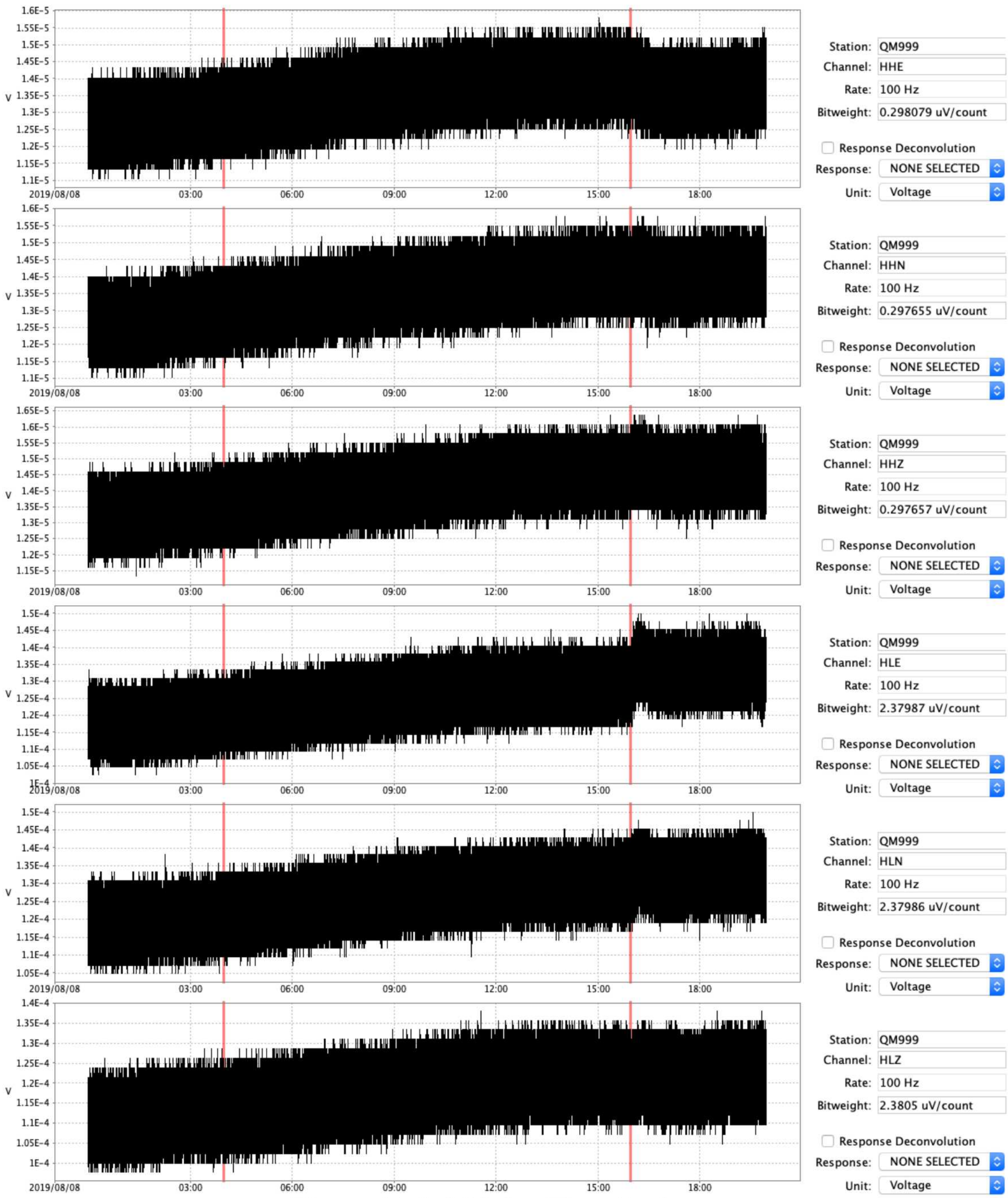


Figure 31 Self Noise Time Series

The time series between the two red lines used to evaluated self noise, in Figure 31 Self Noise Time Series, are indicative of the time series observed at all gain settings and channels. Note the transient immediately right of the window on channel HLE and HLN is anomalous likely due to some environmental change. It was not included in the data used for measuring self noise.

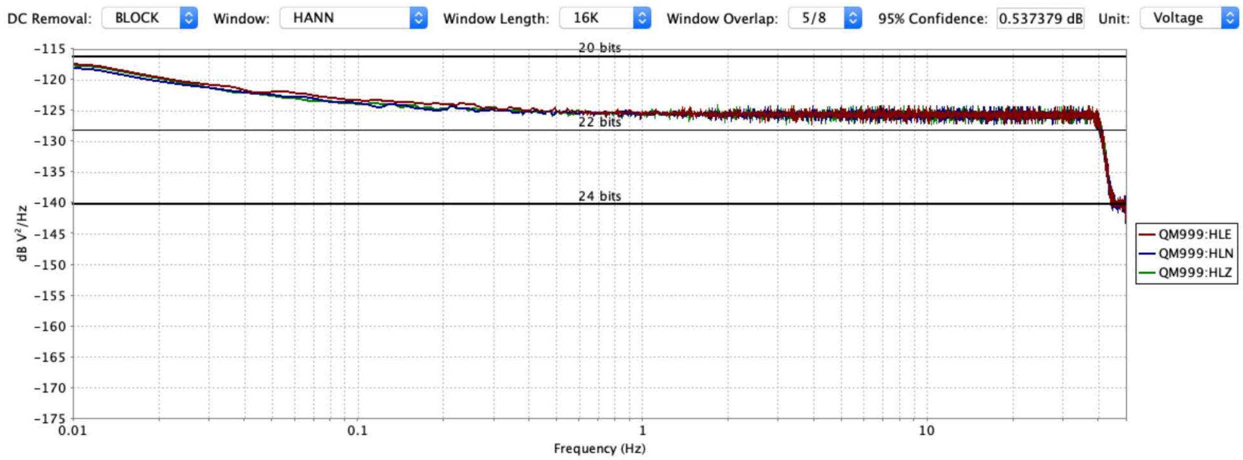


Figure 32 Self Noise Power Spectra, 1x Gain, 100 sps

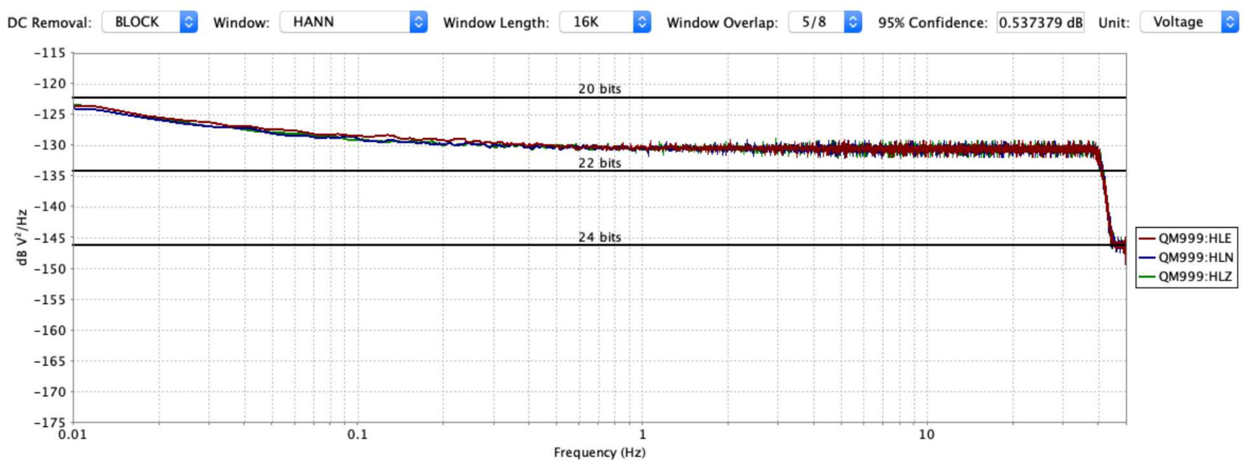


Figure 33 Self Noise Power Spectra, 2x gain, 100 sps

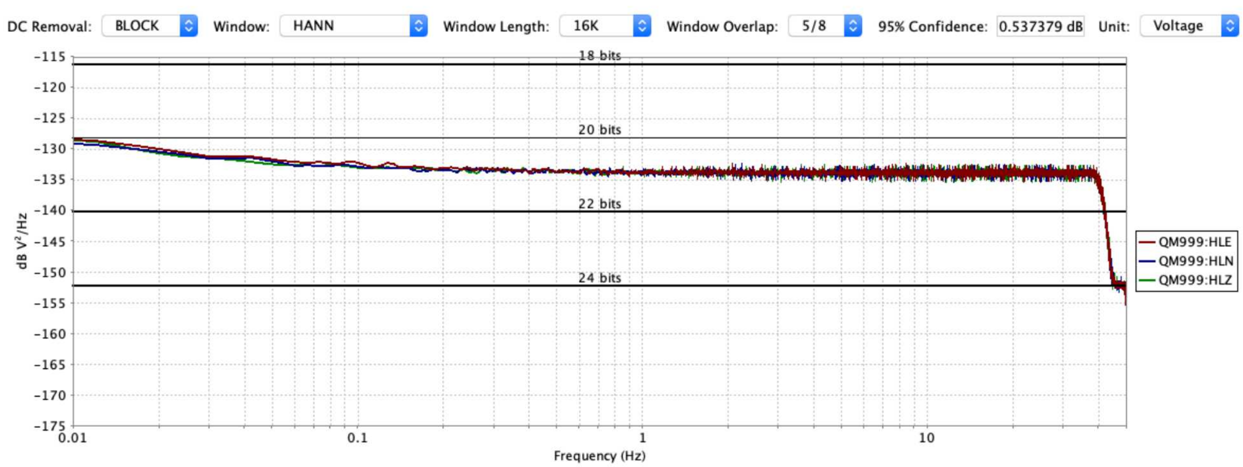


Figure 34 Self Noise Power Spectra, 4x gain, 100 sps

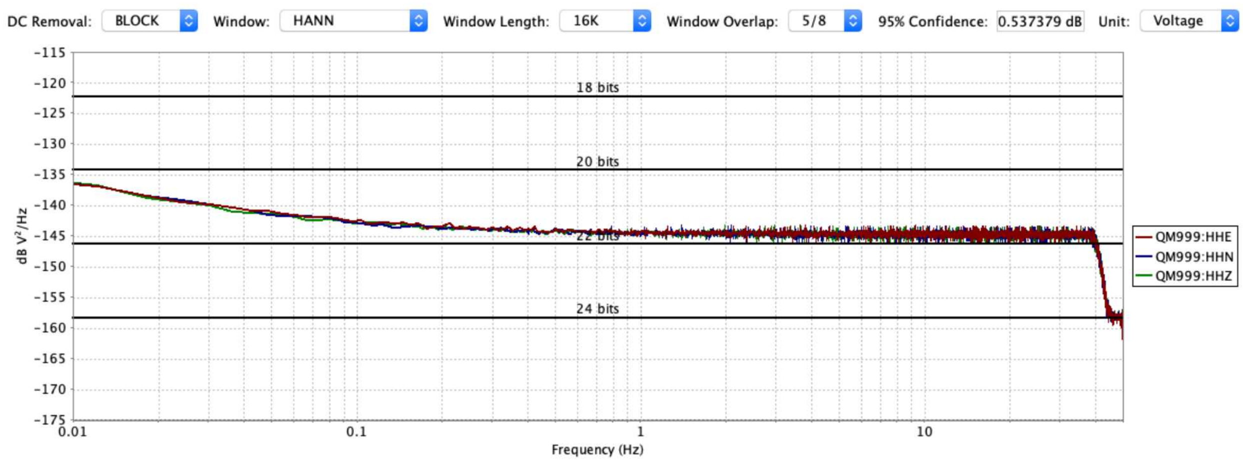


Figure 35 Self Noise Power Spectra, 8Lx Gain, 100 sps

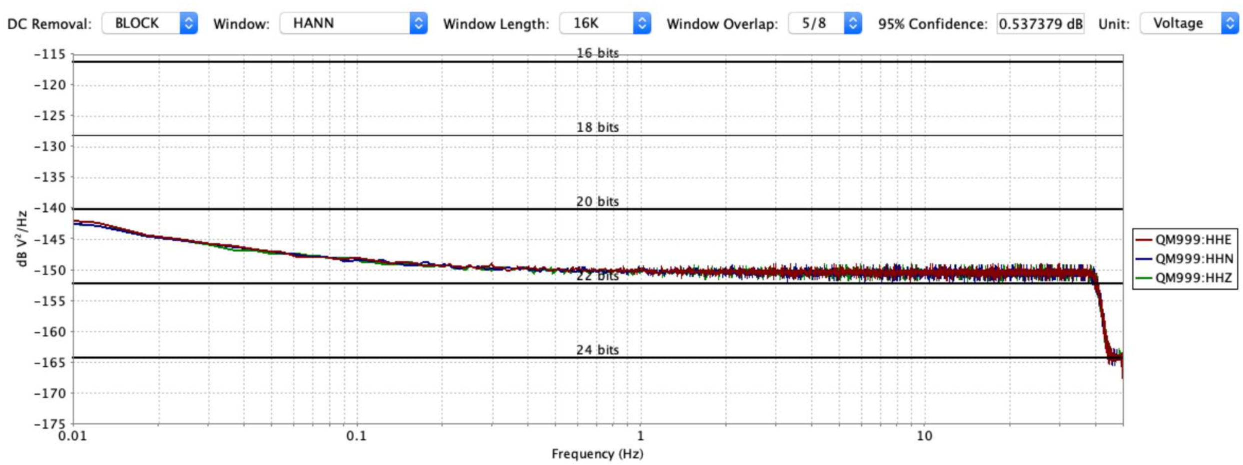


Figure 36 Self Noise Power Spectra, 16x gain, 100 sps

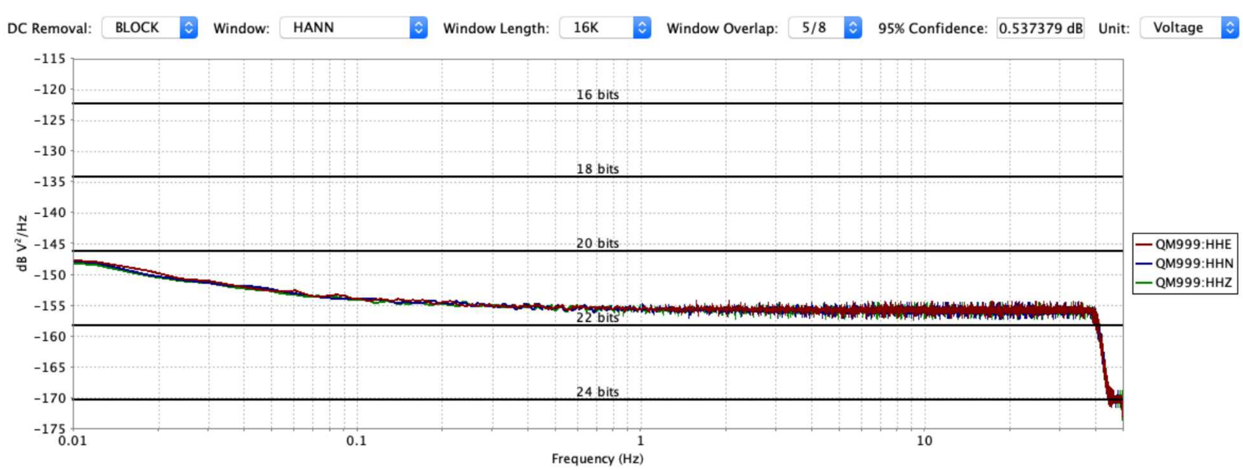


Figure 37 Self Noise Power Spectra, 32x gain, 100 sps

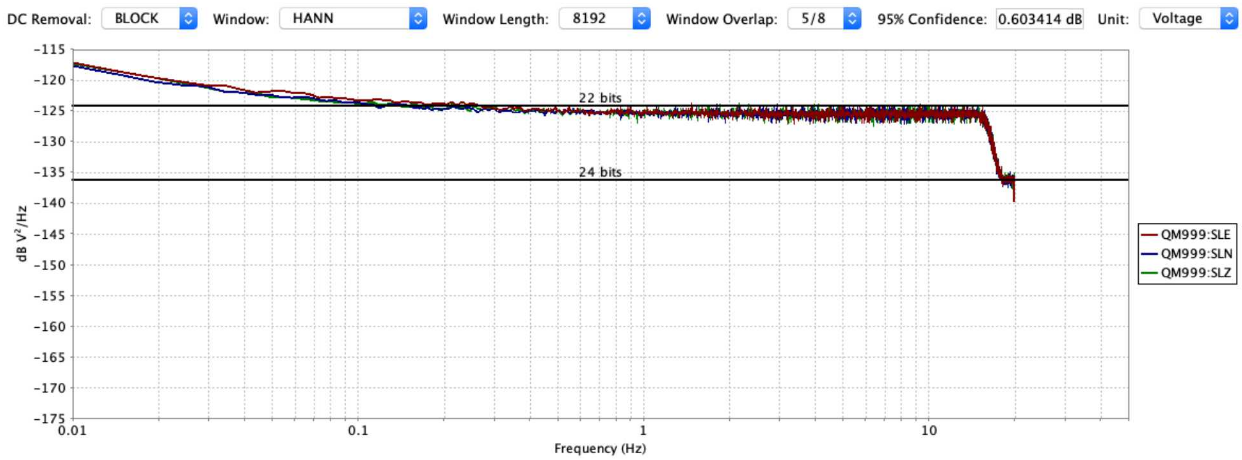


Figure 38 Self Noise Power Spectra, 1x gain, 40 sps

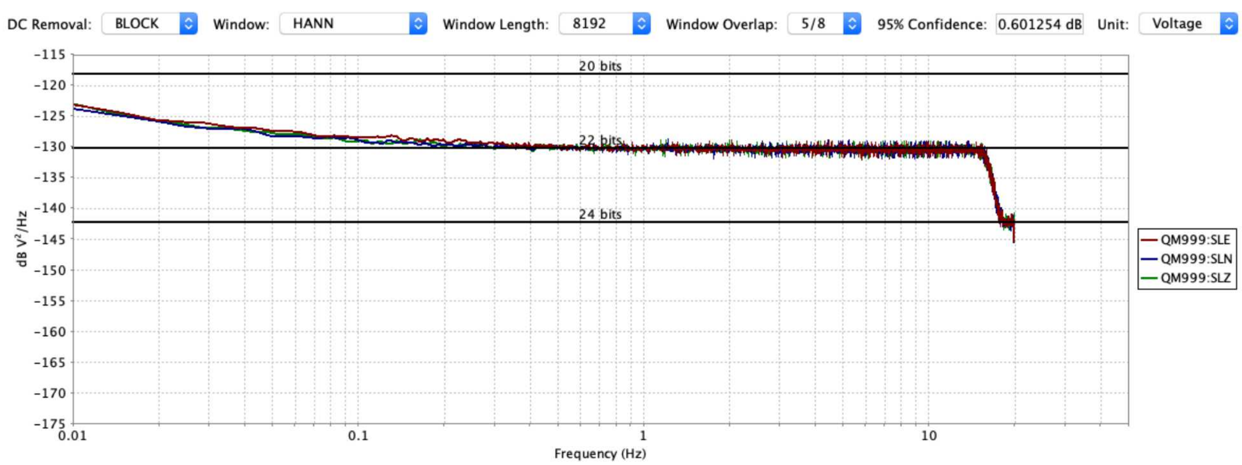


Figure 39 Self Noise Power Spectra, 2x gain, 40 sps

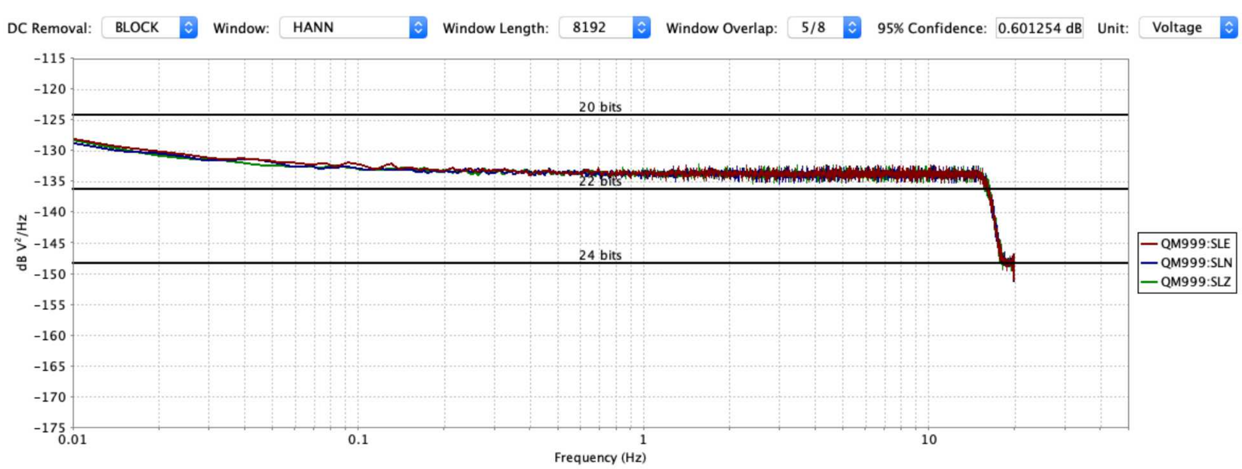


Figure 40 Self Noise Power Spectra, 4x gain, 40 sps

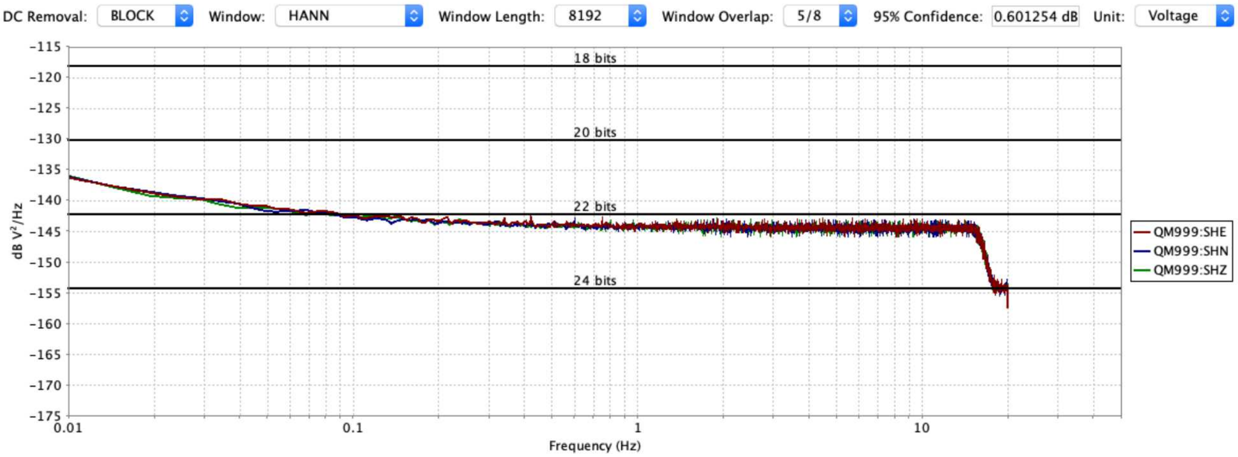


Figure 41 Self Noise Power Spectra, 8Lx gain, 40 sps

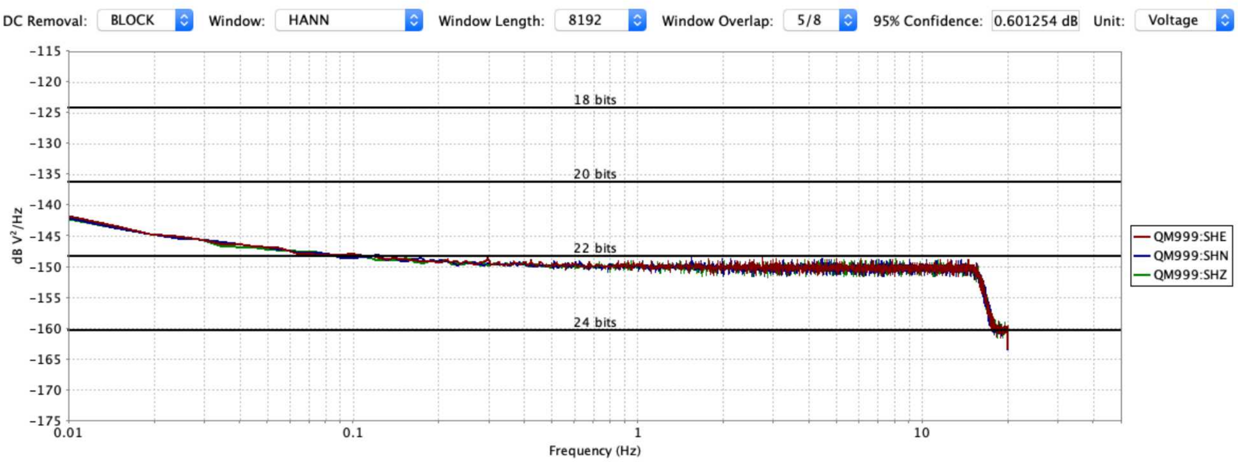


Figure 42 Self Noise Power Spectra, 16x gain, 40 sps

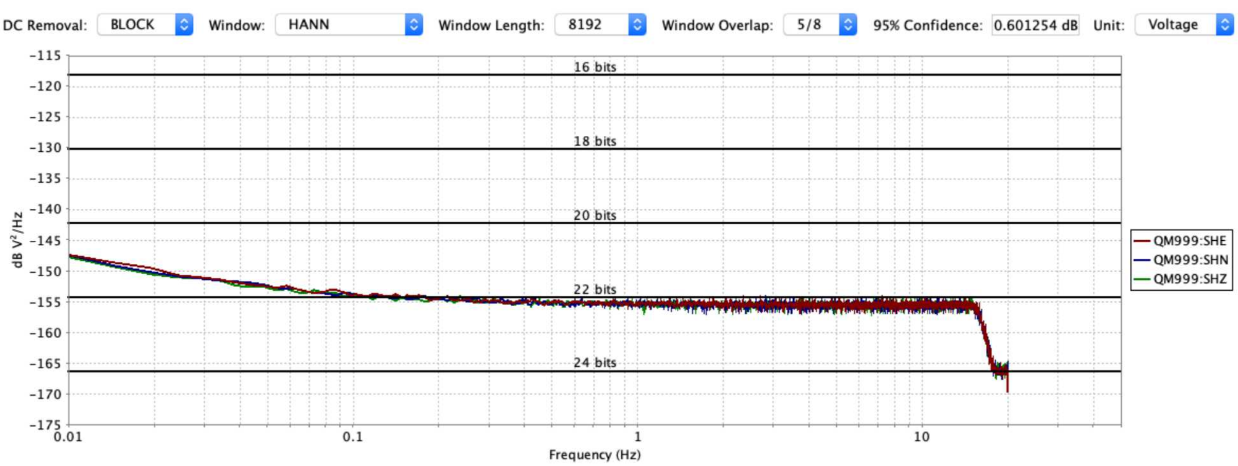


Figure 43 Self Noise Power Spectra, 32x gain, 40 sps

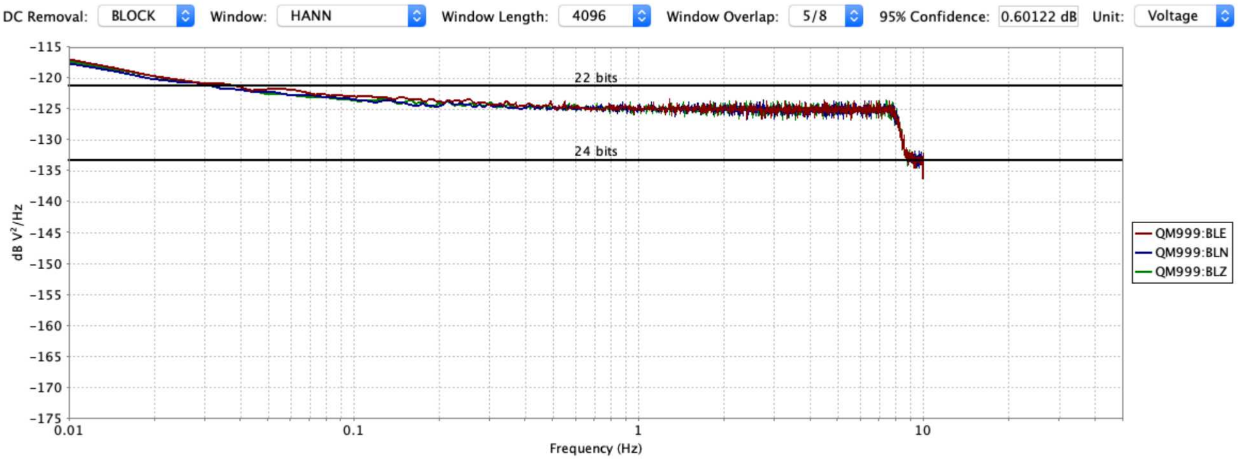


Figure 44 Self Noise Power Spectra, 1x gain, 20 sps

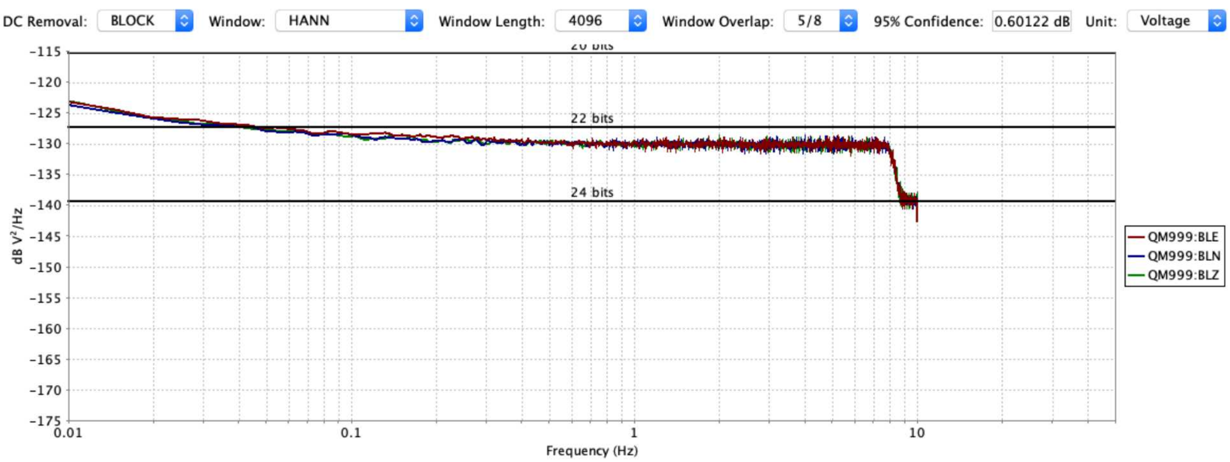


Figure 45 Self Noise Power Spectra, 2x gain, 20 sps

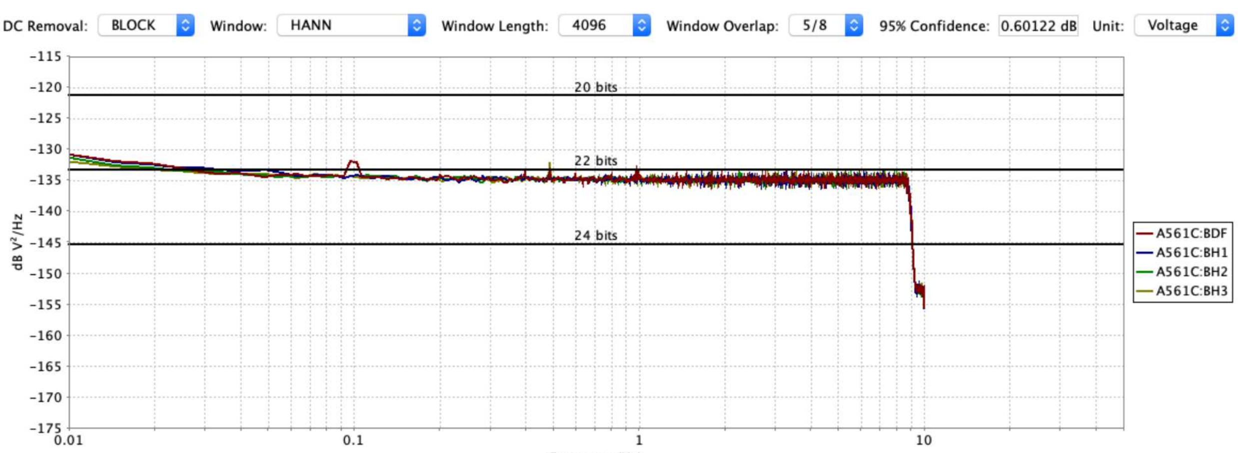


Figure 46 Self Noise Power Spectra, 4x gain, 20 sps

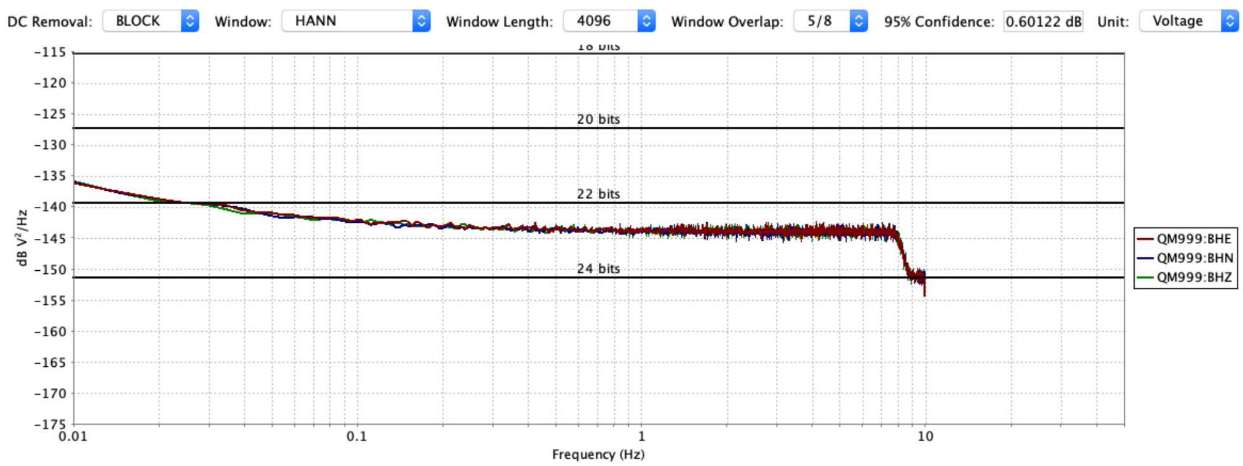


Figure 47 Self Noise Power Spectra, 8Lx gain, 20 sps

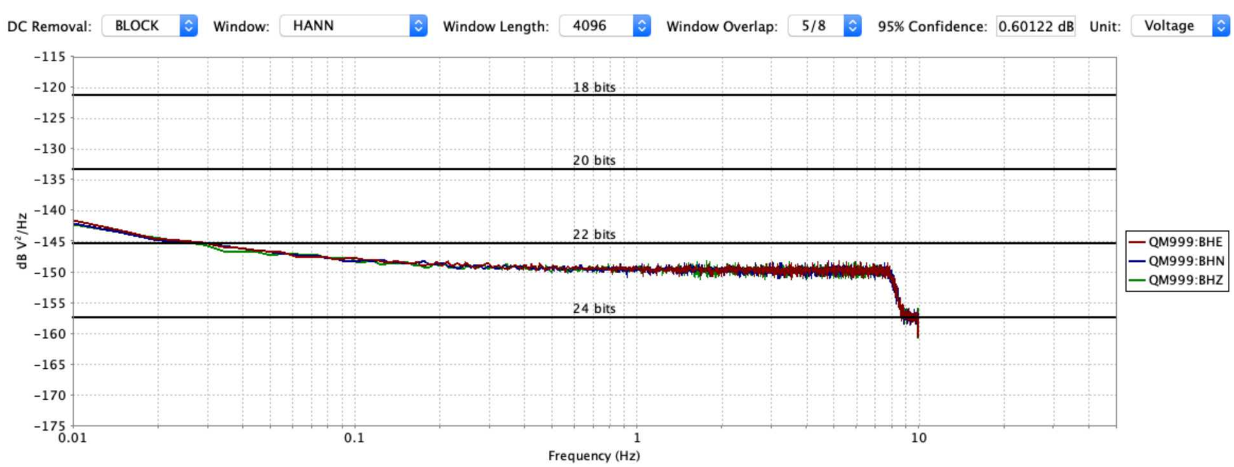


Figure 48 Self Noise Power Spectra, 16x gain, 20 sps

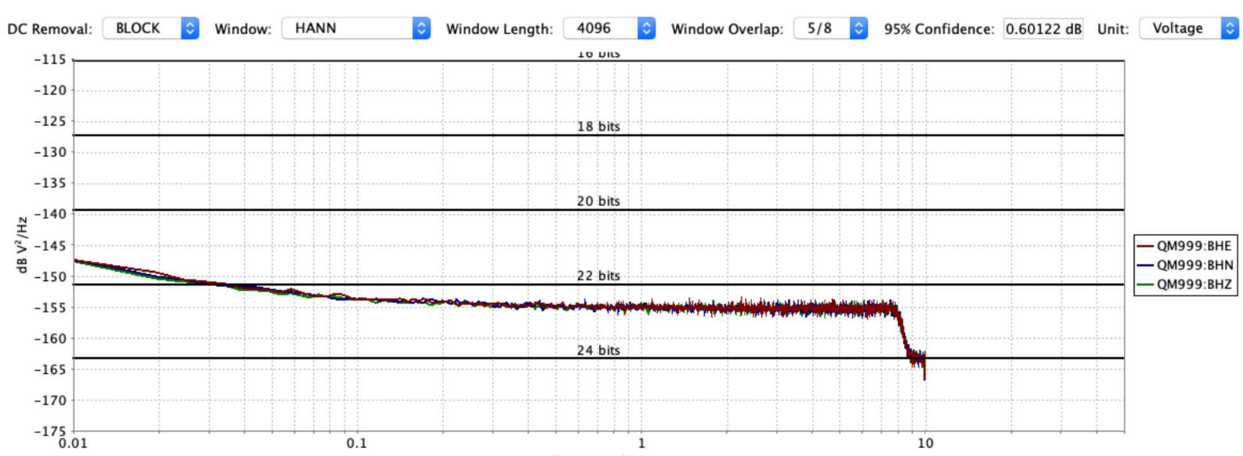


Figure 49 Self Noise Power Spectra, 32x gain, 20 sps

The self-noise is observed to decrease consistent with the change of gain setting, with the exception of a gain of 4x, which is noisier than would otherwise be expected.

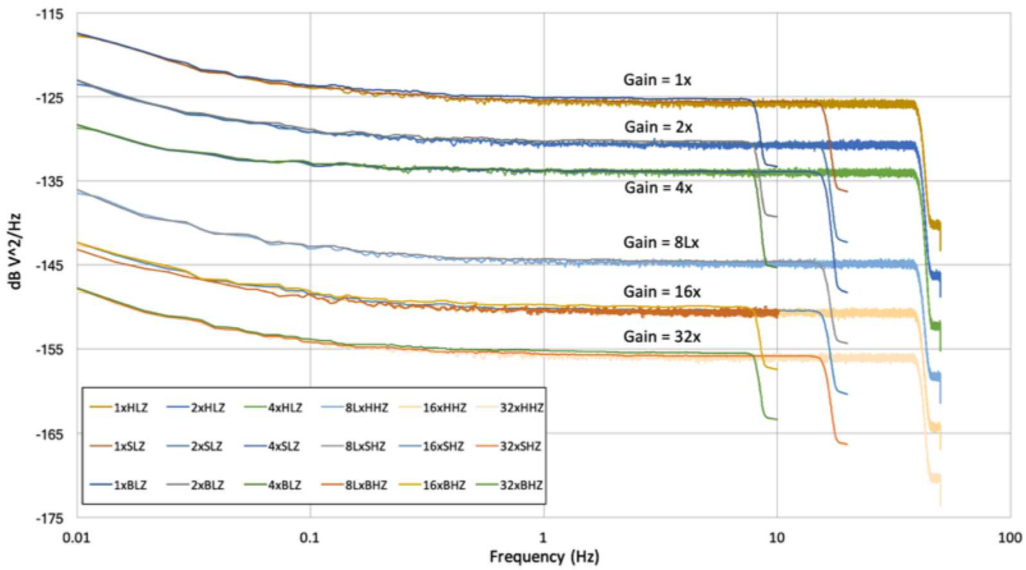


Figure 50 Self Noise Power Spectra, All Gains, 100 sps, 40 sps and 20 sps

Figure 50 provides a representative illustration of computed self noise for each of the sample rates recorded, channels HLZ (gains 1x, 2x and 4x) and HHZ (gains 8Lx, 16x and 32x) are presented. Very little variation in self noise is evident between sample rates at any given gain. Recall the 90% confidence in the measurement is as high as 0.6 dB for the self noise calculations.

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

Digitizer self noise values are reported in units of dB relative to 1 V^2/Hz at the defined third-octave frequencies. The 90% uncertainty of the provided estimates are +/- 0.54 dB, +/- 0.60 dB and +/- 0.60 dB, at 100 sps, 40 sps and 20 sps respectively.

Table 35 Terminated Noise, Gains 1x and 2x, 100 sps

Frequency (Hz)	Gain = 1x			Gain = 2x		
	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
0.01	-117.68 dB	-118.04 dB	-117.47 dB	-123.43 dB	-124.14 dB	-123.56 dB
0.0125	-118.09 dB	-118.51 dB	-117.93 dB	-123.92 dB	-124.44 dB	-123.87 dB
0.016	-118.92 dB	-119.47 dB	-118.84 dB	-124.83 dB	-125.19 dB	-124.75 dB
0.02	-119.77 dB	-120.33 dB	-119.70 dB	-125.69 dB	-125.92 dB	-125.55 dB
0.025	-120.63 dB	-120.95 dB	-120.45 dB	-126.44 dB	-126.61 dB	-126.14 dB
0.0315	-121.50 dB	-121.45 dB	-121.00 dB	-127.13 dB	-127.14 dB	-126.50 dB
0.04	-122.16 dB	-122.14 dB	-121.74 dB	-127.55 dB	-127.37 dB	-127.06 dB
0.05	-122.68 dB	-122.43 dB	-122.02 dB	-127.91 dB	-128.23 dB	-127.50 dB
0.063	-123.24 dB	-122.87 dB	-122.26 dB	-128.22 dB	-128.59 dB	-127.86 dB
0.08	-123.55 dB	-123.58 dB	-122.92 dB	-128.78 dB	-128.76 dB	-128.34 dB
0.1	-123.97 dB	-123.91 dB	-123.37 dB	-129.19 dB	-128.96 dB	-128.65 dB
0.125	-124.06 dB	-124.30 dB	-123.46 dB	-129.54 dB	-129.44 dB	-128.57 dB
0.16	-124.19 dB	-124.69 dB	-123.88 dB	-129.39 dB	-129.64 dB	-129.08 dB
0.2	-124.72 dB	-124.96 dB	-124.02 dB	-130.03 dB	-129.91 dB	-129.24 dB
0.25	-125.07 dB	-124.79 dB	-124.03 dB	-129.61 dB	-129.82 dB	-129.56 dB
0.315	-125.10 dB	-125.17 dB	-124.88 dB	-130.09 dB	-130.18 dB	-129.68 dB
0.4	-125.24 dB	-125.26 dB	-125.08 dB	-130.40 dB	-130.43 dB	-130.08 dB
0.5	-125.25 dB	-125.38 dB	-125.10 dB	-130.18 dB	-130.29 dB	-130.30 dB
0.63	-125.30 dB	-125.47 dB	-125.40 dB	-130.50 dB	-130.37 dB	-130.44 dB
0.8	-125.53 dB	-125.40 dB	-125.36 dB	-130.52 dB	-130.45 dB	-130.30 dB
1	-125.62 dB	-125.69 dB	-125.62 dB	-130.86 dB	-130.55 dB	-130.25 dB
1.25	-125.73 dB	-125.46 dB	-125.65 dB	-130.68 dB	-130.98 dB	-130.44 dB
1.6	-125.61 dB	-125.77 dB	-125.78 dB	-130.48 dB	-130.84 dB	-130.67 dB
2	-125.62 dB	-125.77 dB	-125.68 dB	-130.44 dB	-130.59 dB	-130.59 dB
2.5	-125.72 dB	-125.81 dB	-125.63 dB	-130.76 dB	-130.74 dB	-130.48 dB
3.15	-125.64 dB	-125.82 dB	-125.65 dB	-130.64 dB	-130.85 dB	-130.54 dB
4	-125.77 dB	-125.79 dB	-125.80 dB	-130.71 dB	-130.69 dB	-130.54 dB
5	-125.75 dB	-126.02 dB	-125.44 dB	-130.92 dB	-130.71 dB	-130.55 dB
6.3	-125.72 dB	-125.80 dB	-125.74 dB	-130.57 dB	-130.87 dB	-130.94 dB
8	-125.75 dB	-125.78 dB	-125.69 dB	-130.66 dB	-130.60 dB	-130.84 dB
10	-125.41 dB	-126.14 dB	-125.87 dB	-130.60 dB	-130.64 dB	-130.76 dB
12.5	-125.73 dB	-125.78 dB	-125.84 dB	-130.78 dB	-130.71 dB	-130.77 dB
16	-125.79 dB	-125.93 dB	-125.93 dB	-130.64 dB	-130.57 dB	-130.59 dB
20	-126.02 dB	-125.84 dB	-125.56 dB	-130.86 dB	-130.85 dB	-130.50 dB
25	-125.84 dB	-126.02 dB	-126.02 dB	-130.59 dB	-130.81 dB	-130.77 dB
31.5	-125.68 dB	-125.80 dB	-125.80 dB	-130.96 dB	-130.96 dB	-130.73 dB
40	-126.92 dB	-126.67 dB	-126.90 dB	-131.52 dB	-131.72 dB	-131.59 dB

Table 36 Terminated Noise, Gains 4x and 8Lx, 100 sps

Frequency (Hz)	Gain = 4x			Gain = 8Lx		
	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 5
0.01	-128.58 dB	-129.11 dB	-128.46 dB	-136.36 dB	-136.47 dB	-136.47 dB
0.0125	-129.04 dB	-129.45 dB	-128.81 dB	-136.98 dB	-137.02 dB	-137.02 dB
0.016	-129.87 dB	-129.98 dB	-129.45 dB	-138.12 dB	-137.93 dB	-137.93 dB
0.02	-130.67 dB	-130.50 dB	-130.07 dB	-139.07 dB	-138.75 dB	-138.75 dB
0.025	-131.35 dB	-130.99 dB	-130.68 dB	-139.67 dB	-139.37 dB	-139.37 dB
0.0315	-131.61 dB	-131.68 dB	-131.28 dB	-140.29 dB	-139.99 dB	-139.99 dB
0.04	-132.07 dB	-131.61 dB	-131.38 dB	-141.21 dB	-140.75 dB	-140.75 dB
0.05	-132.58 dB	-132.04 dB	-131.78 dB	-141.51 dB	-141.71 dB	-141.71 dB
0.063	-132.72 dB	-132.80 dB	-132.22 dB	-142.16 dB	-141.80 dB	-141.80 dB
0.08	-132.69 dB	-132.90 dB	-132.34 dB	-142.41 dB	-142.20 dB	-142.20 dB
0.1	-133.11 dB	-132.98 dB	-132.34 dB	-143.04 dB	-142.93 dB	-142.93 dB
0.125	-133.11 dB	-133.11 dB	-132.57 dB	-143.03 dB	-143.33 dB	-143.33 dB
0.16	-133.26 dB	-133.57 dB	-132.92 dB	-143.53 dB	-143.31 dB	-143.31 dB
0.2	-133.34 dB	-133.59 dB	-133.27 dB	-143.69 dB	-143.96 dB	-143.96 dB
0.25	-133.97 dB	-133.56 dB	-133.28 dB	-143.94 dB	-143.84 dB	-143.84 dB
0.315	-133.52 dB	-133.31 dB	-133.43 dB	-143.93 dB	-143.91 dB	-143.91 dB
0.4	-133.74 dB	-133.73 dB	-133.90 dB	-144.36 dB	-144.31 dB	-144.31 dB
0.5	-133.85 dB	-133.84 dB	-133.85 dB	-144.30 dB	-143.94 dB	-143.94 dB
0.63	-133.91 dB	-134.01 dB	-133.39 dB	-144.32 dB	-144.48 dB	-144.48 dB
0.8	-133.81 dB	-134.14 dB	-133.98 dB	-144.52 dB	-144.59 dB	-144.59 dB
1	-133.85 dB	-133.75 dB	-134.10 dB	-144.46 dB	-144.43 dB	-144.43 dB
1.25	-134.12 dB	-134.19 dB	-133.71 dB	-144.75 dB	-144.68 dB	-144.68 dB
1.6	-133.99 dB	-133.84 dB	-133.88 dB	-144.64 dB	-144.34 dB	-144.34 dB
2	-134.13 dB	-133.64 dB	-134.17 dB	-144.72 dB	-144.63 dB	-144.63 dB
2.5	-134.12 dB	-134.34 dB	-134.07 dB	-144.52 dB	-144.49 dB	-144.49 dB
3.15	-134.10 dB	-133.81 dB	-133.92 dB	-144.98 dB	-145.12 dB	-145.12 dB
4	-134.06 dB	-133.89 dB	-133.75 dB	-144.50 dB	-144.92 dB	-144.92 dB
5	-133.97 dB	-134.31 dB	-133.79 dB	-145.00 dB	-144.86 dB	-144.86 dB
6.3	-134.05 dB	-134.15 dB	-134.10 dB	-144.90 dB	-145.12 dB	-145.12 dB
8	-133.99 dB	-133.96 dB	-133.64 dB	-144.80 dB	-145.12 dB	-145.12 dB
10	-134.03 dB	-134.08 dB	-134.21 dB	-144.82 dB	-145.03 dB	-145.03 dB
12.5	-134.02 dB	-133.84 dB	-133.74 dB	-144.95 dB	-144.81 dB	-144.81 dB
16	-134.11 dB	-133.87 dB	-133.89 dB	-145.29 dB	-145.10 dB	-145.10 dB
20	-133.80 dB	-133.92 dB	-134.00 dB	-144.90 dB	-145.06 dB	-145.06 dB
25	-133.92 dB	-134.05 dB	-133.85 dB	-144.40 dB	-144.82 dB	-144.82 dB
31.5	-134.16 dB	-134.16 dB	-133.97 dB	-144.76 dB	-144.73 dB	-144.73 dB
40	-134.94 dB	-134.94 dB	-134.87 dB	-145.75 dB	-145.68 dB	-145.68 dB

Table 37 Terminated Noise, Gains 16x and 32x, 100 sps

Frequency (Hz)	Gain = 16x			Gain = 32x		
	Channel 4	Channel 5	Channel 6	Channel 4	Channel 5	Channel 6
0.01	-142.59 dB	-142.59 dB	-142.15 dB	-148.16 dB	-147.83 dB	-147.72 dB
0.0125	-143.06 dB	-143.11 dB	-142.62 dB	-148.65 dB	-148.31 dB	-148.10 dB
0.016	-143.95 dB	-144.05 dB	-143.73 dB	-149.67 dB	-149.40 dB	-148.89 dB
0.02	-144.75 dB	-144.87 dB	-144.67 dB	-150.58 dB	-150.35 dB	-149.80 dB
0.025	-145.38 dB	-145.44 dB	-145.27 dB	-151.21 dB	-150.98 dB	-150.85 dB
0.0315	-146.23 dB	-145.89 dB	-145.91 dB	-151.63 dB	-151.60 dB	-151.34 dB
0.04	-146.96 dB	-146.59 dB	-146.51 dB	-152.44 dB	-152.00 dB	-152.09 dB
0.05	-147.38 dB	-147.13 dB	-147.11 dB	-152.86 dB	-152.52 dB	-152.70 dB
0.063	-147.53 dB	-147.70 dB	-147.99 dB	-153.48 dB	-153.26 dB	-153.00 dB
0.08	-148.20 dB	-148.15 dB	-148.17 dB	-153.77 dB	-153.88 dB	-153.60 dB
0.1	-148.44 dB	-148.62 dB	-148.20 dB	-154.27 dB	-154.04 dB	-154.14 dB
0.125	-149.23 dB	-148.61 dB	-148.84 dB	-154.52 dB	-154.29 dB	-154.24 dB
0.16	-149.11 dB	-149.42 dB	-149.20 dB	-154.77 dB	-154.78 dB	-154.23 dB
0.2	-149.62 dB	-149.38 dB	-149.59 dB	-154.96 dB	-154.85 dB	-154.70 dB
0.25	-149.71 dB	-149.48 dB	-149.29 dB	-154.99 dB	-155.04 dB	-155.05 dB
0.315	-149.85 dB	-150.12 dB	-149.79 dB	-155.10 dB	-155.43 dB	-155.21 dB
0.4	-149.99 dB	-149.91 dB	-149.79 dB	-155.16 dB	-155.02 dB	-155.34 dB
0.5	-150.52 dB	-150.06 dB	-150.05 dB	-155.95 dB	-155.62 dB	-155.47 dB
0.63	-150.25 dB	-149.80 dB	-150.15 dB	-155.51 dB	-155.42 dB	-155.48 dB
0.8	-150.23 dB	-150.30 dB	-150.40 dB	-155.84 dB	-155.82 dB	-155.74 dB
1	-150.64 dB	-150.07 dB	-150.15 dB	-155.53 dB	-155.63 dB	-155.80 dB
1.25	-150.43 dB	-150.25 dB	-150.34 dB	-155.79 dB	-155.84 dB	-155.78 dB
1.6	-150.19 dB	-150.64 dB	-150.67 dB	-156.00 dB	-155.72 dB	-155.85 dB
2	-150.49 dB	-150.77 dB	-150.55 dB	-155.91 dB	-156.06 dB	-155.92 dB
2.5	-150.67 dB	-150.29 dB	-150.58 dB	-156.20 dB	-155.70 dB	-155.97 dB
3.15	-150.58 dB	-150.47 dB	-150.24 dB	-156.08 dB	-155.82 dB	-155.53 dB
4	-150.30 dB	-150.84 dB	-150.43 dB	-156.27 dB	-155.67 dB	-155.94 dB
5	-150.35 dB	-151.14 dB	-150.80 dB	-155.75 dB	-155.96 dB	-155.74 dB
6.3	-150.83 dB	-150.72 dB	-150.74 dB	-156.12 dB	-155.91 dB	-156.21 dB
8	-150.63 dB	-150.65 dB	-150.80 dB	-155.86 dB	-155.78 dB	-155.71 dB
10	-150.79 dB	-150.64 dB	-150.46 dB	-155.98 dB	-156.21 dB	-155.78 dB
12.5	-150.82 dB	-150.49 dB	-150.45 dB	-156.02 dB	-155.75 dB	-156.12 dB
16	-150.51 dB	-150.91 dB	-150.61 dB	-156.24 dB	-156.02 dB	-155.80 dB
20	-150.53 dB	-150.58 dB	-150.29 dB	-156.03 dB	-156.35 dB	-155.98 dB
25	-150.44 dB	-150.86 dB	-150.73 dB	-155.86 dB	-155.91 dB	-155.86 dB
31.5	-150.78 dB	-150.75 dB	-150.55 dB	-155.95 dB	-156.31 dB	-156.01 dB
40	-151.74 dB	-151.59 dB	-151.59 dB	-157.17 dB	-157.13 dB	-156.88 dB

Table 38 Self Noise RMS over 0.01 Hz to 10 Hz

Gain	Sample Rate	Channel 1	Channel 2	Channel 3
1x	100 sps	1.647 uV rms	1.641 uV rms	1.659 uV rms
		0.692 counts rms	0.689 counts rms	0.697 counts rms
	40 sps	1.684 uV rms	1.678 uV rms	1.693 uV rms
		0.711 counts rms	0.709 counts rms	0.715 counts rms
	20 sps	1.622 uV rms	1.617 uV rms	1.631 uV rms
		0.685 counts rms	0.683 counts rms	0.689 counts rms
		Channel 1	Channel 2	Channel 3
2x	100 sps	929.9 nV rms	929.9 nV rms	936.3 nV rms
		0.781 counts rms	0.781 counts rms	0.787 counts rms
	40 sps	945.7 nV rms	945.5 nV rms	951.8 nV rms
		0.799 counts rms	0.799 counts rms	0.804 counts rms
	20 sps	899.5 nV rms	900.3 nV rms	906.0 nV rms
		0.760 counts rms	0.760 counts rms	0.765 counts rms
		Channel 1	Channel 2	Channel 3
4x	100 sps	634.9 nV rms	633.8 nV rms	638.4 nV rms
		1.066 counts rms	1.065 counts rms	1.072 counts rms
	40 sps	640.1 nV rms	639.1 nV rms	643.3 nV rms
		1.081 counts rms	1.079 counts rms	1.086 counts rms
	20 sps	597.0 nV rms	596.0 nV rms	600.0 nV rms
		1.008 counts rms	1.006 counts rms	1.013 counts rms
		Channel 4	Channel 5	Channel 6
8Lx	100 sps	184.0 nV rms	183.8 nV rms	186.2 nV rms
		0.618 counts rms	0.618 counts rms	0.625 counts rms
	40 sps	189.3 nV rms	189.1 nV rms	191.5 nV rms
		0.639 counts rms	0.639 counts rms	0.646 counts rms
	20 sps	184.7 nV rms	184.3 nV rms	186.4 nV rms
		0.624 counts rms	0.622 counts rms	0.629 counts rms
		Channel 4	Channel 5	Channel 6
16x	100 sps	94.2 nV rms	94.4 nV rms	95.2 nV rms
		0.633 counts rms	0.634 counts rms	0.638 counts rms
	40 sps	96.8 nV rms	96.9 nV rms	97.7 nV rms
		0.653 counts rms	0.655 counts rms	0.659 counts rms
	20 sps	94.2 nV rms	94.3 nV rms	95.1 nV rms
		0.636 counts rms	0.637 counts rms	0.641 counts rms
		Channel 4	Channel 5	Channel 6
32x	100 sps	50.7 nV rms	51.0 nV rms	51.6 nV rms
		0.681 counts rms	0.685 counts rms	0.692 counts rms
	40 sps	51.9 nV rms	52.1 nV rms	52.7 nV rms
		0.700 counts rms	0.703 counts rms	0.711 counts rms
	20 sps	50.0 nV rms	50.3 nV rms	50.8 nV rms
		0.675 counts rms	0.679 counts rms	0.685 counts rms

Table 39 Self Noise RMS over 0.01 Hz to 40 Hz

Gain	Sample Rate	Channel 1	Channel 2	Channel 3
1x	100 sps	3.242 uV rms	3.224 uV rms	3.253 uV rms
		1.362 counts rms	1.355 counts rms	1.367 counts rms
	40 sps	2.160 uV rms	2.153 uV rms	2.167 uV rms
		0.912 counts rms	0.910 counts rms	0.916 counts rms
	20 sps	1.622 uV rms	1.617 uV rms	1.631 uV rms
		0.685 counts rms	0.683 counts rms	0.689 counts rms
		Channel 1	Channel 2	Channel 3
2x	100 sps	1.840 uV rms	1.834 uV rms	1.843 uV rms
		1.546 counts rms	1.541 counts rms	1.548 counts rms
	40 sps	1.213 uV rms	1.212 uV rms	1.218 uV rms
		1.024 counts rms	1.023 counts rms	1.029 counts rms
	20 sps	899.5 nV rms	900.3 nV rms	906.0 nV rms
		0.760 counts rms	0.760 counts rms	0.765 counts rms
		Channel 1	Channel 2	Channel 3
4x	100 sps	1.261 uV rms	1.257 uV rms	1.263 uV rms
		2.117 counts rms	2.112 counts rms	2.121 counts rms
	40 sps	820.1 nV rms	818.4 nV rms	822.7 nV rms
		1.385 counts rms	1.382 counts rms	1.389 counts rms
	20 sps	597.0 nV rms	596.0 nV rms	600.0 nV rms
		1.008 counts rms	1.006 counts rms	1.013 counts rms
		Channel 4	Channel 5	Channel 6
8Lx	100 sps	362.0 nV rms	361.7 nV rms	364.9 nV rms
		1.216 counts rms	1.215 counts rms	1.224 counts rms
	40 sps	243.1 nV rms	243.0 nV rms	245.6 nV rms
		0.821 counts rms	0.821 counts rms	0.828 counts rms
	20 sps	184.7 nV rms	184.3 nV rms	186.4 nV rms
		0.624 counts rms	0.622 counts rms	0.629 counts rms
		Channel 4	Channel 5	Channel 6
16x	100 sps	185.5 nV rms	185.4 nV rms	187.2 nV rms
		1.246 counts rms	1.245 counts rms	1.255 counts rms
	40 sps	124.3 nV rms	124.4 nV rms	125.5 nV rms
		0.839 counts rms	0.841 counts rms	0.846 counts rms
	20 sps	94.2 nV rms	94.3 nV rms	95.1 nV rms
		0.636 counts rms	0.637 counts rms	0.641 counts rms
		Channel 4	Channel 5	Channel 6
32x	100 sps	100.0 nV rms	100.3 nV rms	101.6 nV rms
		1.342 counts rms	1.347 counts rms	1.362 counts rms
	40 sps	66.6 nV rms	66.9 nV rms	67.6 nV rms
		0.899 counts rms	0.903 counts rms	0.911 counts rms
	20 sps	50.0 nV rms	50.3 nV rms	50.8 nV rms
		0.675 counts rms	0.679 counts rms	0.685 counts rms

Average self noise of 100 sps channels the over the 0.01 Hz – 10 Hz passband, ranged from as much as 1.649 uV rms for the gain of 1x to as low as 51.1 nV rms at a gain of 32x. No rms noise value varied more than 0.99% (at gain 32x) from their respective average rms noise values. Rms noise values remained well below 2 counts rms (1.072 counts rms at a gain of 4x) across all gain settings.

Average self noise evaluated at 20 and 40 sps varied no more than 6.0% (20 sps at a gain of 4x) from the respective values for the average self noise rms of 100 sps data. Similarly, self noise values remained well below the equivalent of 2 counts rms across all gain settings.
Over the frequency range of 0.01 Hz to 40 Hz, we limit our comments to the 100 sps data as the limits in frequency content of the 40 sps and 20 sps obviously lower the rms noise computed over this frequency range. Average self noise of 100 sps channels over the passband, ranged from as much as 3.240 uV rms for the gain of 1x to as low as 100.6 nV rms at a gain of 32x. No rms noise value exceeded 0.98% from their respective average rms noise values. Rms noise values did not exceed the equivalent of 2 counts rms while operating all gains except a gain of 4x, which exceeded 2 counts (2.121 counts).

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 3.7 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

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

The 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 peak-to-peak full scales, noise levels, and dynamic ranges that were identified in the evaluations of the sample rates and gain levels over the frequency range 0.01 Hz to 10 Hz.

Table 40 Dynamic Range, 0.01 Hz to 10 Hz, 100 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	138.68 dB	138.71 dB	138.62 dB	-	-	-
2x	137.62 dB	137.62 dB	137.56 dB	-	-	-
4x	134.92 dB	134.93 dB	134.87 dB	-	-	-
8Lx	-	-	-	139.65 dB	139.66 dB	139.55 dB
16x	-	-	-	139.44 dB	139.43 dB	139.36 dB
32x	-	-	-	138.81 dB	138.76 dB	138.65 dB

Table 41 Dynamic Range, 0.01 Hz to 10 Hz, 40 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	138.49 dB	138.52 dB	138.44 dB	-	-	-
2x	137.48 dB	137.48 dB	137.42 dB	-	-	-
4x	134.84 dB	134.86 dB	134.80 dB	-	-	-
8Lx	-	-	-	139.41 dB	139.42 dB	139.31 dB
16x	-	-	-	139.21 dB	139.20 dB	139.13 dB
32x	-	-	-	138.61 dB	138.57 dB	138.47 dB

Table 42 Dynamic Range, 0.01 Hz to 10 Hz, 20 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	138.81 dB	138.84 dB	138.76 dB	-	-	-
2x	137.91 dB	137.90 dB	137.85 dB	-	-	-
4x	135.45 dB	135.46 dB	135.41 dB	-	-	-
8Lx	-	-	-	139.62 dB	139.64 dB	139.54 dB
16x	-	-	-	139.45 dB	139.44 dB	139.37 dB
32x	-	-	-	138.93 dB	138.87 dB	138.79 dB

Table 43 Dynamic Range, 0.01 Hz to 40 Hz, 100 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	132.79 dB	132.84 dB	132.77 dB	-	-	-
2x	131.69 dB	131.72 dB	131.68 dB	-	-	-
4x	128.96 dB	128.98 dB	128.94 dB	-	-	-
8Lx	-	-	-	133.78 dB	133.78 dB	133.71 dB
16x	-	-	-	133.56 dB	133.57 dB	133.48 dB
32x	-	-	-	132.91 dB	132.88 dB	132.77 dB

The observed dynamic range values over the 0.01 Hz and 10 Hz passband varied across all sample rates from 138.44 dB (chan 3, 40 sps) to 138.81 dB (chan 1, 20 sps) at a gain of 1x, while at a gain of 32x observed dynamic ranges varied from 138.47 dB (chan 6, 40 sps) to 138.93 dB (chan 4 20 sps).

Over the frequency range of 0.01 Hz to 40 Hz, we limit our comments to the 100 sps data as the limits in frequency content of the 40 sps and 20 sps data obviously raise the dynamic range as signal above their respective Nyquist frequency is absent. Dynamic ranges varied from as little as 128.94 dB (chan 3), at a gain of 4x to as high as 133.78 dB (chans 4 and 5) at a gain of 8Lx.

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 $(dB)^2/Hz$ versus frequency.

3.10.2 Configuration

There is no test configuration for the dynamic range test.

3.10.3 Analysis

The time-series data and PSD computed in 3.8 section 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. A representative channel's data, from the isolation noise tests, has the response and sensitivity of a selection of sensors applied to determine equivalent infrasound and seismic system noise.

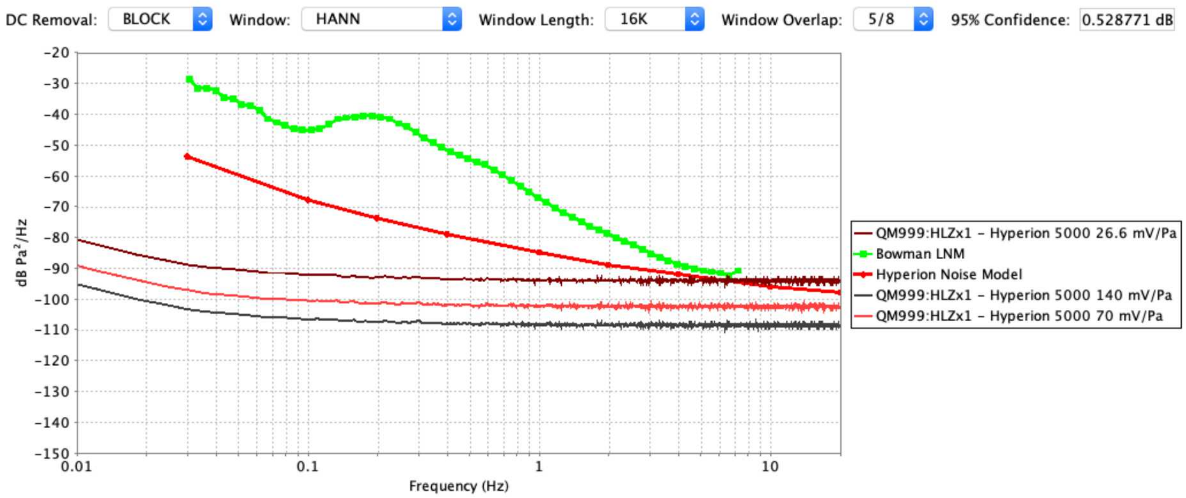


Figure 51 System Noise, Hyperion 5000 series, 140 mV/Pa, 70 mV/Pa, 26.6 mV/Pa, Gain 1x

System noise of the Q330M+ with the Hyperion 5000 series response (26.6 mV/Pa) rises above the self noise of the Hyperion sensor, while the higher sensitivity units' self noise remains below the sensors noise model.

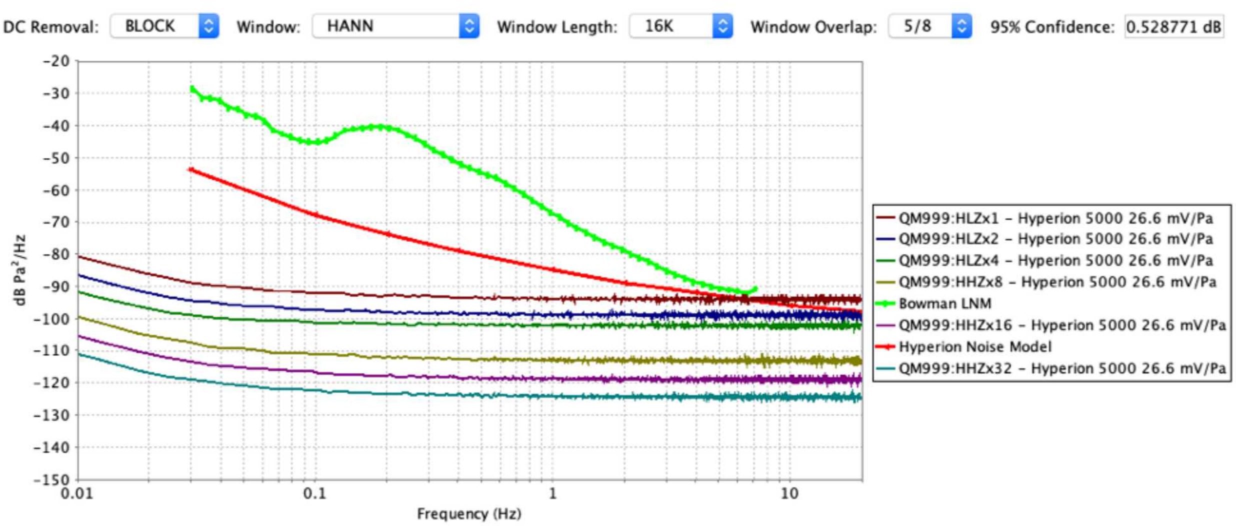


Figure 52 System Noise, Hyperion 5000 series, 26.6 mV/Pa, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

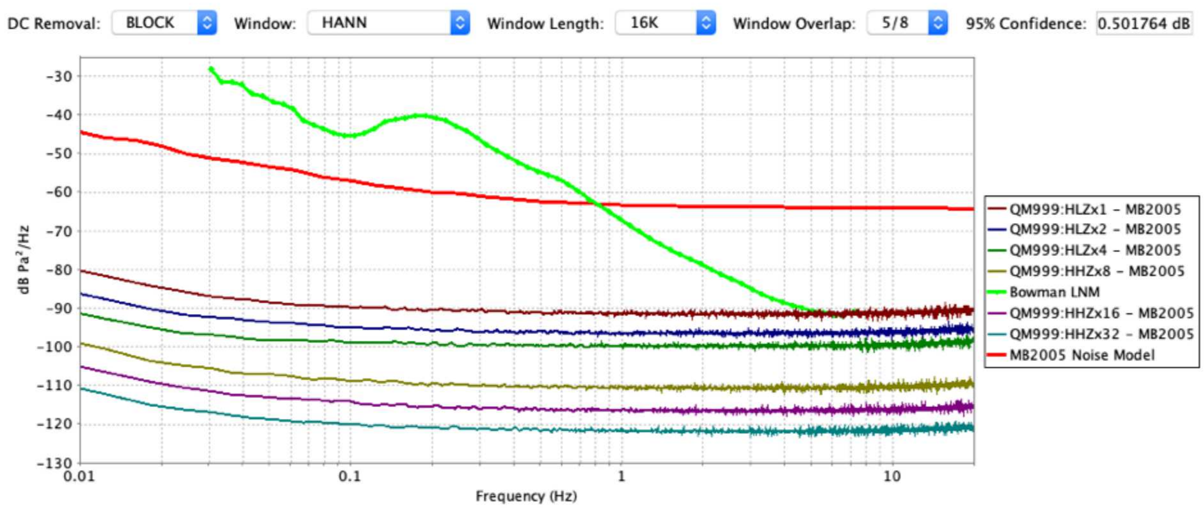


Figure 53 System Noise, MB2005, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

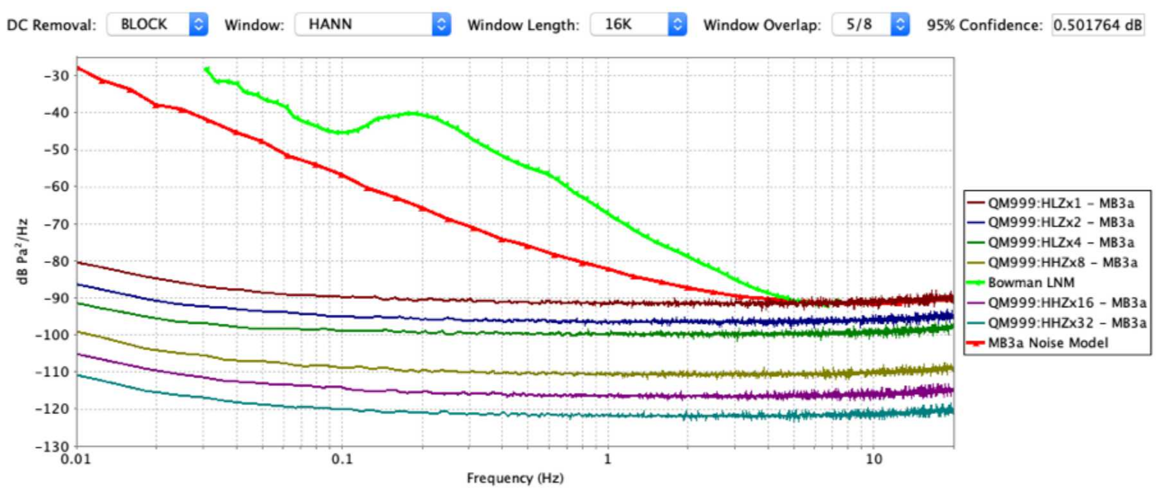


Figure 54 System Noise, MB3a, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

With the MB2005 (20 mV/Pa) response applied, system noise is well below the self noise, even at a gain of 1x. When system noise has the response of the Hyperion 5000 series (26.6 mV/Pa) or MB3a (20 mV/Pa) applied, as shown in Figure 52 and Figure 54, respectively, the system noise clearly illustrates the need to operate the Q330M+ at gain settings greater than 1x, as the system noise at a gain of 1x is above each sensors' self noise; above 6.5 Hz and 5.5 Hz, for the Hyperion and MB3a, respectively.

Seismic system noise, utilizing seismometer responses for the Guralp CMG3T (1500 Vs/m), Geotech GS-13 (2000 Vs/m), Streckheisen STS-2 (1500 Vs/m) and STS-5a (1500 Vs/m) and Nanometrics T-120 (1200 Vs/m) are plotted below.

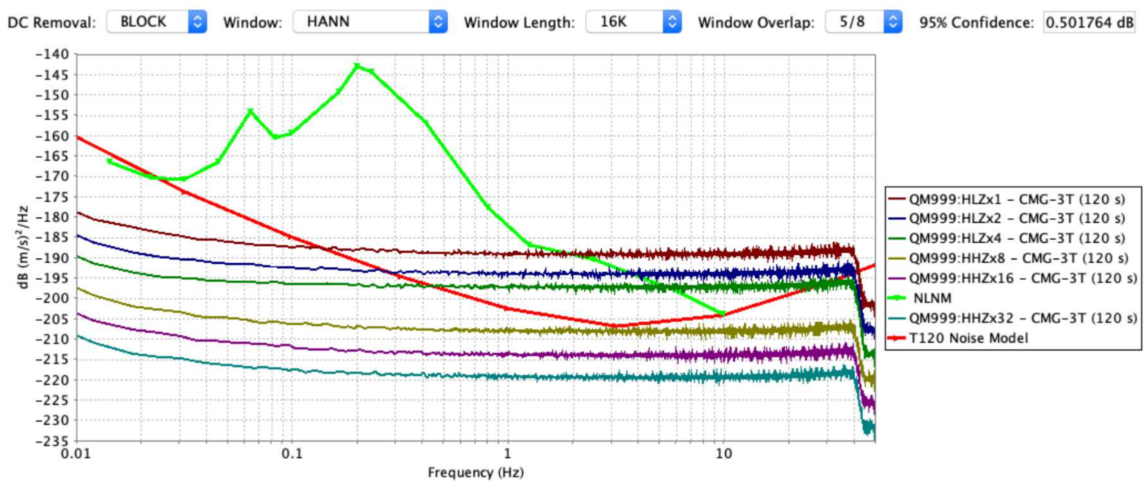


Figure 55 System Noise, CMG-3T, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

System noise in CMG3-T equivalent units exceed that of the CMG-3T noise model, above 0.47 Hz, 0.59 Hz and 0.73 Hz, at gains of 1x, 2x and 4x respectively. At a gain of 8Lx equivalent system noise exceed the self noise of the CMG3-T from 1.9 Hz to 18 Hz.

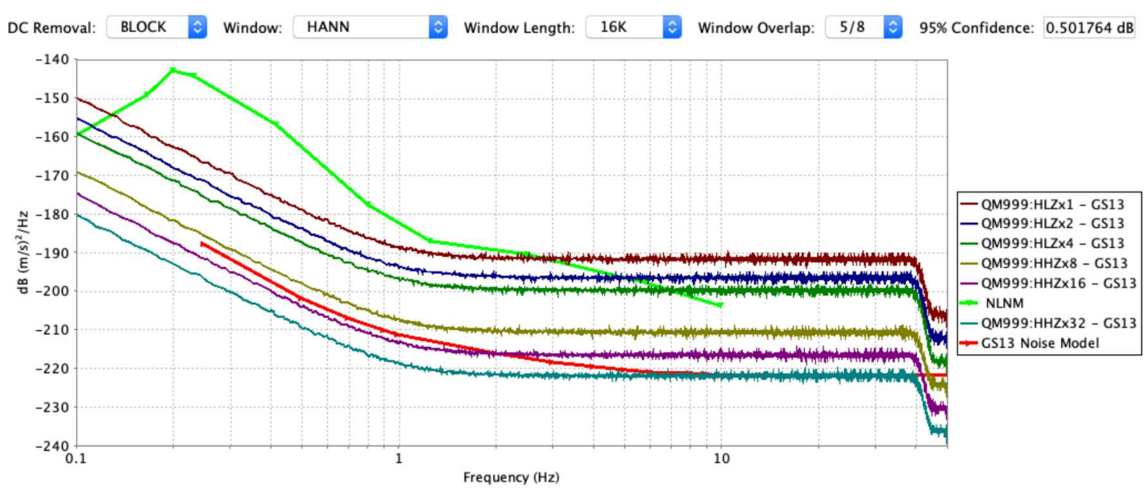


Figure 56 System Noise, GS-13, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

When expressed in GS-13 equivalent units system noise is well above that of the GS-13 noise model at gains of 1x, 2x, 4x and 8Lx. With the Q330M+ configured with a gain of 16x, system noise, at frequencies above 2.3 Hz, exceeds that of the GS-13. At a gain of 32x the equivalent system noise of the Q330M+ is below that of the GS-13 below 7.9 Hz; above this frequency system noise approximates that of a GS-13.

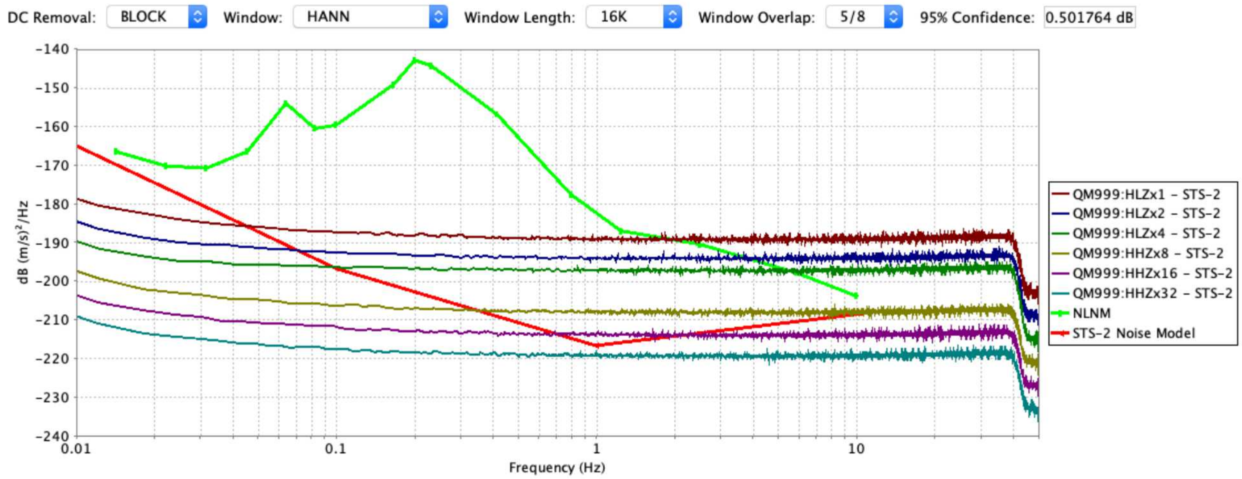


Figure 57 System Noise, STS-2, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

At all but a gain of 32x does the system noise of the Q330M+ remain below the self noise of an STS-2. System noise exceeds self noise of an STS2 at and above the following frequencies 0.045 Hz, 0.067 Hz, 0.098 Hz and 0.39 Hz, at gains of 1x, 2x, 4x and 8Lx, respectively. System noise at a gain of 16x, exceeds the self noise of an STS-2 between the frequencies 0.70 Hz and 2.3 Hz.

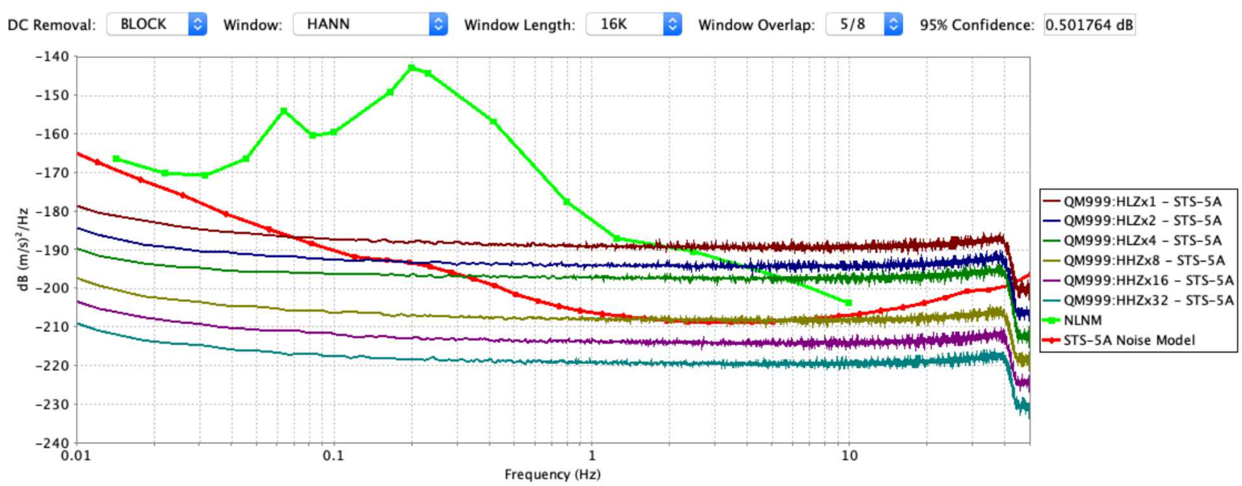


Figure 58 System Noise, STS-5a, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

System noise of the Q330M+ expressed in units of STS-5a response, exceeds the self noise of the sensor above the following frequencies: 0.07 Hz, 0.17 Hz and 0.33 Hz at gains of 1x, 2x and 4x, respectively. At a gain of 8Lx, the Q330 system noise only exceeds the STS-5a noise model between 1.6 Hz and 7.3 Hz.

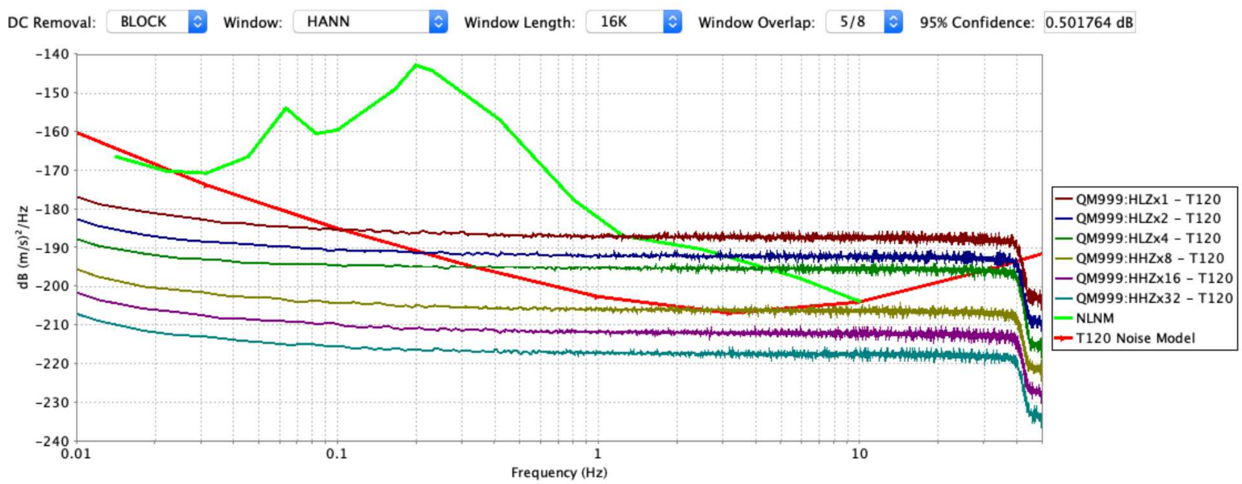


Figure 59 System Noise, T-120, Gains 1x, 2x, 4x, 8Lx, 16x, 32x

At gains below 16x, system noise of the Q330M+, with a T-120 response applied, exceeds self noise the sensor. At a gains of 1x and 2x, above 0.11 Hz and 0.23 Hz, respectively, system noise exceeds that of the T-120 self noise. System noise exceeds T-120 self noise over the frequency ranges of 0.36 Hz to 32 Hz and 2.6 Hz to 4.8 Hz, at gains of 4x and 8Lx, respectively.

3.11 Temperature Self Noise

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

3.11.1 Measurand

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

3.11.2 Configuration

The digitizer input channel is connected to a shorting resistor as shown in the diagram below. Termination resistors are located at outside of the chamber (held at room temperature) to avoid the expected effects of the resistors' exposure to the temperature extremes.

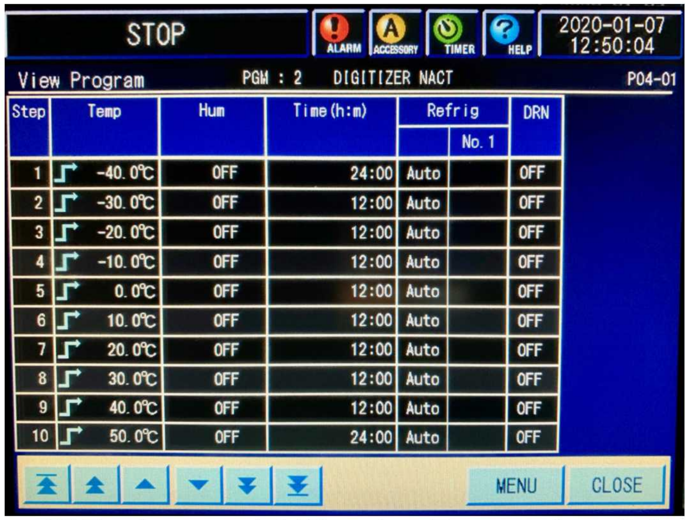
Figure 60 Self Noise Configuration Diagram

Figure 61 Input Shorted Offset Temperature Test

Table 44 Input Terminated Noise Termination Resistors

Termination Resistor
200 ohm (100 x 2 ohm)

Approximately 8 hours of data is recorded beginning hours after the digitizer has acclimatized to the new temperature setting.



Step	Temp	Hum	Time (h:m)	Refrig		DRN
					No. 1	
1	-40.0℃	OFF	24:00	Auto		OFF
2	-30.0℃	OFF	12:00	Auto		OFF
3	-20.0℃	OFF	12:00	Auto		OFF
4	-10.0℃	OFF	12:00	Auto		OFF
5	0.0℃	OFF	12:00	Auto		OFF
6	10.0℃	OFF	12:00	Auto		OFF
7	20.0℃	OFF	12:00	Auto		OFF
8	30.0℃	OFF	12:00	Auto		OFF
9	40.0℃	OFF	12:00	Auto		OFF
10	50.0℃	OFF	24:00	Auto		OFF

Figure 62 Environmental Chamber Temperature Schedule

3.11.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using between a 32K-sample Hann window. The window length and data duration were chosen such that there were a few points below the lower limit of the evaluation pass-band of 0.01 Hz and the 90% confidence interval is less than 0.94 dB.

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

Over frequencies (in Hertz):

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

In addition, the total RMS noise over the application pass-band of 0.02 to 4.0 Hz 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

3.11.4 Result

The time series plot over the time over the temperature testing time period are shown below. Only the data from 100 Hz is shown as the other sample rates are otherwise identical.

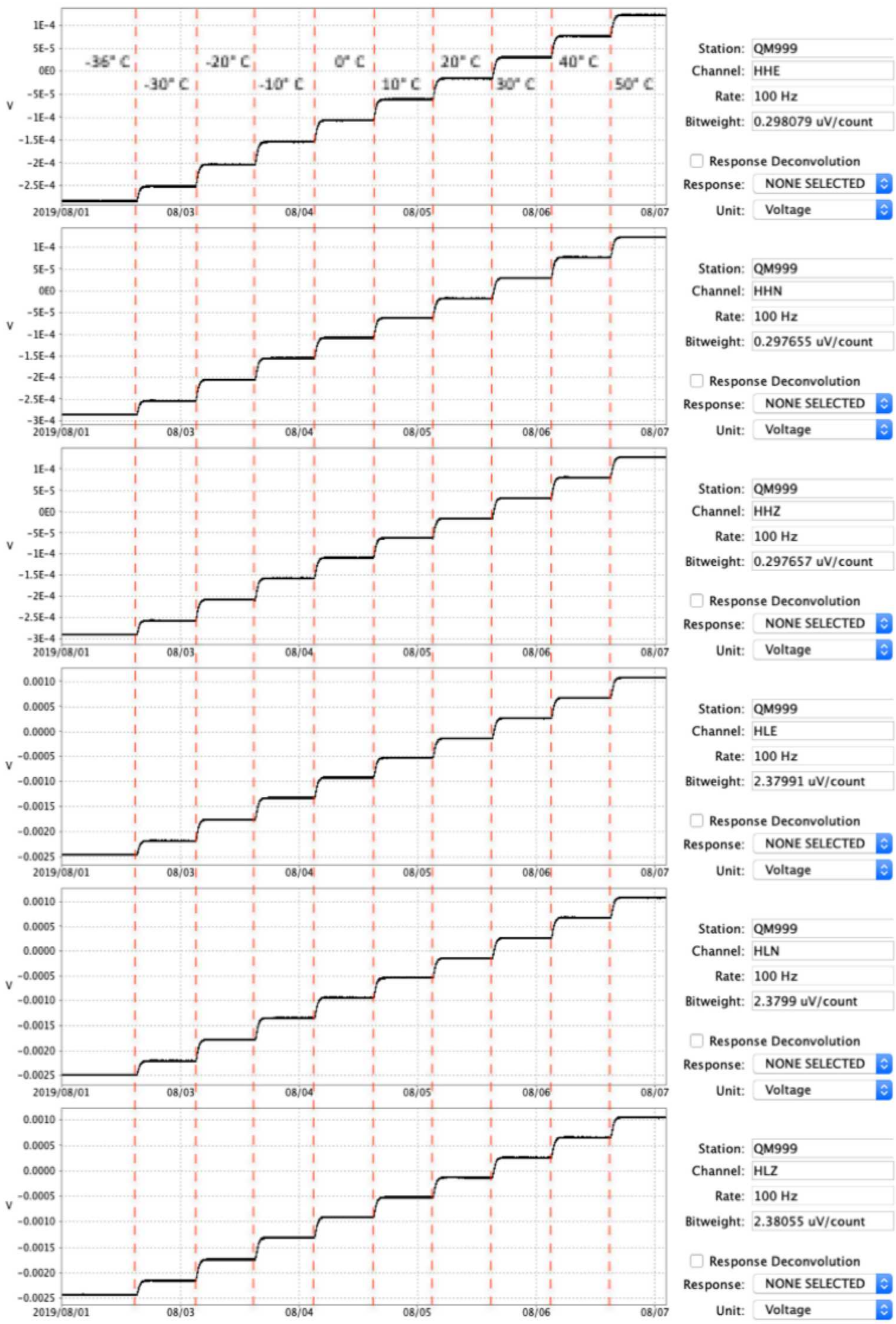


Figure 63 Self Noise Time Series over -36° C to 50° C

The plot in Figure 63 Self Noise Time Series over -36° C to 50° C clearly illustrates the linear relationship between the input shorted offset voltage and temperature. The following table provides the rate change in DC offset between temperatures and the rate of change over the temperature extremes. DC offset were relatively small and the observed rate of change in DC offset with temperature remains relatively constant over the temperatures over which DC offset was evaluated.

The offset of the voltage illustrated in the plot are shown in the following table.

Table 45 DC Offset and Rate of Change of DC Offset with Temperature, Gains 1x and 8Lx

Temp.	HLZ	HLN	HLE	HHZ	HHN	HHE
	Gain 1x			Gain 8Lx		
	DC Offset					
	DC Offset Rate of Change					
-36° C	-2.4323 mV	-2.4897 mV	-2.4575 mV	-0.2896 mV	-0.2861 mV	-0.2845 mV
	-0.0464 mV/C	-0.0469 mV/C	-0.0466 mV/C	-0.0054 mV/C	-0.0054 mV/C	-0.0053 mV/C
-30° C	-2.1541 mV	-2.2082 mV	-2.1780 mV	-0.2570 mV	-0.2539 mV	-0.2525 mV
	-0.0464 mV/C	-0.0469 mV/C	-0.0466 mV/C	-0.0054 mV/C	-0.0054 mV/C	-0.0053 mV/C
-20° C	-1.7384 mV	-1.7866 mV	-1.7592 mV	-0.2079 mV	-0.2054 mV	-0.2042 mV
	-0.0428 mV/C	-0.0437 mV/C	-0.0433 mV/C	-0.0051 mV/C	-0.0050 mV/C	-0.0050 mV/C
-10° C	-1.3103 mV	-1.3498 mV	-1.3258 mV	-0.1568 mV	-0.1551 mV	-0.1541 mV
	-0.0400 mV/C	-0.0409 mV/C	-0.0405 mV/C	-0.0048 mV/C	-0.0047 mV/C	-0.0047 mV/C
0° C	-0.9105 mV	-0.9404 mV	-0.9205 mV	-0.1089 mV	-0.1080 mV	-0.1072 mV
	-0.0389 mV/C	-0.0400 mV/C	-0.0394 mV/C	-0.0047 mV/C	-0.0046 mV/C	-0.0046 mV/C
10° C	-0.5218 mV	-0.5408 mV	-0.5262 mV	-0.0622 mV	-0.0620 mV	-0.0614 mV
	-0.0384 mV/C	-0.0396 mV/C	-0.0389 mV/C	-0.0046 mV/C	-0.0045 mV/C	-0.0045 mV/C
20° C	-0.1381 mV	-0.1448 mV	-0.1374 mV	-0.0160 mV	-0.0166 mV	-0.0161 mV
	-0.0393 mV/C	-0.0405 mV/C	-0.0400 mV/C	-0.0047 mV/C	-0.0047 mV/C	-0.0046 mV/C
30° C	0.2547 mV	0.2605 mV	0.2627 mV	0.0314 mV	0.0300 mV	0.0301 mV
	-0.0399 mV/C	-0.0413 mV/C	-0.0409 mV/C	-0.0048 mV/C	-0.0047 mV/C	-0.0047 mV/C
40° C	0.6538 mV	0.6734 mV	0.6714 mV	0.0796 mV	0.0774 mV	0.0772 mV
	-0.0386 mV/C	-0.0400 mV/C	-0.0399 mV/C	-0.0047 mV/C	-0.0046 mV/C	-0.0046 mV/C
50° C	1.0399 mV	1.0733 mV	1.0704 mV	0.1264 mV	0.1235 mV	0.1228 mV
Average Rate of Change - Entire Temperature Range						
	-2.4444 mV/C	-2.5022 mV/C	-2.4699 mV/C	-0.2910 mV/C	-0.2875 mV/C	-0.2860 mV/C

The power spectra for the data collected at gain of 1x and 8Lx and temperature are shown in the plots below.

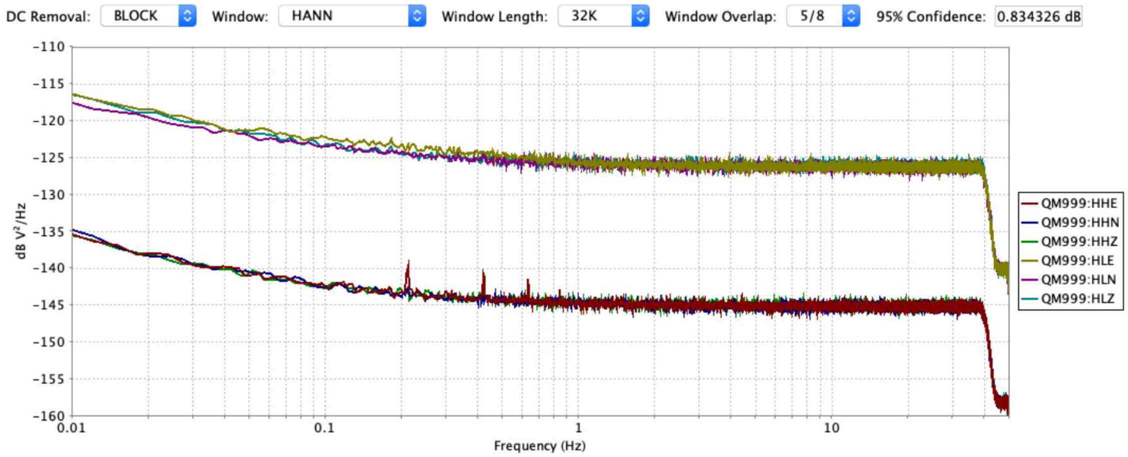


Figure 64 Self Noise, Gain 1x and 8Lx, Ambient Temperature -36° C

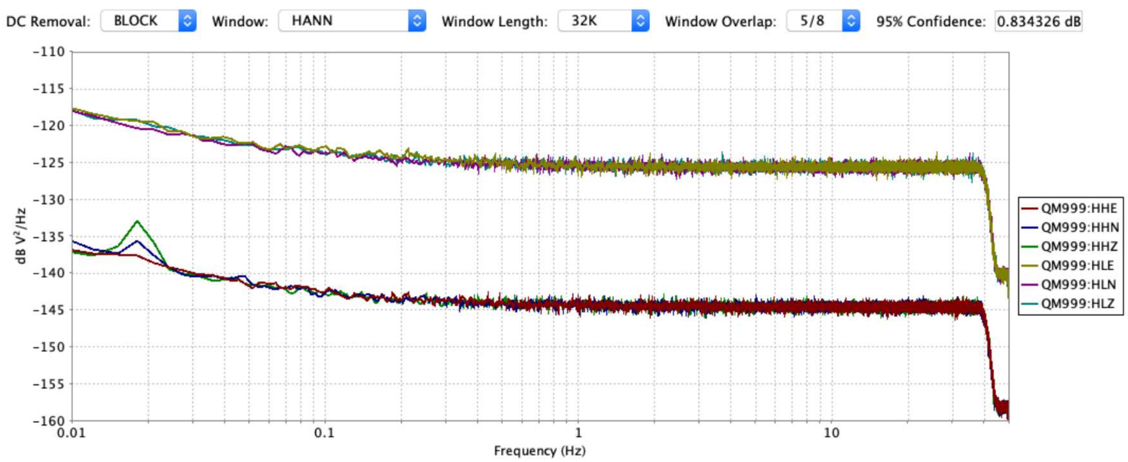


Figure 65 Self Noise, Gain 1x and 8Lx, Ambient Temperature 50° C

The above plots illustrate that the self noise of all channels increases slightly, approximately 4 dB and 1 dB higher, for the gains of 1x and 8x, respectively, at 50° C over that of the -36° C observations, excluding the increase on the gain x8L channels (HHZ, HHN and HHE) between 0.015 Hz and 0.021 Hz visible in the 50° C self noise plot.

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.

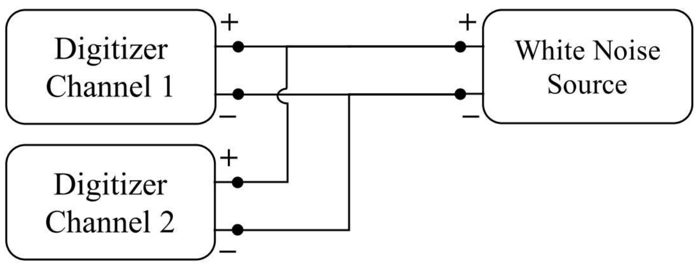


Figure 66 Response Verification Configuration Diagram

Figure 67 Relative Transfer Function Configuration Picture

Table 46 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	Stanford Research Systems, DS3360	123762	+1V / - 1 V

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

3.12.3 Analysis

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

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

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

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

3.12.4 Result

The coherence and relative amplitude and phase response were computed between channel 1 and the remaining three channels for all of the evaluated sample rate and gain configurations. In all cases, the coherence was identically 1.0 across the entire pass-band. The coherence, relative amplitude, and relative phase are shown in the plots below. Coherence is consistently very high at all gain and sample rates, hence only the first coherence plot is provided.

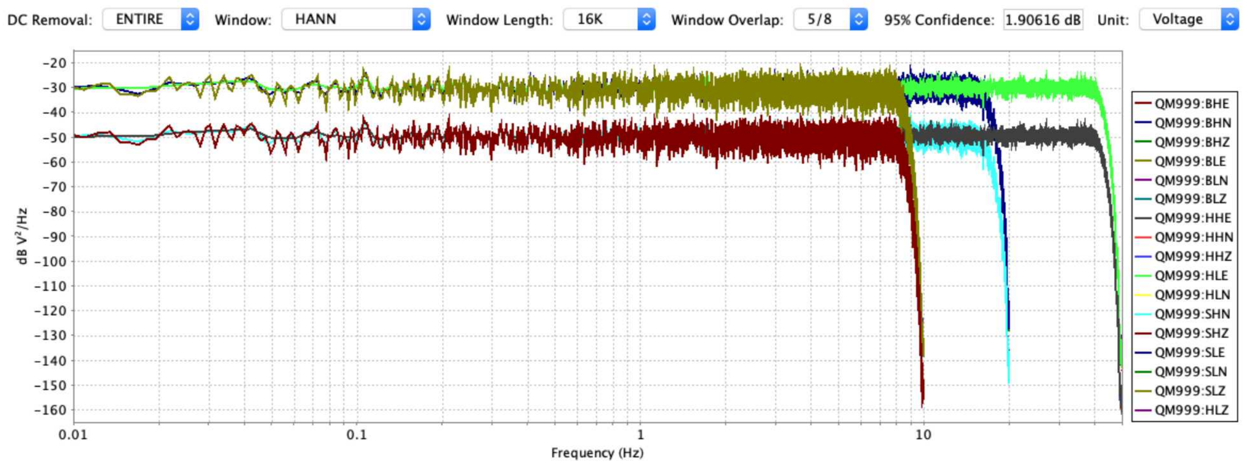


Figure 68 White Noise Power Spectra, 1x and 8x Gains, 100 sps, 40 sps and 20 sps

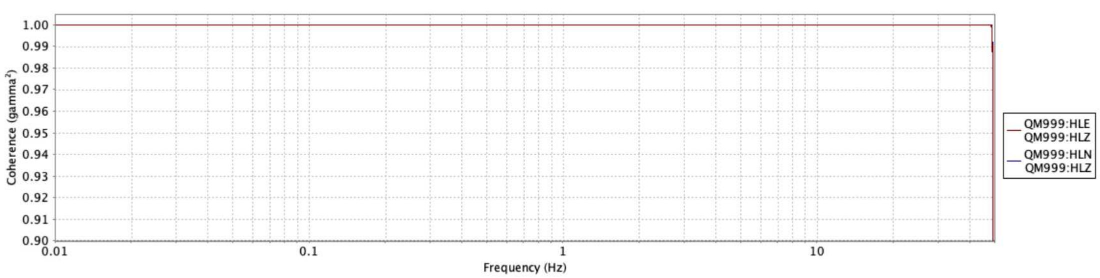


Figure 69 White Noise Coherence, Gain 1x, 200 sps

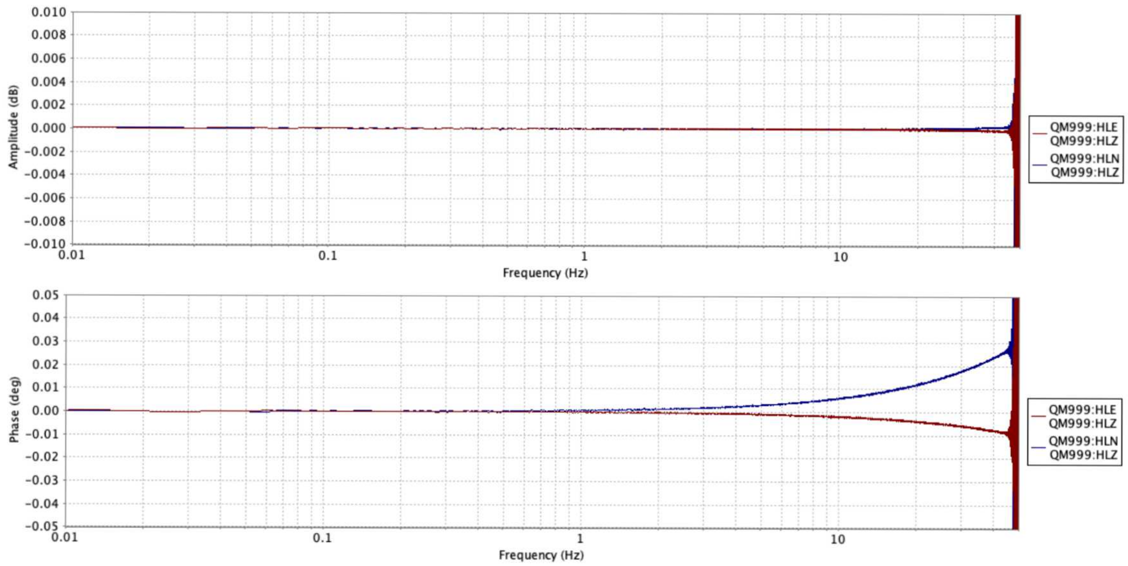


Figure 70 Relative Amplitude and Phase, Gain 1x, 100 sps

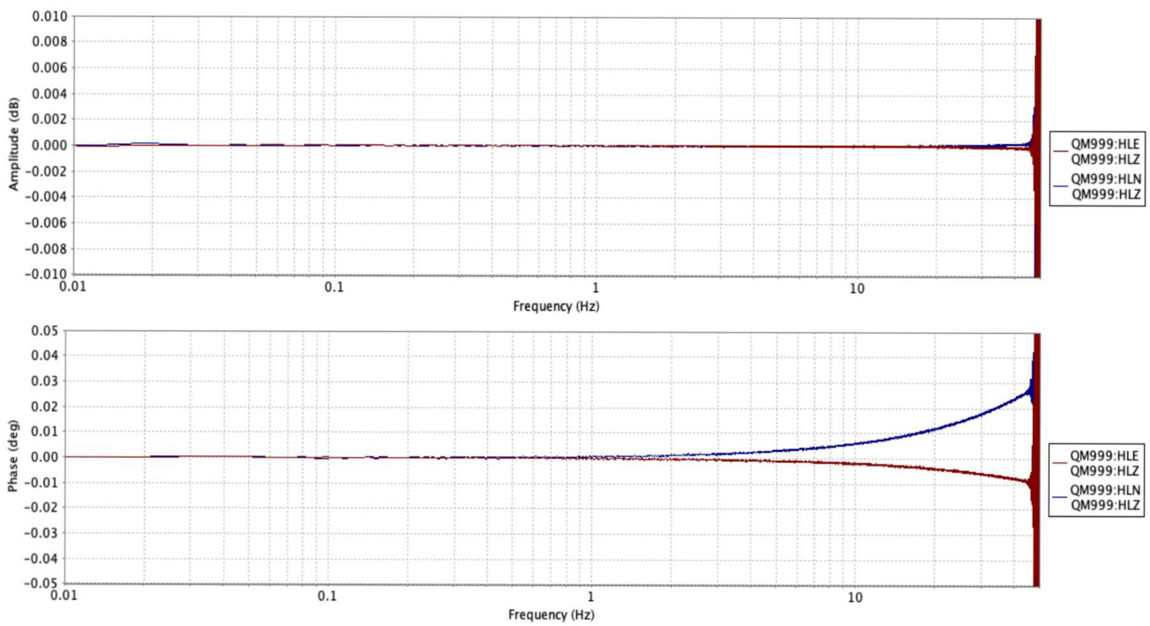


Figure 71 Relative Amplitude and Phase, Gain 2x, 100 sps

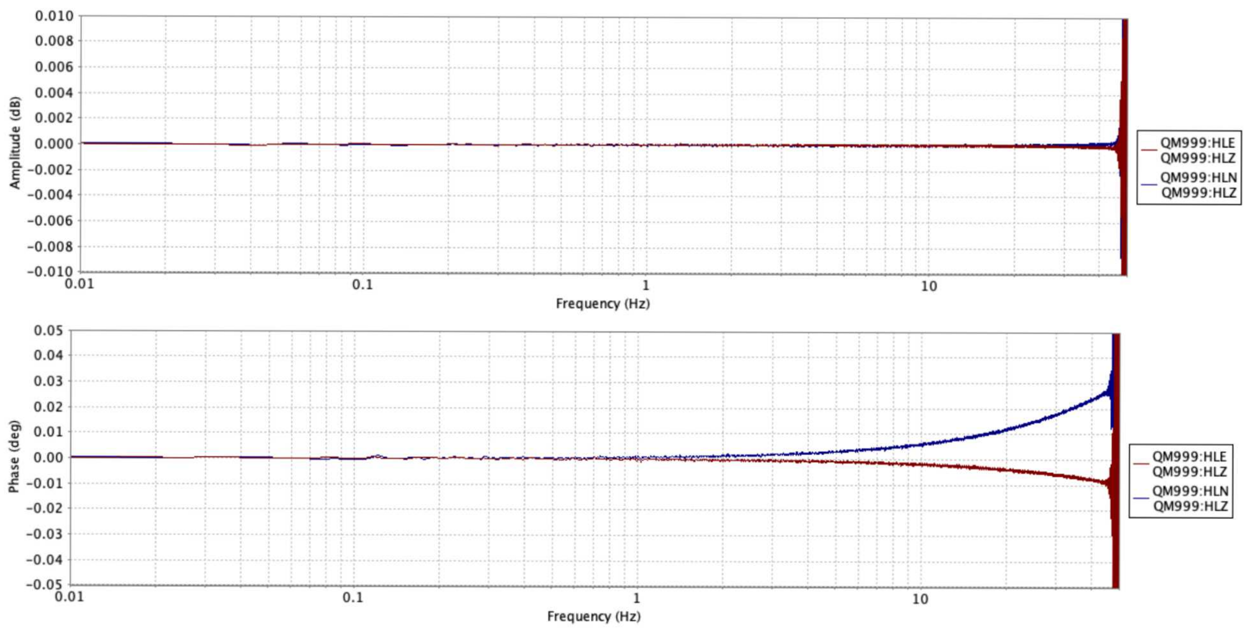


Figure 72 Relative Amplitude and Phase, Gain 4x, 100 sps

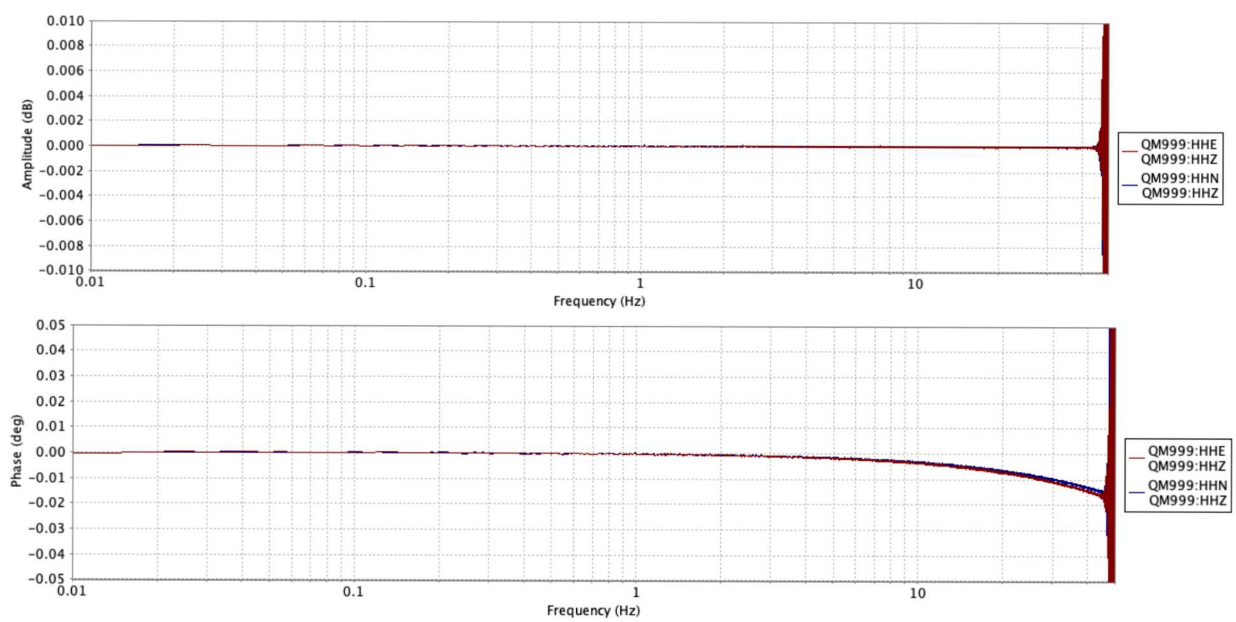


Figure 73 Relative Amplitude and Phase, Gain 8Lx, 100 sps

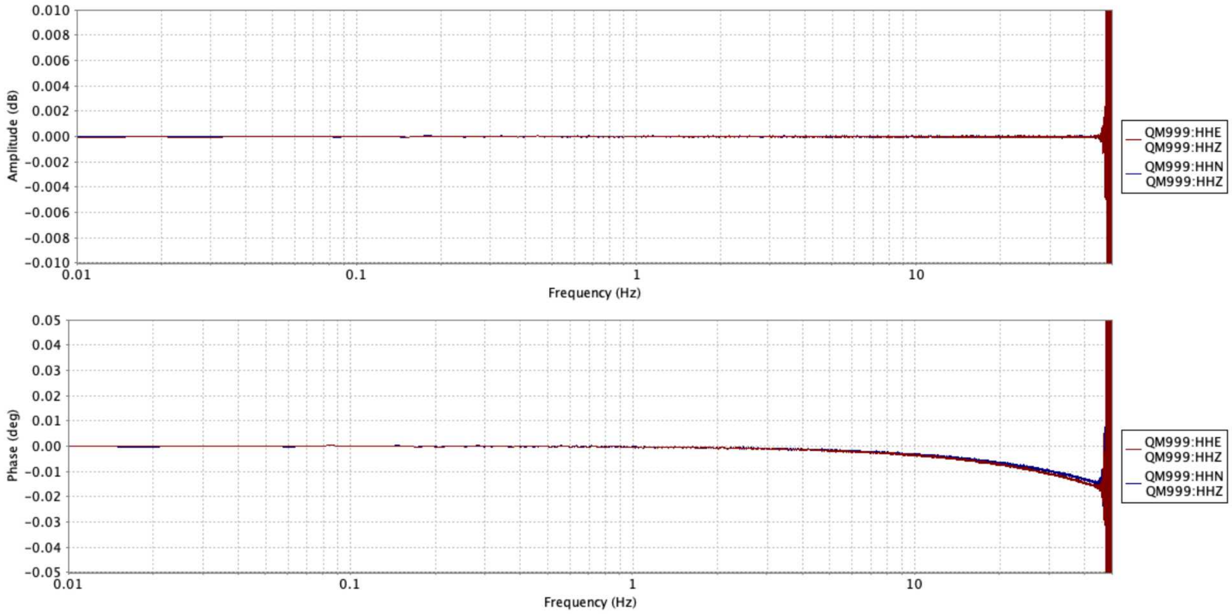


Figure 74 Relative Amplitude and Phase, Gain 16x, 100 sps

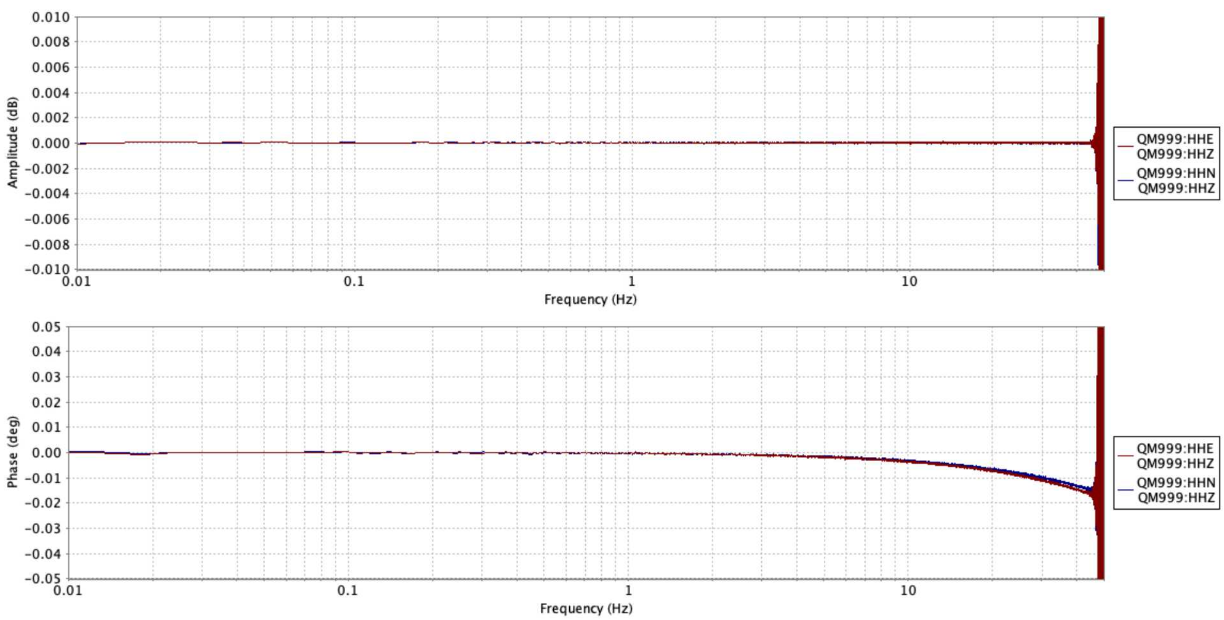


Figure 75 Relative Amplitude and Phase, Gain 32x, 100 sps

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-off in the phase responses, as much as 0.025 degrees in the 100 sps data at all gains evaluated. This roll-off in phase may be attributed to slight differences in timing, which will be investigated further in the Relative Transfer Function section.

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.

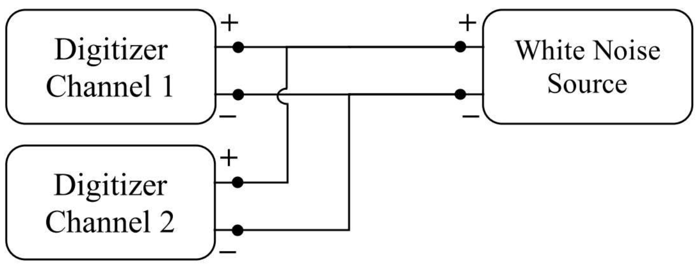


Figure 76 Relative Transfer Function Configuration Diagram

Figure 77 Relative Transfer Function Configuration Picture

Table 47 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	Stanford Research Systems, DS3360	123762	+1V / - 1 V

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

3.13.3 Analysis

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

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

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

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

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

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

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

Phase delays were observed to be consistent at each sample across gain settings tested. Representative phase delay versus frequency plots for each sample rate are shown below as the phase delay plots for the remaining sample rates and gains were identical. To the extent that the delay is a constant time offset, the phase delay is observed to be linear with respect to frequency.

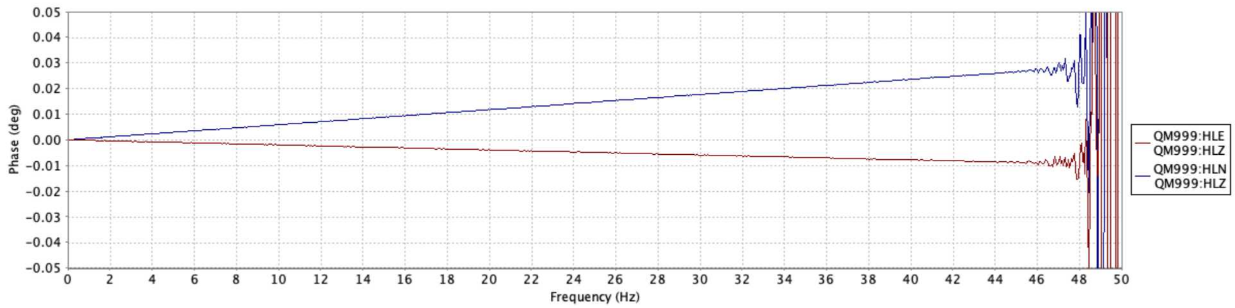


Figure 78 Relative Transfer Function Relative Phase, Gain 1x, 100 sps

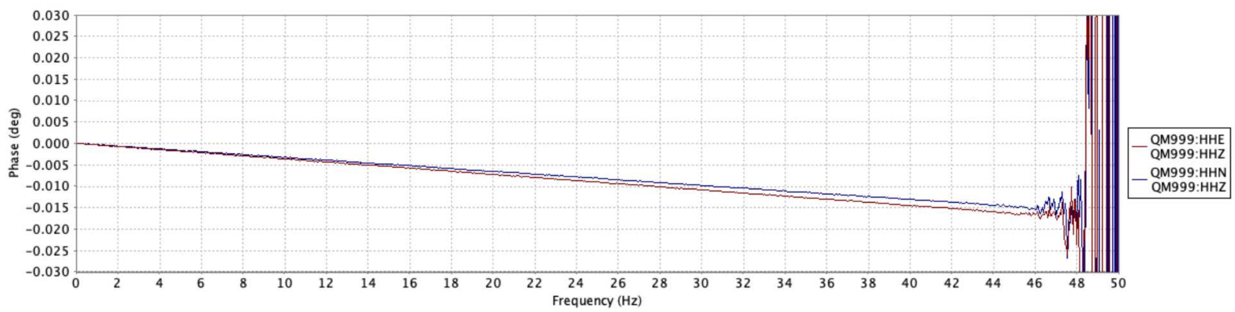


Figure 79 Relative Transfer Function Relative Phase, Gain 8Lx, 100 sps

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 48 Relative Transfer Function Timing Skew relative to Channel 1

Gain	Sample Rate	Channel 2	Channel 3
1x	100 sps	1.6394 us	-0.5430 us
2x	100 sps	1.6412 us	-0.5415 us
4x	100 sps	1.6442 us	-0.5400 us
1x	40 sps	1.6414 us	-0.5398 us
2x	40 sps	1.6432 us	-0.5362 us
4x	40 sps	1.6490 us	-0.5350 us
1x	20 sps	1.6389 us	-0.5375 us
2x	20 sps	1.6402 us	-0.5319 us
4x	20 sps	1.6460 us	-0.5343 us

Table 49 Relative Transfer Function Timing Skew relative to Channel 4

Gain	Sample Rate	Channel 5	Channel 6
8Lx	100 sps	-0.9096 us	-1.0096 us
16x	100 sps	-0.9169 us	-1.0151 us
32x	100 sps	-0.9196 us	-1.0181 us
8Lx	40 sps	-0.9098 us	-1.0138 us
16x	40 sps	-0.9222 us	-1.0149 us
32x	40 sps	-0.9239 us	-1.0176 us
8Lx	20 sps	-0.9082 us	-1.0249 us
16x	20 sps	-0.9266 us	-1.0212 us
32x	20 sps	-0.9358 us	-1.0238 us

Channels 1 – 3 and 4 – 6 were observed to have timing skews within 2.19 microseconds and 0.12 microseconds of one another, respectively.

3.14 Analog Bandwidth

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

3.14.1 Measurand

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

3.14.2 Configuration

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

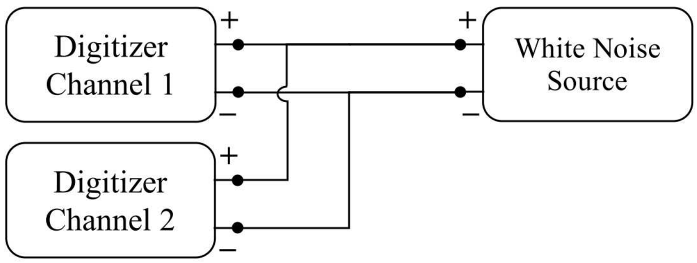


Figure 80 Analog Bandwidth Configuration Diagram

Figure 81 Analog Bandwidth Configuration Picture

Table 50 Analog Bandwidth Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	Stanford Research Systems, DS3360	123762	+1V / - 1 V

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

3.14.3 Analysis

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

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

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 Q330M+ digitizer channels was consistent across gain settings at each sample rate, therefore representative power spectra are shown in the plots below.

Figure 82 Analog Bandwidth, Gain 1x

Figure 83 Analog Bandwidth, Gain 32x

Table 51 Analog Bandwidth, 100 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	41.30 Hz	41.30 Hz	41.30 Hz	-	-	-
2x	41.40 Hz	41.40 Hz	41.40 Hz	-	-	-
4x	41.30 Hz	41.30 Hz	41.30 Hz	-	-	-
8Lx	-	-	-	41.30 Hz	41.30 Hz	41.30 Hz
16x	-	-	-	41.40 Hz	41.40 Hz	41.40 Hz
32x	-	-	-	41.30 Hz	41.30 Hz	41.30 Hz

Table 52 Analog Bandwidth, 40 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	16.20 Hz	16.20 Hz	16.20 Hz	-	-	-
2x	16.20 Hz	16.20 Hz	16.20 Hz	-	-	-
4x	16.20 Hz	16.20 Hz	16.20 Hz	-	-	-
8Lx	-	-	-	16.20 Hz	16.20 Hz	16.20 Hz
16x	-	-	-	16.20 Hz	16.20 Hz	16.20 Hz
32x	-	-	-	16.20 Hz	16.20 Hz	16.20 Hz

Table 53 Analog Bandwidth, 20 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	8.16 Hz	8.16 Hz	8.16 Hz	-	-	-
2x	8.05 Hz	8.05 Hz	8.05 Hz	-	-	-
4x	8.07 Hz	8.07 Hz	8.07 Hz	-	-	-
8Lx	-	-	-	8.16 Hz	8.16 Hz	8.16 Hz
16x	-	-	-	8.05 Hz	8.05 Hz	8.05 Hz
32x	-	-	-	8.07 Hz	8.07 Hz	8.07 Hz

All of the channels evaluated were observed to have the same high frequency pass-band limit for common gain settings. As a percentage of the sampling rate, the high frequency pass-band limit varies from 80.50% (20 sps, gains 2x and 16x) to 82.8% (100 sps gains 2x and 16x).

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.

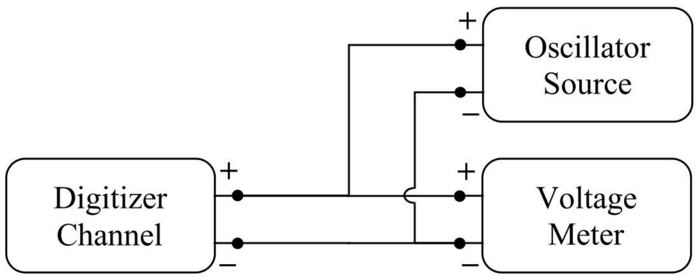


Figure 84 Total Harmonic Distortion Configuration Diagram

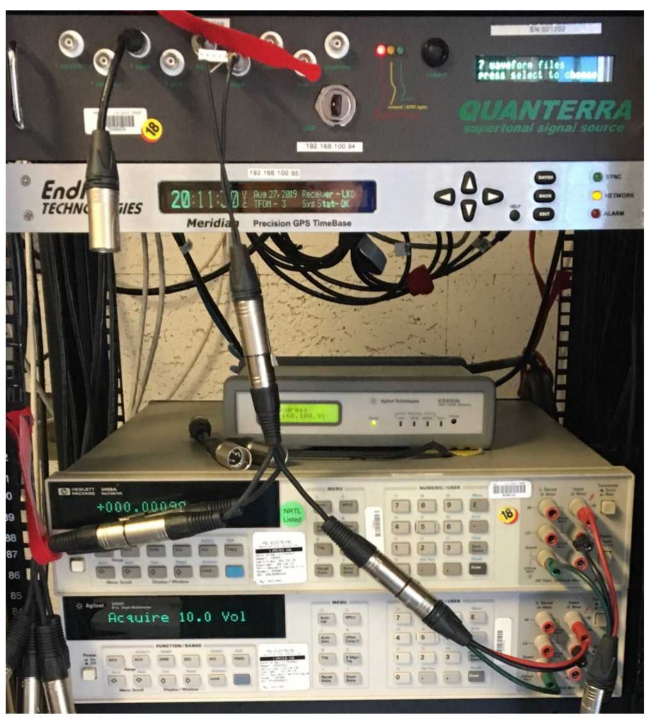


Figure 85 Total Harmonic Distortion Configuration Picture

Table 54 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Oscillator	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	+0.64 V / -0.64 V
Voltage Meter	Agilent 3458A	MY45048371	1 V full scale

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

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

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

A minimum of 1 hour of data is recorded.

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

3.15.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 1k-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 and to ensure that the 90% confidence interval is less than approximately 1 dB.

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

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 sinusoid that was used to measure harmonic distortion.

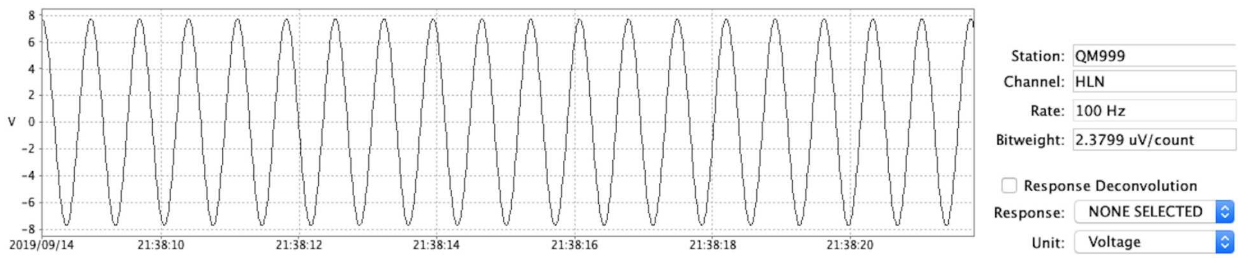


Figure 86 Total Harmonic Distortion Time Series

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

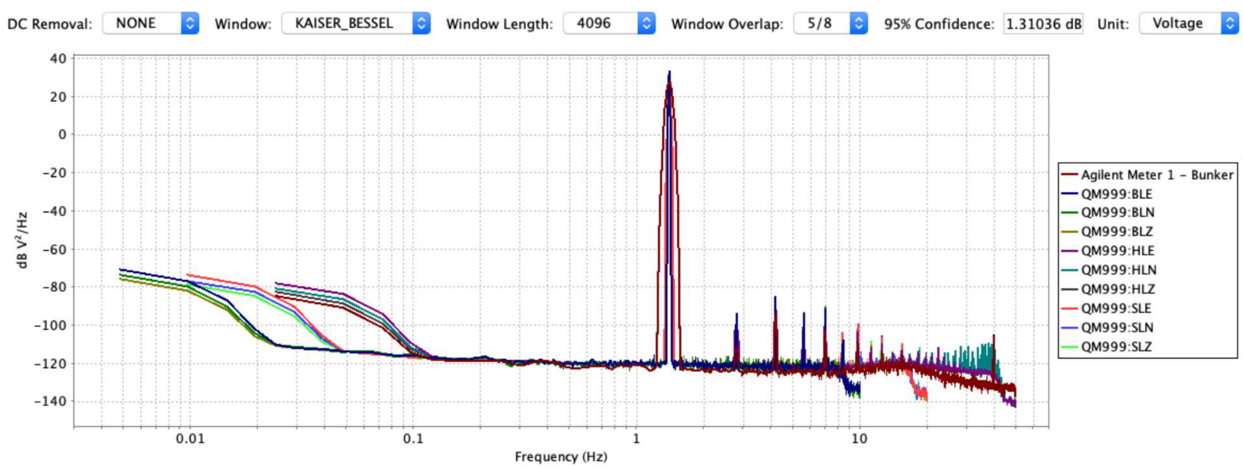


Figure 87 THD Power Spectra, Gain 1x

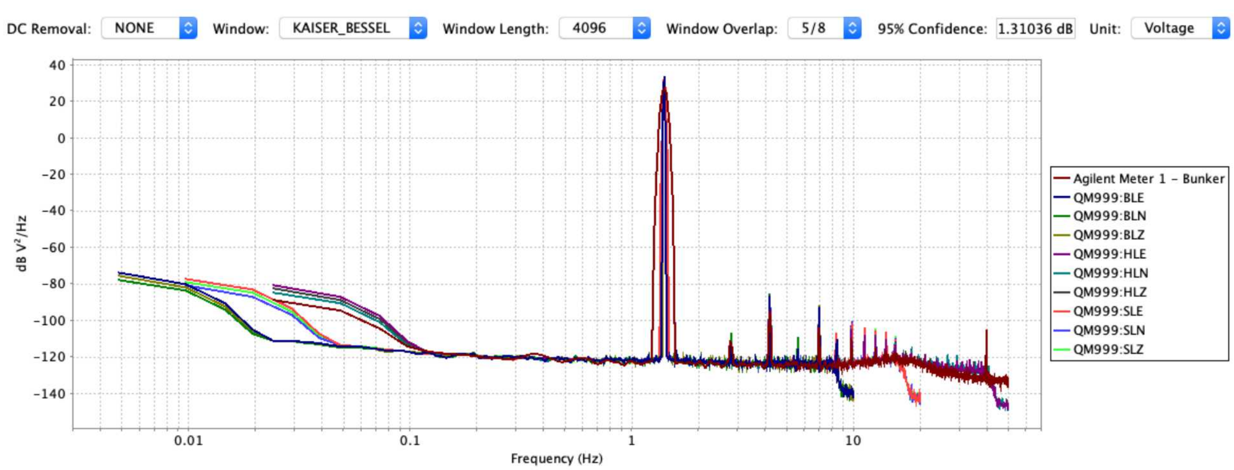


Figure 88 THD Power Spectra, Gain 2x

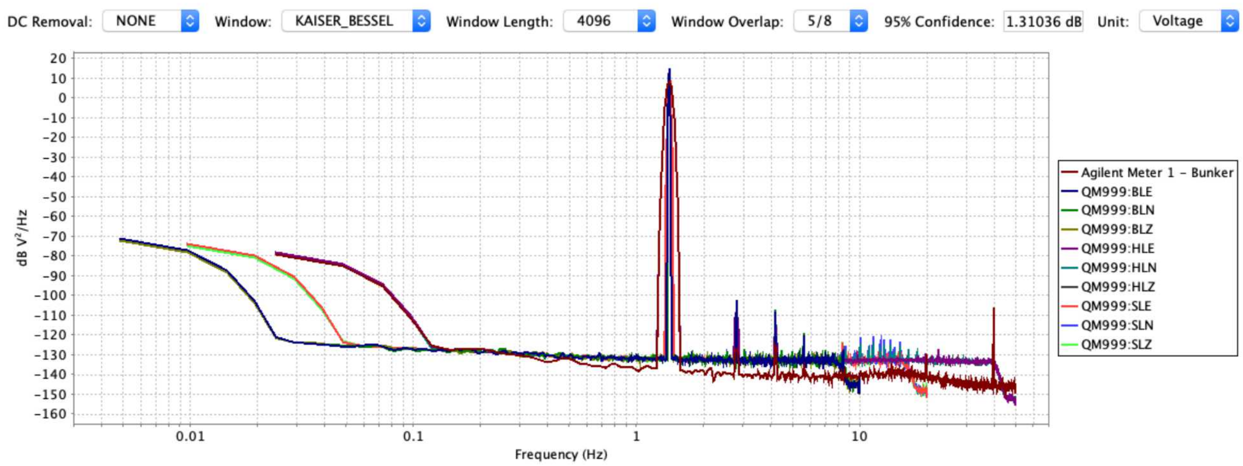


Figure 89 THD Power Spectra, Gain 4x

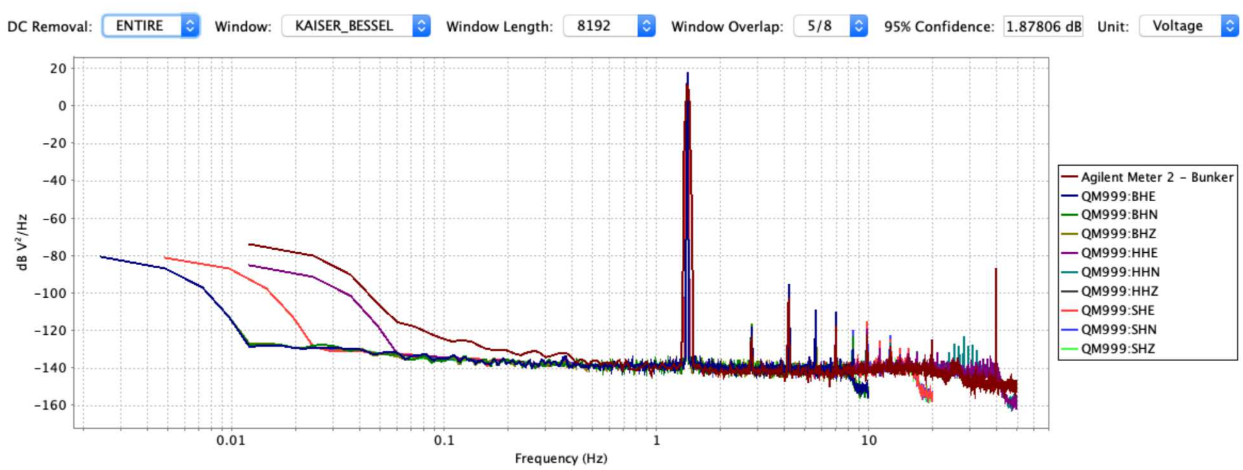


Figure 90 THD Power Spectra, Gain 8Lx

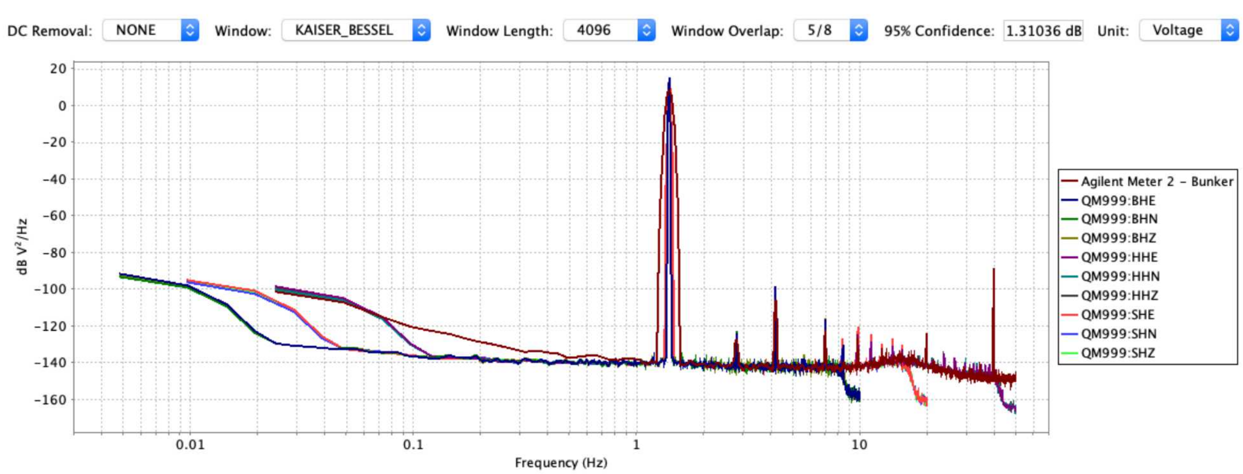


Figure 91 THD Power Spectra, Gain 16x

Table 55 Total Harmonic Distortion, 100 sps

Gain	Reference Meter	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-120.98 dB	-116.36 dB	-116.46 dB	-116.68 dB	-	-	-
2x	-121.96 dB	-118.05 dB	-117.93 dB	-118.52 dB	-	-	-
4x	-130.51 dB	-115.81 dB	-117.01 dB	-115.60 dB	-	-	-
8x	-114.38 dB	-	-	-	-113.74 dB	-113.70 dB	-113.53 dB
16x	-114.38 dB	-	-	-	-113.74 dB	-113.70 dB	-113.53 dB

Table 56 Total Harmonic Distortion, 40 sps

Gain	Reference Meter	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-120.98 dB	-116.45 dB	-116.56 dB	-116.77 dB	-	-	-
2x	-121.96 dB	-118.14 dB	-118.01 dB	-118.63 dB	-	-	-
4x	-130.51 dB	-116.06 dB	-117.21 dB	-116.14 dB	-	-	-
8x	-114.38 dB	-	-	-	-113.78 dB	-113.75 dB	-113.57 dB
16x	-114.38 dB	-	-	-	-113.78 dB	-113.75 dB	-113.57 dB

Table 57 Total Harmonic Distortion, 20 sps

Gain	Reference Meter	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-120.98 dB	-116.82 dB	-116.92 dB	-117.14 dB	-	-	-
2x	-121.96 dB	-118.75 dB	-118.48 dB	-119.23 dB	-	-	-
4x	-130.51 dB	-116.22 dB	-117.39 dB	-116.23 dB	-	-	-
8x	-114.38 dB	-	-	-	-113.88 dB	-113.86 dB	-113.71 dB
16x	-114.38 dB	-	-	-	-113.88 dB	-113.86 dB	-113.71 dB

At a gain of 32x the Agilent meter noise exceeds that of the Quanterra ULDO therefore a measurement of THD at gain of 32x is not possible. Measurement of harmonic distortion proved challenging: at gains of 1x and 2x, THD of the data channels were only a few dB below that of the reference, which is insufficient for determining the source of the distortion. Similarly, at gains of 8x and 16x, observed harmonic distortion and the data channels were essentially the same, and again does not allow one to determine the source of the distortion. At a gain of 4x however, there was sufficient difference in observed distortion between that of the reference and the data channels; here observed harmonic distortion varied between -115.60 dB and -117.39 dB.

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.

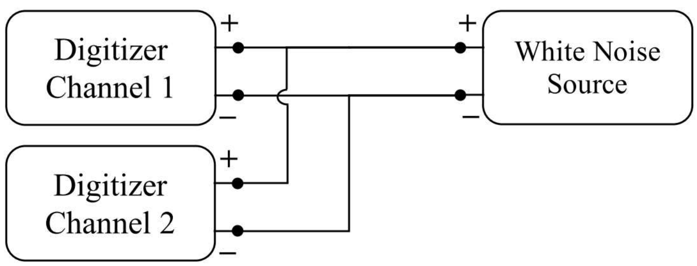


Figure 92 Modified Noise Power Ratio Configuration Diagram

Figure 93 Modified Noise Power Ratio Configuration Picture

Table 58 Modified Noise Power Ratio Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	Stanford Research Systems, DS3360	123762	+1V / - 1 V

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

3.16.3 Analysis

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

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

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

3.16.4 Result

A representative waveform time series plot is shown below channels HLN and HLZ sampled at 100 Hz.

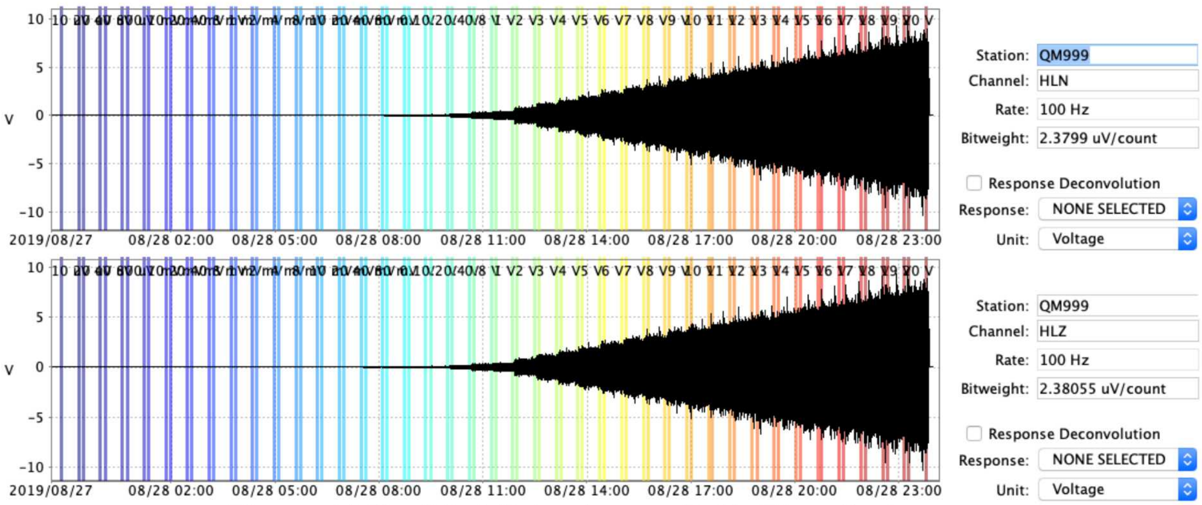


Figure 94 Modified Noise Power Ratio Time Series

The Modified Noise Power Ratio is computed at a sample rate of 100 Hz and at a gain of 1x and 8x, channels HLZ vs HLN, HLE and HHZ vs HHN and HHE, respectively. The amplitude and noise of the power spectra are integrated over 0.01 – 50 Hz. The figures and plot are shown below.

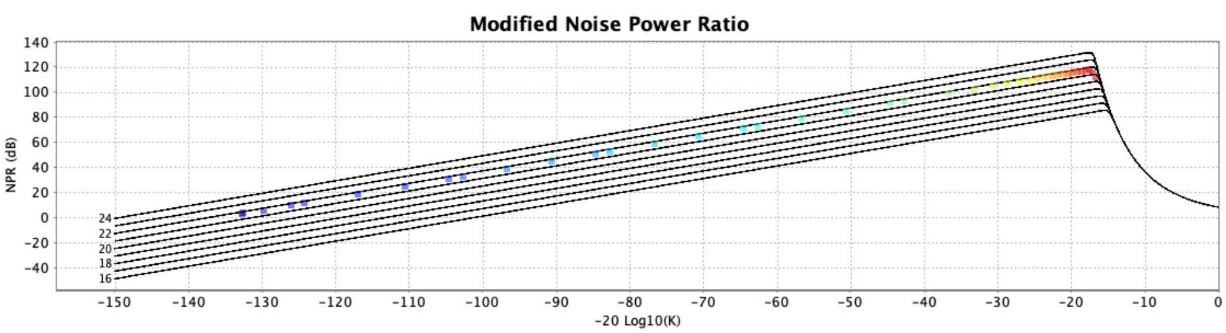


Figure 95 Modified Noise Power Ratio, Channels 1 and 2, Gain 1x

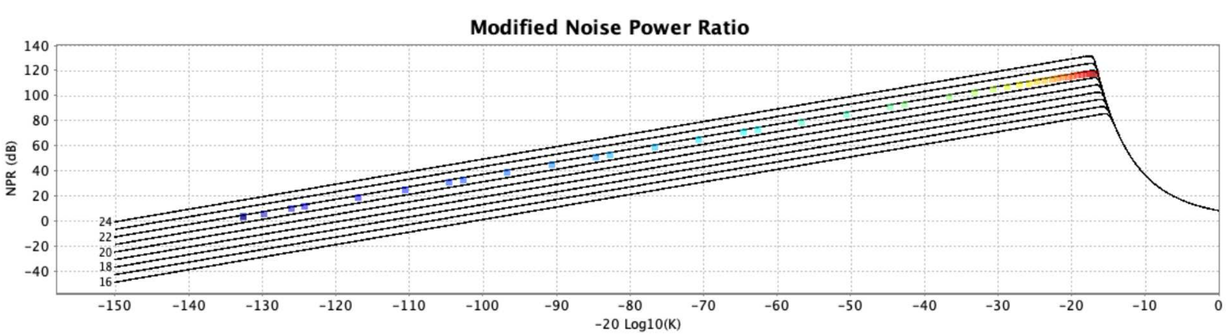


Figure 96 Modified Noise Power Ratio, Channels 1 and 3, Gain 1x

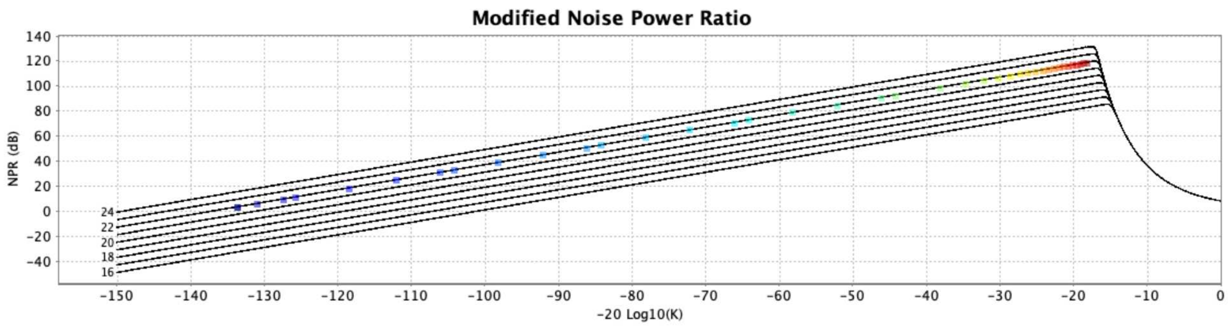


Figure 97 Modified Noise Power Ratio, Channels 4 and 5, Gain 8Lx

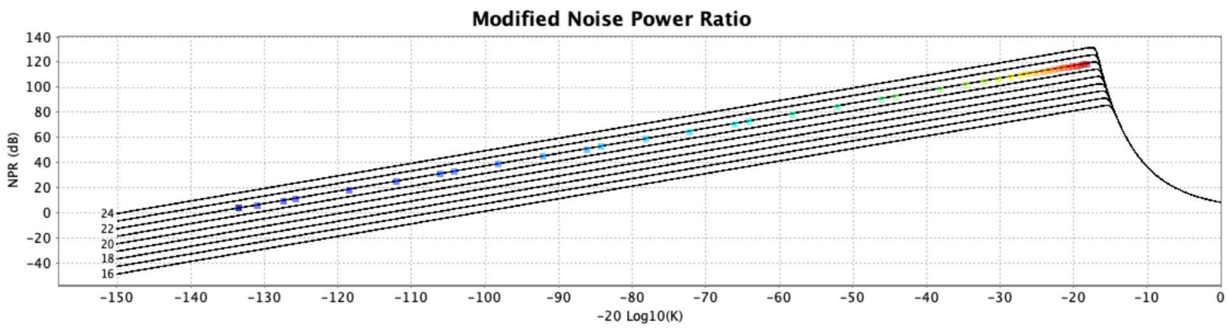


Figure 98 Modified Noise Power Ratio, Channels 4 and 6, Gain 8Lx

The plots of MNPR show that at the evaluated gains, 1x and 8Lx, the Q330M+ has slightly less than 22 bits of linear performance over the entire range of amplitudes.

Table 59 Modified Noise Power Ratio, HLZ vs HLN, HLZ vs HLE, Gain 1x

	HLZ vs HLN			HLZ vs HLE		
Amplitude	RMS Amplitude	-20 log K	Noise Power Ratio	RMS Amplitude	-20 log K	Noise Power Ratio
10 uV	0.000003289 V rms	-132.67	3.39 dB	0.000003316 V rms	-132.60	3.43 dB
20 uV	0.000003306 V rms	-132.63	3.41 dB	0.000003306 V rms	-132.63	3.39 dB
40 uV	0.000004582 V rms	-129.79	5.91 dB	0.000004570 V rms	-129.81	5.88 dB
80 uV	0.000007091 V rms	-126.00	9.70 dB	0.000007086 V rms	-126.00	9.65 dB
0.1 mV	0.000008625 V rms	-124.30	11.38 dB	0.000008617 V rms	-124.30	11.35 dB
0.2 mV	0.00002004 V rms	-116.97	18.71 dB	0.00002001 V rms	-116.99	18.65 dB
0.4 mV	0.00004176 V rms	-110.60	25.08 dB	0.00004176 V rms	-110.60	25.07 dB
0.8 mV	0.00008321 V rms	-104.61	31.05 dB	0.00008319 V rms	-104.61	31.05 dB
1 mV	0.0001041 V rms	-102.66	33.01 dB	0.0001041 V rms	-102.66	33.00 dB
2 mV	0.0002077 V rms	-96.66	39.02 dB	0.0002077 V rms	-96.66	38.99 dB
4 mV	0.0004153 V rms	-90.64	45.00 dB	0.0004153 V rms	-90.64	45.01 dB
8 mV	0.0008302 V rms	-84.63	51.09 dB	0.0008302 V rms	-84.63	51.02 dB
10 mV	0.001038 V rms	-82.68	52.95 dB	0.001038 V rms	-82.68	52.96 dB
20 mV	0.002078 V rms	-76.66	59.02 dB	0.002078 V rms	-76.66	58.98 dB
40 mV	0.004156 V rms	-70.64	65.06 dB	0.004156 V rms	-70.64	65.00 dB
80 mV	0.008305 V rms	-64.62	71.08 dB	0.008305 V rms	-64.62	71.02 dB
0.1 V	0.01038 V rms	-62.69	73.00 dB	0.01038 V rms	-62.69	72.97 dB
0.2 V	0.02076 V rms	-56.67	78.97 dB	0.02076 V rms	-56.67	78.97 dB
0.4 V	0.04152 V rms	-50.64	85.05 dB	0.04152 V rms	-50.64	85.00 dB
0.8 V	0.08303 V rms	-44.63	91.05 dB	0.08303 V rms	-44.63	91.00 dB
1 V	0.1037 V rms	-42.69	92.97 dB	0.1037 V rms	-42.69	92.95 dB
2 V	0.2078 V rms	-36.66	99.02 dB	0.2078 V rms	-36.66	98.98 dB
3 V	0.3114 V rms	-33.14	102.52 dB	0.3114 V rms	-33.14	102.48 dB
4 V	0.4150 V rms	-30.65	105.02 dB	0.4150 V rms	-30.65	104.95 dB
5 V	0.5187 V rms	-28.71	106.94 dB	0.5187 V rms	-28.71	106.90 dB
6 V	0.6232 V rms	-27.12	108.52 dB	0.6232 V rms	-27.12	108.49 dB
7 V	0.7263 V rms	-25.79	109.85 dB	0.7263 V rms	-25.79	109.79 dB
8 V	0.8299 V rms	-24.63	110.97 dB	0.8299 V rms	-24.63	110.93 dB
9 V	0.9333 V rms	-23.61	111.99 dB	0.9333 V rms	-23.61	111.93 dB
10 V	1.038 V rms	-22.69	112.90 dB	1.038 V rms	-22.69	112.80 dB
11 V	1.142 V rms	-21.86	113.70 dB	1.142 V rms	-21.86	113.59 dB
12 V	1.245 V rms	-21.10	114.44 dB	1.245 V rms	-21.10	114.28 dB
13 V	1.349 V rms	-20.41	115.12 dB	1.349 V rms	-20.41	114.94 dB
14 V	1.454 V rms	-19.76	115.74 dB	1.454 V rms	-19.76	115.53 dB
15 V	1.558 V rms	-19.16	116.32 dB	1.558 V rms	-19.16	116.02 dB
16 V	1.659 V rms	-18.61	116.83 dB	1.659 V rms	-18.61	116.53 dB
17 V	1.765 V rms	-18.07	117.33 dB	1.765 V rms	-18.07	116.94 dB
18 V	1.868 V rms	-17.58	117.80 dB	1.868 V rms	-17.58	117.35 dB
19 V	1.973 V rms	-17.11	115.48 dB	1.973 V rms	-17.11	117.56 dB
20 V	2.075 V rms	-16.67	112.45 dB	2.075 V rms	-16.67	117.14 dB

Table 60 Modified Noise Power Ratio, HHZ vs HHN, HHZ vs HHE, Gain 8Lx

	HHZ vs HHN			HHZ vs HHE		
Amplitude	RMS Amplitude	-20 log K	Noise Power Ratio	RMS Amplitude	-20 log K	Noise Power Ratio
0.00000125 V	0.000000372 V rms	-133.55	3.39 dB	0.000000375 V rms	-133.47	3.44 dB
0.0000025 V	0.000000370 V rms	-133.58	3.38 dB	0.000000373 V rms	-133.52	3.41 dB
0.000005 V	0.000000498 V rms	-131.01	5.65 dB	0.000000500 V rms	-130.97	5.64 dB
0.00001 V	0.000000757 V rms	-127.37	9.28 dB	0.000000758 V rms	-127.36	9.25 dB
0.0000125 V	0.000000918 V rms	-125.70	10.93 dB	0.000000917 V rms	-125.70	10.90 dB
0.000025 V	0.000002112 V rms	-118.45	18.15 dB	0.000002114 V rms	-118.45	18.11 dB
0.00005 V	0.000004399 V rms	-112.08	24.55 dB	0.000004398 V rms	-112.08	24.52 dB
0.0001 V	0.000008762 V rms	-106.10	30.55 dB	0.000008761 V rms	-106.10	30.48 dB
0.000125 V	0.00001096 V rms	-104.15	32.46 dB	0.00001096 V rms	-104.15	32.44 dB
0.00025 V	0.00002187 V rms	-98.15	38.50 dB	0.00002187 V rms	-98.15	38.44 dB
0.0005 V	0.00004373 V rms	-92.13	44.47 dB	0.00004373 V rms	-92.13	44.48 dB
0.001 V	0.00008741 V rms	-86.12	50.48 dB	0.00008741 V rms	-86.12	50.45 dB
0.00125 V	0.0001093 V rms	-84.17	52.44 dB	0.0001093 V rms	-84.17	52.44 dB
0.0025 V	0.0002188 V rms	-78.15	58.48 dB	0.0002188 V rms	-78.15	58.42 dB
0.005 V	0.0004376 V rms	-72.13	64.51 dB	0.0004376 V rms	-72.13	64.46 dB
0.01 V	0.0008744 V rms	-66.11	70.48 dB	0.0008744 V rms	-66.11	70.45 dB
0.0125 V	0.001092 V rms	-64.18	72.41 dB	0.001092 V rms	-64.18	72.42 dB
0.025 V	0.002186 V rms	-58.16	78.49 dB	0.002186 V rms	-58.16	78.44 dB
0.05 V	0.004372 V rms	-52.14	84.49 dB	0.004372 V rms	-52.14	84.45 dB
0.1 V	0.008742 V rms	-46.12	90.49 dB	0.008742 V rms	-46.12	90.46 dB
0.125 V	0.01092 V rms	-44.18	92.42 dB	0.01092 V rms	-44.18	92.41 dB
0.25 V	0.02188 V rms	-38.15	98.46 dB	0.02188 V rms	-38.15	98.43 dB
0.375 V	0.03278 V rms	-34.64	101.98 dB	0.03278 V rms	-34.64	101.95 dB
0.5 V	0.04369 V rms	-32.14	104.46 dB	0.04369 V rms	-32.14	104.44 dB
0.625 V	0.05461 V rms	-30.20	106.40 dB	0.05461 V rms	-30.20	106.36 dB
0.75 V	0.06562 V rms	-28.61	107.97 dB	0.06562 V rms	-28.61	107.95 dB
0.875 V	0.07647 V rms	-27.28	109.31 dB	0.07647 V rms	-27.28	109.26 dB
1 V	0.08738 V rms	-26.12	110.46 dB	0.08738 V rms	-26.12	110.42 dB
1.125 V	0.09826 V rms	-25.10	111.43 dB	0.09826 V rms	-25.10	111.43 dB
1.25 V	0.1093 V rms	-24.18	112.38 dB	0.1093 V rms	-24.18	112.36 dB
1.375 V	0.1202 V rms	-23.35	113.16 dB	0.1202 V rms	-23.35	113.14 dB
1.5 V	0.1311 V rms	-22.60	113.96 dB	0.1311 V rms	-22.60	113.90 dB
1.625 V	0.1421 V rms	-21.90	114.62 dB	0.1421 V rms	-21.90	114.62 dB
1.75 V	0.1531 V rms	-21.25	115.22 dB	0.1531 V rms	-21.25	115.25 dB
1.875 V	0.1640 V rms	-20.65	115.77 dB	0.1640 V rms	-20.65	115.83 dB
2 V	0.1747 V rms	-20.10	116.35 dB	0.1747 V rms	-20.10	116.34 dB
2.125 V	0.1858 V rms	-19.57	116.86 dB	0.1858 V rms	-19.57	116.87 dB
2.25 V	0.1967 V rms	-19.07	117.35 dB	0.1967 V rms	-19.07	117.37 dB
2.375 V	0.2077 V rms	-18.60	117.77 dB	0.2077 V rms	-18.60	117.81 dB
2.5 V	0.2185 V rms	-18.16	118.21 dB	0.2185 V rms	-18.16	118.29 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 amplitude to the observed amplitude on the digitizer input channels in dB.

3.17.2 Configuration

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

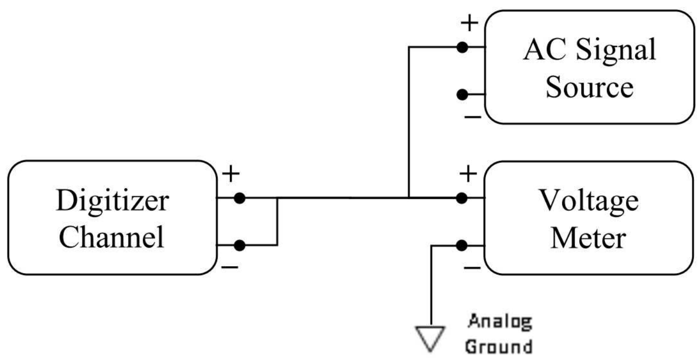


Figure 99 Common Mode Rejection Configuration Diagram

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

Figure 100 Common Mode Rejection Configuration Picture

Table 61 Common Mode Rejection Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	DC Signal Source	Stanford Research Systems, DS3360	123762
Voltage Meter	Voltage Meter	Agilent 3458A	MY45048371

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

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

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

3.17.3 Analysis

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

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

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

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

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

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

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

3.17.4 Result

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

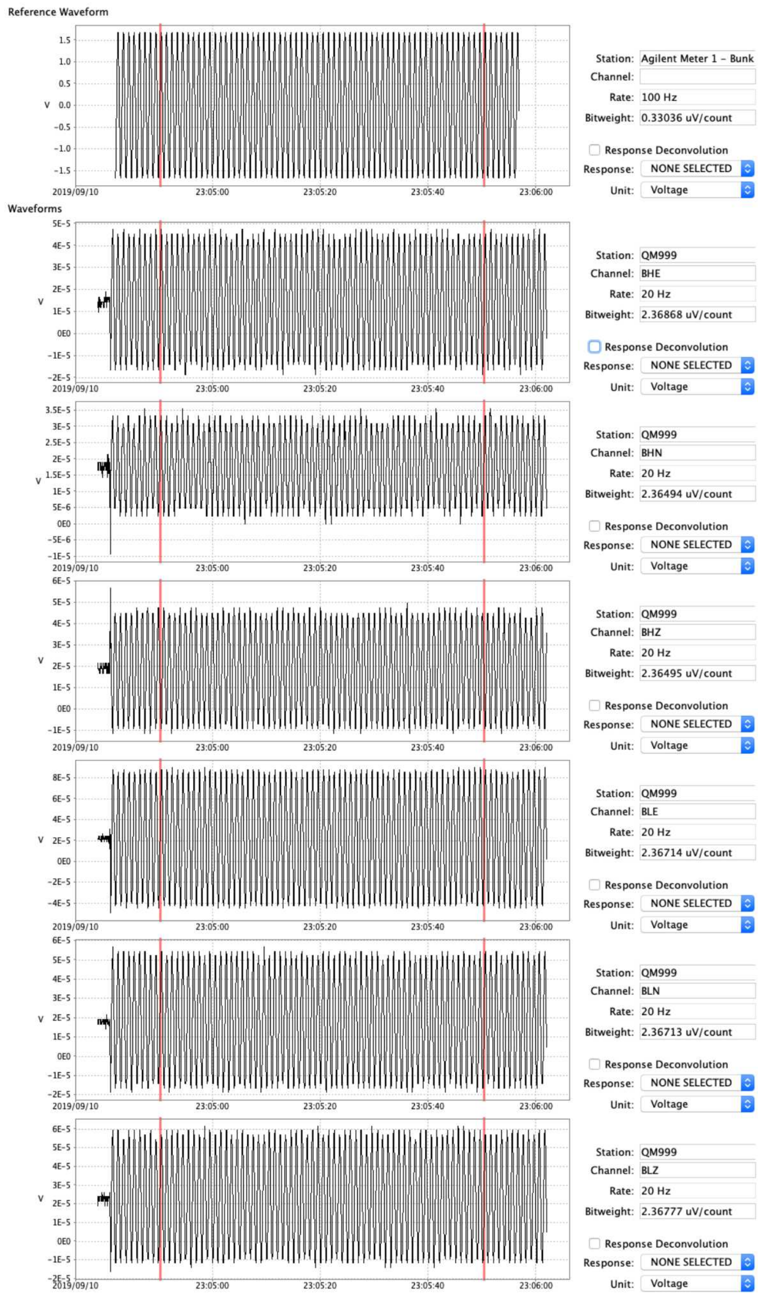


Figure 101 Common Mode Rejection Time Series, Gain 1x

The following table contains the computed common mode rejection ratio.

Table 62 Common Mode Rejection Ratio

Sample Rate	Input	Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
100 sps	4.0 V	1x	93.71 dB	93.65 dB	88.19 dB	95.77 dB	101.57 dB	94.78 dB
	2.0 V	2x	87.22 dB	87.42 dB	81.83 dB	90.62 dB	96.34 dB	87.78 dB
	1.0 V	4x	81.26 dB	81.51 dB	75.81 dB	85.04 dB	91.06 dB	81.69 dB
	0.5 V	8x	83.40 dB	81.63 dB	75.08 dB	83.72 dB	73.43 dB	77.12 dB
	0.25 V	16x	76.47 dB	75.39 dB	69.42 dB	78.40 dB	67.85 dB	70.48 dB
	0.125 V	32x	70.48 dB	69.53 dB	63.54 dB	73.05 dB	62.08 dB	64.19 dB
40 sps	4.0 V	1x	93.70 dB	93.64 dB	88.19 dB	95.78 dB	101.59 dB	94.78 dB
	2.0 V	2x	87.23 dB	87.42 dB	81.83 dB	90.62 dB	96.36 dB	87.78 dB
	1.0 V	4x	81.26 dB	81.52 dB	75.80 dB	85.04 dB	91.07 dB	81.69 dB
	0.5 V	8x	83.41 dB	81.64 dB	75.08 dB	83.74 dB	73.43 dB	77.10 dB
	0.25 V	16x	76.49 dB	75.37 dB	69.42 dB	78.42 dB	67.84 dB	70.49 dB
	0.125 V	32x	70.49 dB	69.53 dB	63.54 dB	73.06 dB	62.08 dB	64.20 dB
20 sps	4.0 V	1x	93.69 dB	93.65 dB	88.19 dB	95.78 dB	101.56 dB	94.78 dB
	2.0 V	2x	87.23 dB	87.41 dB	81.83 dB	90.62 dB	96.36 dB	87.79 dB
	1.0 V	4x	81.27 dB	81.52 dB	75.80 dB	85.03 dB	91.09 dB	81.69 dB
	0.5 V	8x	83.38 dB	81.63 dB	75.08 dB	83.73 dB	73.44 dB	77.09 dB
	0.25 V	16x	76.48 dB	75.40 dB	69.42 dB	78.47 dB	67.85 dB	70.48 dB
	0.125 V	32x	70.48 dB	69.55 dB	63.53 dB	73.05 dB	62.08 dB	64.18 dB

The observed common mode rejection ranged from as low as 62.08 dB (gain 32x) to as high as 101.59 dB (gain 1x).

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.

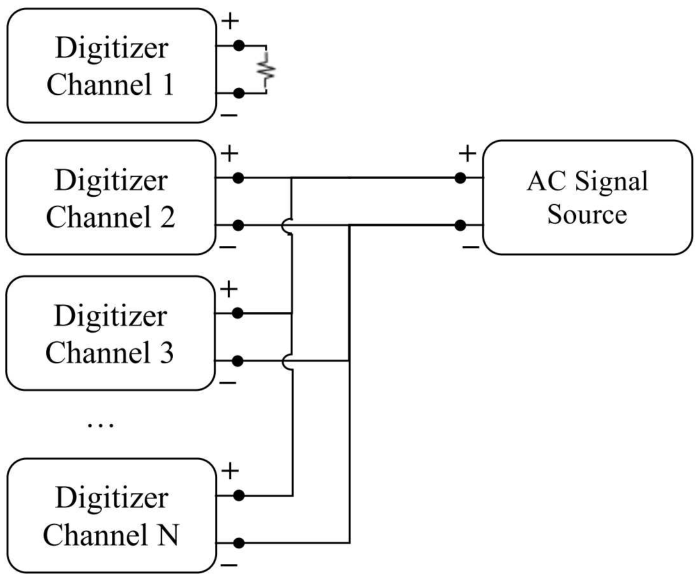


Figure 102 Crosstalk Configuration Diagram

Figure 103 Crosstalk Configuration Picture

Table 63 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	DC Signal Source	Stanford Research Systems, DS3360	123762
Voltage Meter	Voltage Meter	Agilent 3458A	MY45048371

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

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

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

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

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

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

3.18.4 Result

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

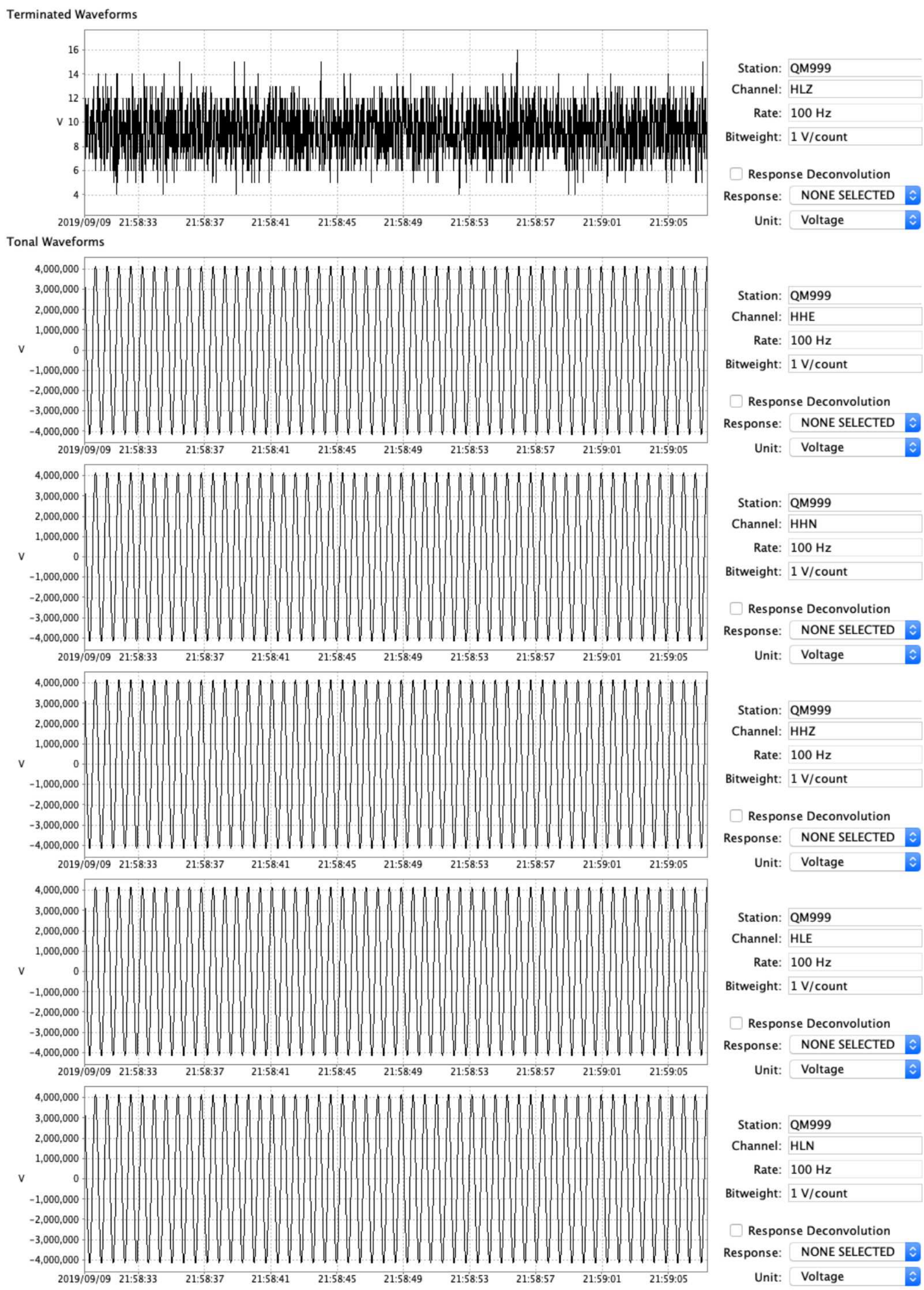


Figure 104 Crosstalk Time Series

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

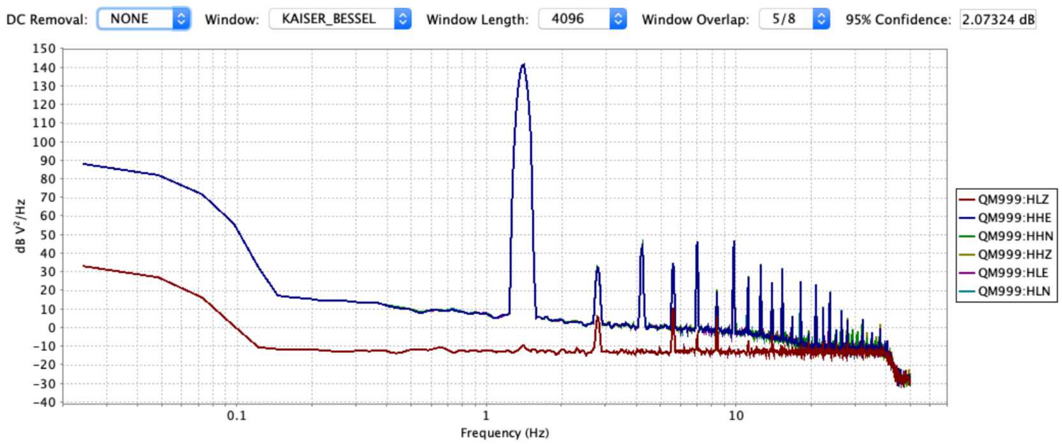


Figure 105 Crosstalk Power Spectra, 100 sps

The following table contains the computed crosstalk ratios.

Table 64 Crosstalk

Sample rate	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
100 sps	-147.55 dB	-148.66 dB	-151.95 dB	-150.05 dB	-153.02 dB	-151.50 dB
40 sps	-147.74 dB	-147.85 dB	-152.92 dB	-150.00 dB	-153.99 dB	-151.86 dB
20 sps	-147.23 dB	-147.93 dB	-152.86 dB	-149.84 dB	-153.31 dB	-148.87 dB

The observable levels of crosstalk of the sensor channels were all between -153.99 dB and -147.23 dB. None of the terminated channels exhibited cross-talk, at any appreciable level, at the fundamental frequency. The cross-talk levels observed therefore represent maximum possible cross-talk levels.

3.19 Time Tag Accuracy

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

3.19.1 Measurand

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

3.19.2 Configuration

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

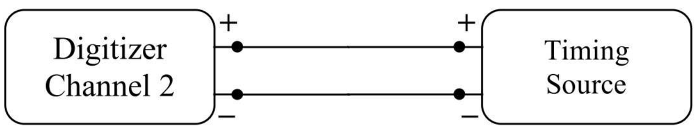


Figure 106 Timing Configuration Diagram

Figure 107 Time Tag Accuracy Configuration Picture

Two means of providing timing to the digitizer are tested here: timing derived from an internal GPS receiver, and timing derived from timing information provided by a local precision timing protocol (PTP) server. A grandmaster clock with its own GPS receiver served as our PTP server.

Table 65 Time Tag Accuray Testbed Equipment

Manufacturer / Model	Serial Number	Nominal Configuration
End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	+/- 5V PPM
Supplied GPS Antenna	N/A	N/A
PTP grandmaster clock	N/A	N/A

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

3.19.3 Analysis

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

3.19.4 Result

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

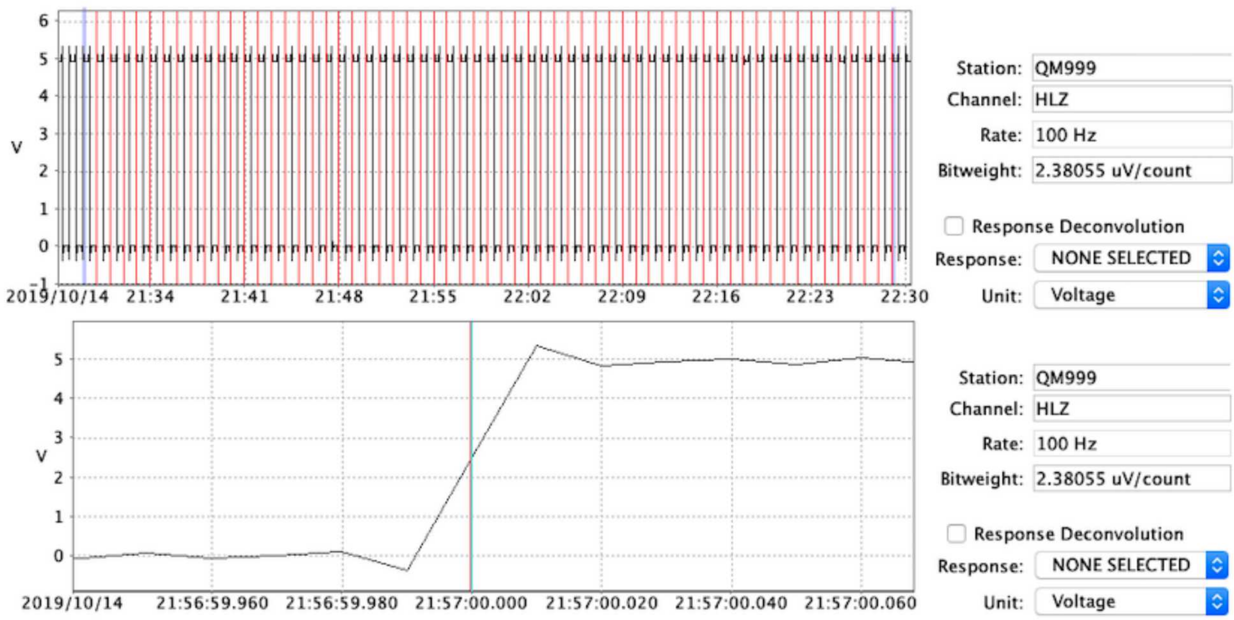


Figure 108 Example Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets.

Table 66 Time Tag Accuracy

Timing Source	100 sps	40 sps	20 sps
GPS antenna	-62.096 us	-62.164 us	-62.029 us
Grandmaster Clock - PTP	-72.495 us	-72.324 us	-72.225 us

The measured time tag accuracy values were consistent for all of the recording channels and less than 63 microseconds while the digitizer utilized its internal GPS receiver for timing and less than 73 microseconds while it utilized the PTP server for timing. This difference in time tag accuracies between the two the timing methods may be a reflection of the limitations of the PTP server-provided timing and not necessarily a variation in time-tag accuracy of the digitizer.

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.

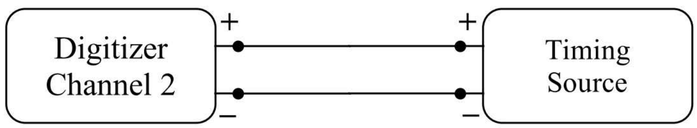


Figure 109 Timing Configuration Diagram

Table 67 Timing Drift Testbed Equipment

Manufacturer / Model	Serial Number	Nominal Configuration
End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	+/- 5V PPM
Supplied GPS Antenna	N/A	N/A
grandmaster clock PTP server	N/A	N/A

Two means of providing timing to the digitizer are tested here: timing derived from an internal GPS receiver, and timing derived from timing information provided by a local precision timing protocol (PTP) server. A grandmaster clock with its own GPS receiver served as our PTP server.

The digitizer clock is allowed to stabilize before the GPS antenna is covered, or before the grandmaster clock is covered, resulting in the digitizer's loss of timing lock. The digitizer is allowed to drift before the GPS antenna is uncovered, or the grandmaster clock is uncovered, and allowed to regain its timing lock.

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

3.20.3 Analysis

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

The levels of timing error and rates of change are observed while the digitizer has GPS lock, or grandmaster clock PTP server has GPS lock, and while each is drifting without GPS lock, and after the timing has recovering once the digitizer's GPS lock, or grandmaster clock GPS, has a lock.

3.20.4 Result

The figures below show the timing offsets over time as the digitizer timing drifts and during the recovery of internal GPS receiver lock or PTP timing lock.

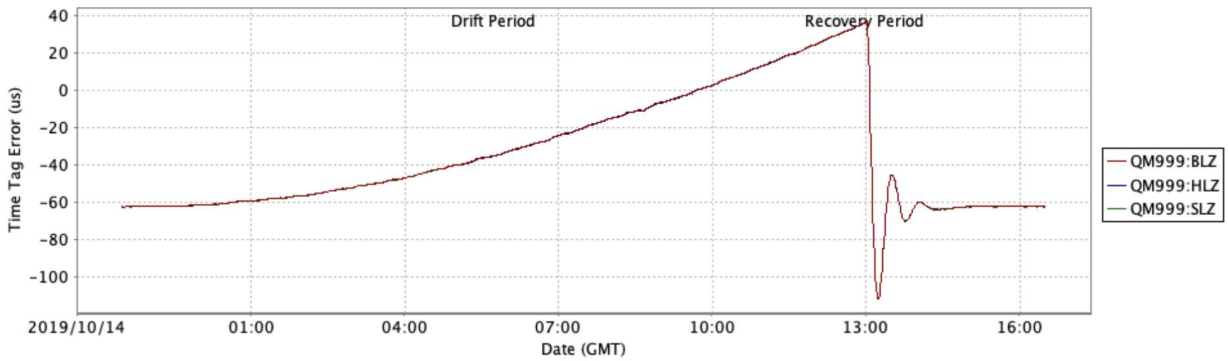


Figure 110 Observed Timing Drift and Recovery Period, Internal GPS-Based Timing

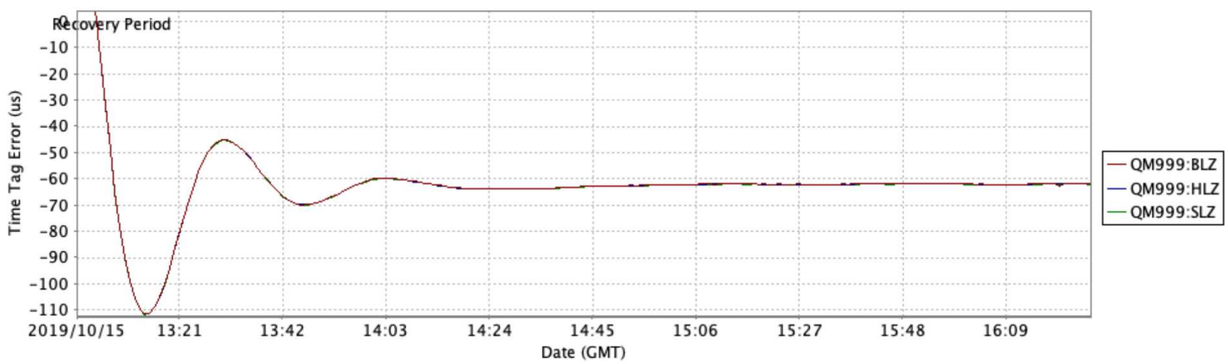


Figure 111 Moment of Timing Recovery, Internal GPS-Based Timing

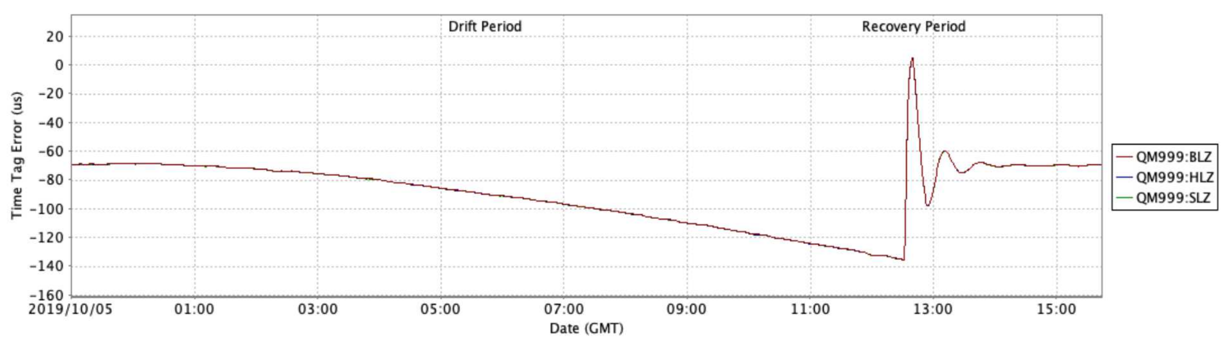


Figure 112 Observed Timing Drift and Recovery Period, PTP-Based Timing

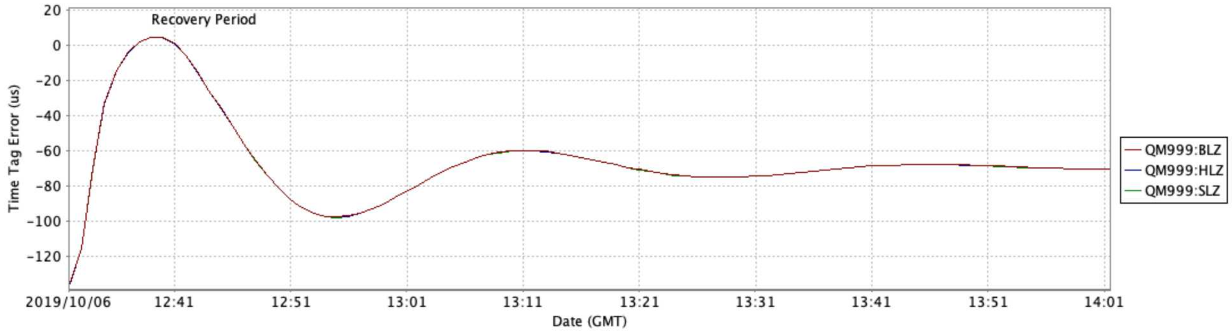


Figure 113 Moment of Timing Recovery, PTP-Based Timing

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 68 Time Tag Drift and Recovery

	100 sps	40 Hz	20 Hz
Stabilized offset – pre-drift, internal GPS timing	-62.096 us	-62.164 us	-62.029 us
Stabilized offset – pre-drift, PTP timing	-72.495 us	-72.324 us	-72.225 us
Initial Drift Rate, internal GPS timing	-6.9844 us/hr	-7.004 us/hr	-6.9978 us/hr
Initial Drift Rate, PTP timing	-5.1674 us/hr	-5.1632 us/hr	-5.159 us/hr
Recovery Rate, internal GPS timing	-206.05 us/hr	-206.39 us/hr	-206.2 us/hr
Recovery Rate, PTP timing	-105.0 us/hr	-104.79 us/hr	-104.78 us/hr
Stabilized offset – post-drift, internal GPS timing	-62.116 us	-62.191 us	-62.072 us
Stabilized offset – post-drift, PTP timing	-70.083 us	-69.924 us	-70.079 us

Drift rate while the digitizer's GPS receiver, or the PTP server, was unlocked, was relatively consistent at 7 us/hr and 5 us/hr, respectively. Timing recovered rates at 206 us/hr for internal GPS timing and 5 us/hr for PTP-based timing. When the digitizer's GPS antenna was uncovered, allowing reception of GPS signal, the Q330M+ regained lock and recovered to a stabilized offset within 1.5 hours, after a total drift of 98.95 us, which occurred over the 14 hour period during which the GPS antenna was covered. Similarly, when the grandmaster clock was uncovered, allowing accurate PTP timing, the digitizer's timing recovered within 1.5 hours after timing had drifted 66.26 us over 13.5 hours.

4 SUMMARY

Input Impedance
The measured input impedance of the Q330M+ digitizer channels were consistently 156.9 kohm, for settings of 1x through 4x.

Power Consumption
The Q330M+ digitizer was observed to consume 4.287 watts of power during operation.

DC Accuracy
Observed bit weights varied no more than 0.19% from nominal, at a gain of 1x. A gain of 8Lx provided the lowest maximum variation in gain from nominal across all channels.

AC Accuracy
Maximum deviation from nominal bit weights across all gain settings was 0.800% for the 20 sps data at a gain of 1x. A gain of 16x provided the lowest maximum variation in gain from nominal across all channels, 0.093% for 100 sps data.

AC Full Scale
For all sample rates and gain levels, the primary and auxiliary 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.

AC Over Scale
At all sample rates, applied voltages greater than full scale were observed across all channels with obvious clipping visible in the timeseries.

Input Shorted Offset
The maximum observed input shorted offsets across all gains, with respect to nominal full scale, ranged from a maximum of 0.0001% at gains 2x and 4x (all sample rates) to a maximum of 0.0006% at gains of 1x and 8x (all sample rates).

Self Noise
Average self noise of 100 sps channels the over the 0.01 Hz – 10 Hz passband, ranged from as much as 1.649 uV rms for the gain of 1x to as low as 51.1 nV rms at a gain of 32x. No rms noise value varied more than 0.99% (at gain 32x) from their respective average rms noise values. Rms noise values remained well below 1 count rms, with the exception of a gain of 4x where it was just over 1 count rms.

Temperature Self Noise
Self noise of all channels increases slightly with temperature, approximately 4 dB and 1 dB higher, for the gains of 1x and 8x, respectively, at 50° C over that of the -36° C observations, excluding the increase on the gain x8L channels (HHZ, HHN and HHE) between 0.015 Hz and 0.021 Hz.

Dynamic Range
The observed dynamic range values over the 0.01 Hz and 10 Hz passband varied across all sample rates from 138.44 dB (chan 3, 40 sps) to 138.81 dB (chan 1, 20 sps) at a gain of 1x, while at a gain of 32x observed dynamic ranges varied from 138.47 dB (chan 6, 40 sps) to 138.93 dB (chan 4 20 sps).

System Noise
System noise, expressed in equivalent units for a Hyperion (26.6 mV/Pa) or MB3a requires the Q330M+ to be operated at gain of at least 2x such that its self noise remains below that of the sensor. For the MB2005 self noise, the digitizer system noise, at all gains evaluated, remains well below that of each sensor. The digitizer gain would need to be at least 16x while recording data from CMG-3T, STS-5a and T-120, and at gain of 32x for the STS-2, for the Q330 M+ system noise to remain below that of these sensors. A gain of 32x is required for system noise to remain below or approximate to that of the GS-13's self noise.

Response Verification
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-off in the phase responses, consistent with small amounts of timing skew between channels.

Relative Transfer Function
All of the channels were observed to have a timing skew that was no more than 2.19 microseconds of one another.

Analog Bandwidth
As a percentage of the sampling rate, the high frequency pass-band limit varies from 80.50% (20 sps, gains 2x and 16x) to 82.8% (100 sps gains 2x and 16x).

Total Harmonic Distortion
At a gain of 4x observed harmonic distortion varied between -115.60 dB and -117.39 dB.

Modified Noise Power Ratio
The plots of MNPR show that at the evaluated gains, 1x and 8Lx, the Q330M+ has just under 22 bits of performance over the entire range of amplitudes.

Common Mode
The observed common mode rejection ranged from as low as 62.08 dB (gain 32x) to as high as 101.59 dB (gain 1x).

Cross Talk
The observable levels of crosstalk of the sensor channels were all between -153.99 dB and -147.23 dB. None of the terminated channels exhibited cross-talk, at any appreciable level, at the fundamental frequency.

Time Tag Accuracy
The measured time tag accuracy values were consistent for all of the recording channels on each digitizer and less than 63 microseconds while the digitizer utilized its internal GPS receiver for timing and less than 73 microseconds while it utilized the PTP server for timing.

Time Tag Drift
Drift rates while the digitizer's GPS receiver, or PTP server, was unlocked, were relatively consistent at 7 us/hr and 5 us/hr, respectively. Stable timing was re-established 1.5 hours after the timing signal was recovered, whether using the digitizer's internal GPS receiver or the PTP server for timing.

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.

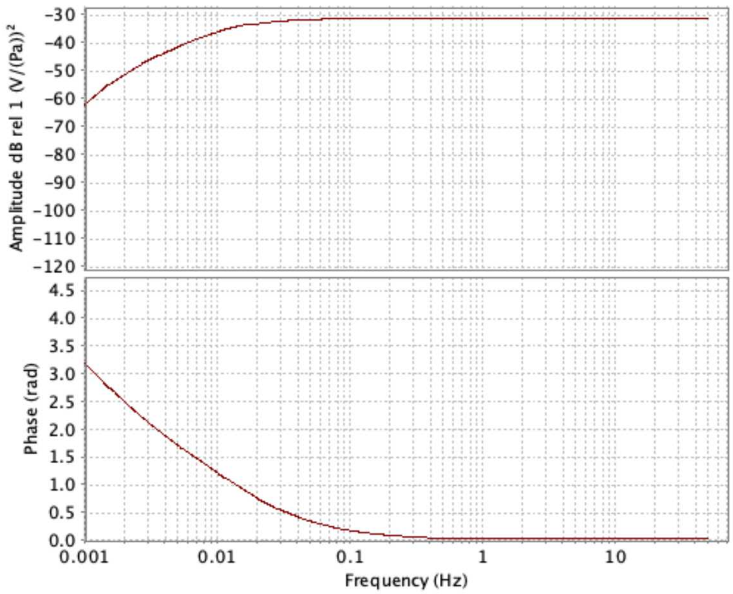
5. McDonald, Timothy S. (1994), *Modified Noise Power Ratio Testing of High Resolution digitizers*, SAND94-0221.

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: Amplitude and Phase Response

APPENDIX A: RESPONSE MODELS

4.1 Hyperion IFS-5013 Response



Sensitivity:
26.6 mV/Pa at 1.0 Hz

Poles:

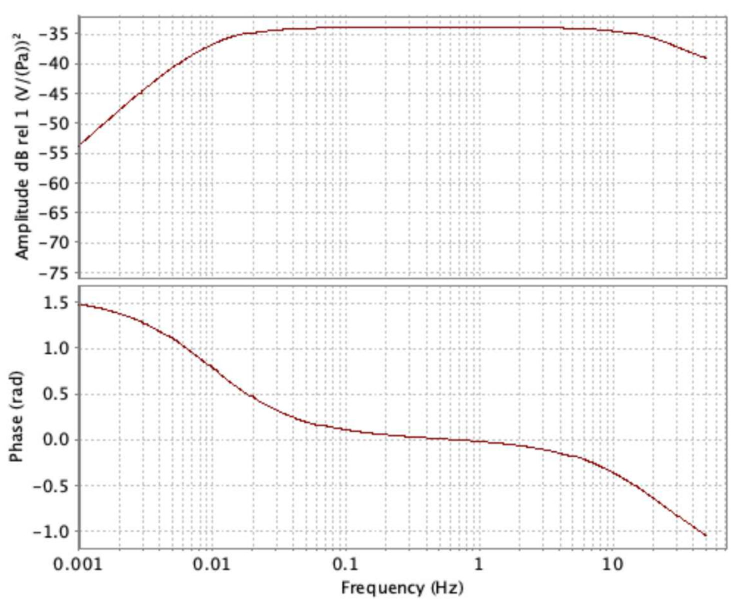
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
26.6029 mV/Pa

4.2 MB3a Response



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

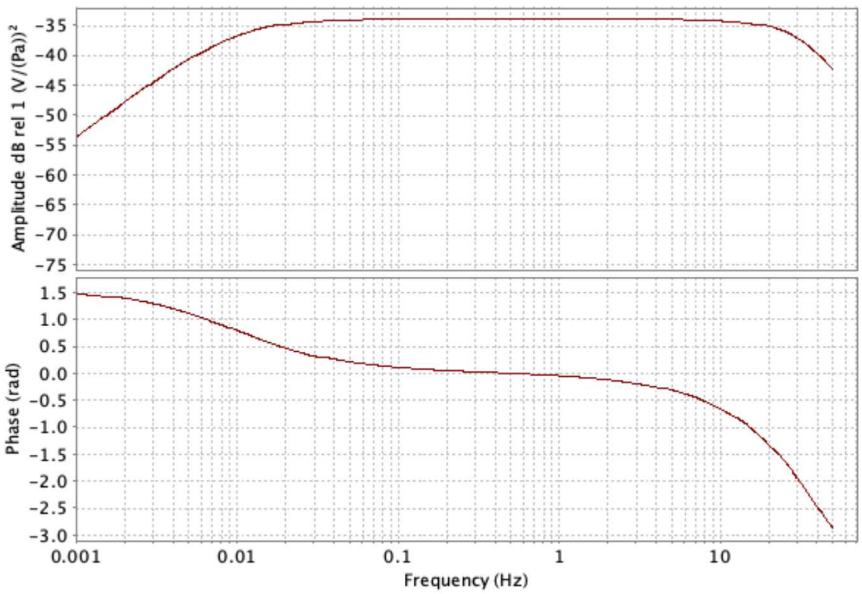
-156.25	0.0
-142.112	706.193
-142.112	-706.193
-0.062834	0.0

Zeros:

-1156.25	0.0
0.0	0.0

A:
1,403.53 V/Pa

4.3 MB2005 Response



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

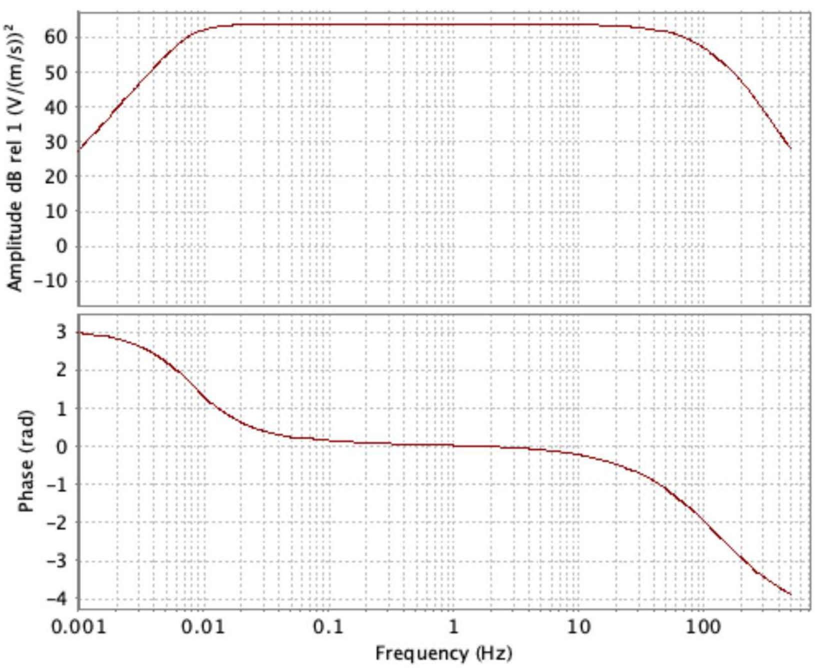
-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.0628	0.0

Zeros:

-468820.0	0.0
0.0	0.0

A:
466,950 MV/Pa

4.4 CMG-3T Response



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

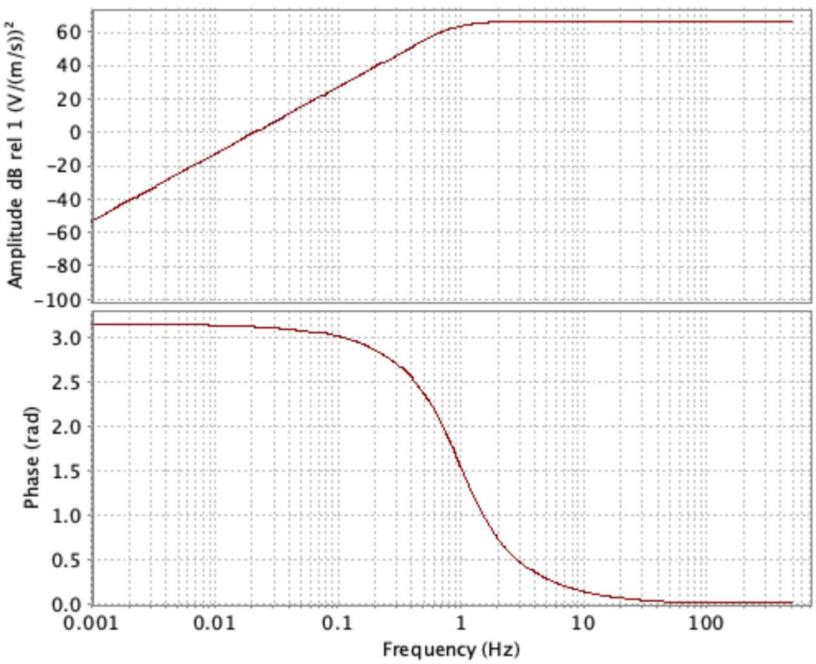
-1130.0	0.0
-1010.0	0.0
-503.0	0.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
861,208 MV·s/m

4.5 GS-13 Response



Sensitivity:
2,000 V·s/m at 5.0 Hz

Poles:

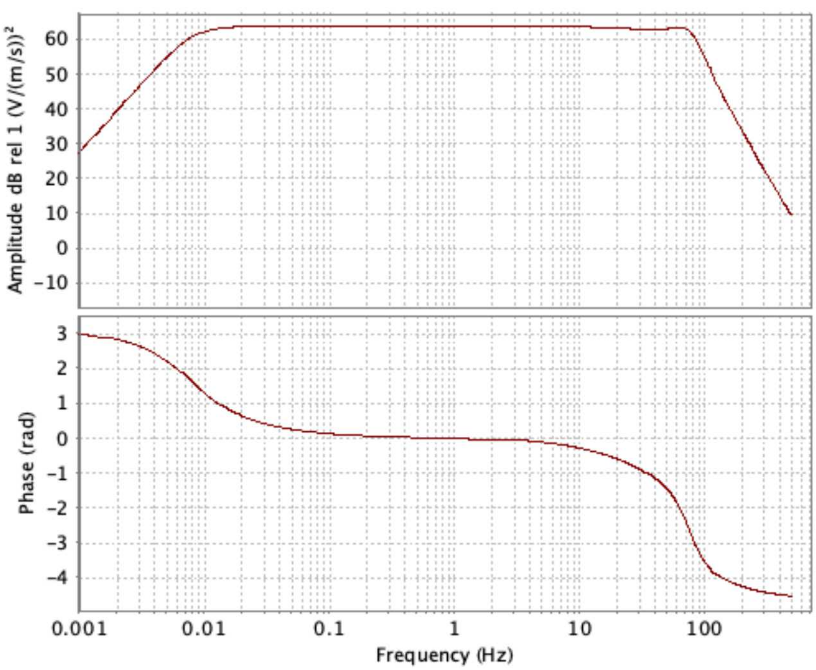
-4.443	4.443
-4.443	-4.443

Zeros:

0.0	0.0
0.0	0.0

A:
2,001.6 V·s/m

4.6 STS-2 Response



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

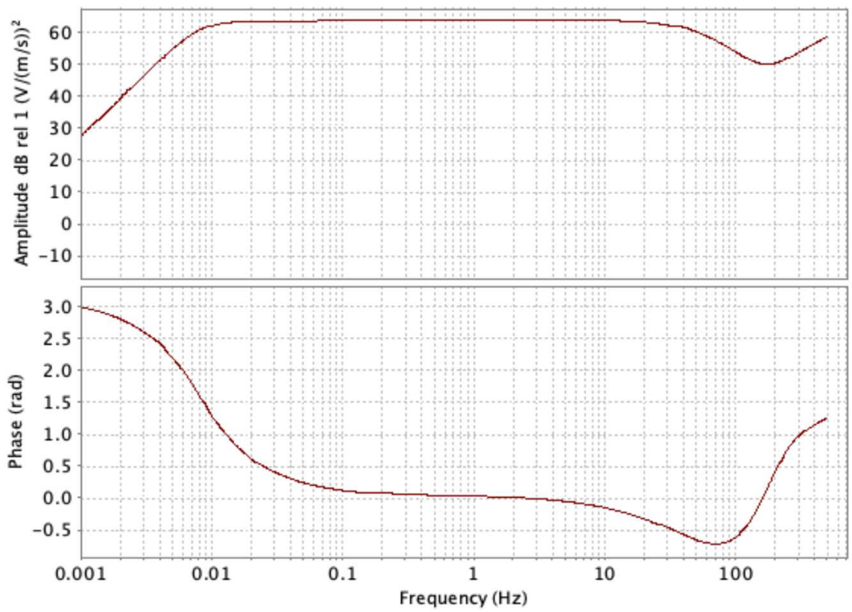
-251.0	0.0
-131.0	467.0
-131.0	-467.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
88,586.7 MV·s/m

4.7 STS-5a Response



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

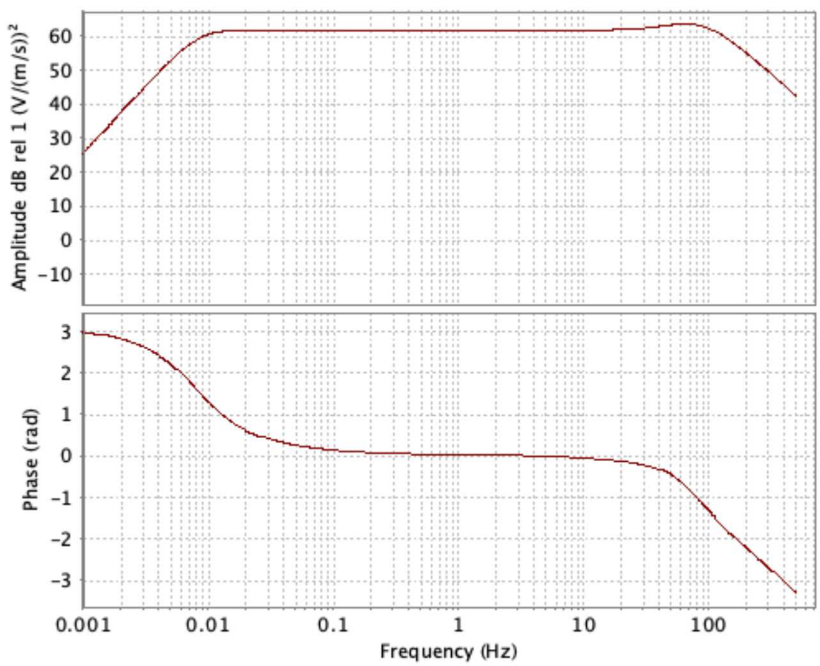
-961.0	0.0
-339.0	116.0
-339.0	-116.0
-16.0	0.0
-16.0	0.0
-0.037	-0.037
-0.037	0.037

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:
0.275035 V·s/m

4.8 T-120 Response



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

APPENDIX B: TESTBED CALIBRATIONS

Agilent 3458A # MY45048371

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

Limited Calibration Certificate

Document #: 6652541_11753062

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 28, 2018
Dates Tested (Start – End)	December 13, 2018 - December 17, 2018
Date Approved	December 18, 2018
Calibration Expiration Date	December 18, 2019

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-ADJ
Software Used	MET/CAL 8.3.2.37
Tamper Seal	None

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.

Calibration Data Report

Primary Electrical Lab

Unit Under Test:	Agilent 3458A Digital Multimeter	Test Result:	PASS
Asset Number:	6652541	Test Type:	AS-FOUND
Serial Number:	MY45048371	Calibration Date:	12/13/2018
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
- 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	5/17/2020
44972	Fluke 5725A Amplifier	12/18/2018
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/19/2019
6664630	Fluke 5730A Multifunction Calibrator	3/5/2019
6678754	Fluke 5790A-5 AC Measurement Standard	7/12/2019

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 35.8 deg.C

DC Volts

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99812	100.00082	100.00188	mV	2.26#	43	
-100.00000 mV		-100.00188	-100.00069	-99.99812	mV	2.26#	37	
1.00000000 V		0.99998965	1.00000724	1.00001035	V	2.97#	70	
-1.00000000 V		-1.00001035	-1.00000633	-0.99998965	V	2.97#	61	
-10.0000000 V		-10.0000987	-10.0000748	-9.9999013	V	3.92#	76	
-5.0000000 V		-5.0000501	-5.0000381	-4.9999499	V	3.71#	76	
-2.0000000 V		-2.0000209	-2.0000130	-1.9999791	V	3.24#	62	
2.0000000 V		1.9999791	2.0000150	2.0000209	V	3.24#	72	
5.0000000 V		4.9999499	5.0000393	5.0000501	V	3.71#	79	Mar
10.0000000 V		9.9999013	10.0000761	10.0000987	V	3.92#	77	
100.000000 V		99.998821	100.000851	100.001179	V	3.51#	72	

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

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
1000.00000 V		999.98900	1000.01031	1000.01100	V	2.42#	94	Mar
DC Current								
100.000 nA		91.597	99.958	108.403	nA	1.85#	0	
1.000000 µA		0.969900	0.999967	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999918	10.030100	µA	5.2	0	
100.00000 µA		99.95000	99.99923	100.05000	µA	5.7	2	
1.0000000 mA		0.9997500	0.9999938	1.0002500	mA	7.6	3	
10.000000 mA		9.997500	9.999971	10.002500	mA	8.1	1	
100.00000 mA		99.97500	100.00111	100.02500	mA	6.1	4	
1.0000000 A		0.9995000	1.0000210	1.0005000	A	7.6	4	
Resistance								
10.00000 Ohm	10.000528	9.99943	10.00061	10.00163	Ohm	5.8	8	
100.00000 Ohm	100.005370	99.99987	100.00629	100.01087	Ohm	6.5	17	
1.0000000 kOhm	0.99999750	0.9999465	1.0000057	1.0000485	kOhm	9.1	16	
10.000000 kOhm	9.9998170	9.999307	9.999903	10.000327	kOhm	9.4	17	
100.00000 kOhm	99.998110	99.99301	99.99898	100.00321	kOhm	8.2	17	
1.0000000 MOhm	0.99994470	0.9998427	0.9999551	1.0000467	MOhm	9.3	10	
10.000000 MOhm	9.9979120	9.995812	9.998052	10.000012	MOhm	7.2	7	
100.00000 MOhm	100.012100	99.96109	100.01220	100.06311	MOhm	6.0	0	
1.00117000 GOhm		0.9811366	1.0020674	1.0212034	GOhm	>10	4	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9381	100.1700	µA	7.4	36	
100.0000 µA @ 45 Hz		99.8300	99.9836	100.1700	µA	10.0	10	
100.0000 µA @ 1 kHz		99.8300	99.9824	100.1700	µA	10.0	10	
1.000000 mA @ 20 Hz		0.998300	0.999485	1.001700	mA	10.0	30	
1.000000 mA @ 45 Hz		0.998300	0.999943	1.001700	mA	>10	3	
1.000000 mA @ 5 kHz		0.998300	1.000221	1.001700	mA	6.3	13	
1.000000 mA @ 10 kHz		0.995013	1.000508	1.004987	mA	3.47#	10	
10.00000 mA @ 20 Hz		9.98300	9.99492	10.01700	mA	10.0	30	
10.00000 mA @ 45 Hz		9.98300	9.99945	10.01700	mA	>10	3	
10.00000 mA @ 5 kHz		9.98300	10.00114	10.01700	mA	7.7	7	
10.00000 mA @ 10 kHz		9.94970	10.00223	10.05030	mA	4.0	4	
100.0000 mA @ 20 Hz		99.8300	99.9541	100.1700	mA	10.0	27	
100.0000 mA @ 45 Hz		99.8300	99.9994	100.1700	mA	>10	0	
100.0000 mA @ 5 kHz		99.8300	100.0274	100.1700	mA	8.5	16	
100.0000 mA @ 10 kHz		99.4800	100.0514	100.5200	mA	5.5	10	
1.000000 A @ 40 Hz		0.998300	0.999912	1.001700	A	6.8	5	
1.000000 A @ 5 kHz		0.998357	1.000873	1.001643	A	3.95#	53	
AC Volts								
10.00000 mV @ 10 Hz	9.997600	9.97740	9.99865	10.01780	mV	7.2	5	
10.00000 mV @ 40 Hz	9.997400	9.99298	9.99824	10.00182	mV	2.94#	19	
10.00000 mV @ 20 kHz	9.998200	9.99378	9.99926	10.00262	mV	2.94#	24	
10.00000 mV @ 50 kHz	9.998700	9.98760	9.99743	10.00980	mV	4.1	11	
10.00000 mV @ 100 kHz	10.002100	9.95099	9.98921	10.05321	mV	>10	25	
10.00000 mV @ 300 kHz	10.002200	9.60011	9.88661	10.40429	mV	>10	29	
100.0000 mV @ 10 Hz	99.99460	99.7926	99.9972	100.1966	mV	>10	1	
100.0000 mV @ 40 Hz	99.99370	99.9467	99.9988	100.0407	mV	>10	11	
100.0000 mV @ 20 kHz	99.99610	99.9491	99.9898	100.0431	mV	>10	13	
100.0000 mV @ 50 kHz	99.99640	99.8944	99.9923	100.0984	mV	>10	4	
100.0000 mV @ 100 kHz	100.00050	99.7985	99.9849	100.2025	mV	>10	8	
100.0000 mV @ 300 kHz	100.01540	99.0052	99.9458	101.0256	mV	>10	7	
1.000000 V @ 10 Hz	1.0000704	0.998050	1.000026	1.002091	V	>10	2	
1.000000 V @ 40 Hz	1.0000150	0.999545	1.000032	1.000485	V	>10	4	
1.000000 V @ 20 kHz	1.0000142	0.999544	0.999944	1.000484	V	>10	15	
1.000000 V @ 50 kHz	1.0000213	0.999001	1.000022	1.001041	V	>10	0	
1.000000 V @ 100 kHz	1.0000411	0.998021	1.000099	1.002061	V	>10	3	
1.000000 V @ 300 kHz	1.0002413	0.990139	1.001570	1.010344	V	>10	13	
10.00000 V @ 10 Hz	10.000805	9.98060	10.00055	10.02101	V	>10	1	
10.00000 V @ 40 Hz	10.000198	9.99550	10.00038	10.00490	V	>10	4	
10.00000 V @ 20 kHz	10.000233	9.99553	9.99996	10.00493	V	>10	6	
10.00000 V @ 50 kHz	10.000474	9.99027	10.00076	10.01067	V	>10	3	

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 100 kHz	10.000967	9.98077	9.99982	10.02117	V	>10	6	
10.00000 V @ 300 kHz	10.002521	9.90150	10.00006	10.10355	V	>10	2	
100.0000 V @ 10 Hz	100.00787	99.8059	100.0039	100.2099	V	>10	2	
100.0000 V @ 40 Hz	100.00162	99.9546	100.0027	100.0486	V	>10	2	
100.0000 V @ 20 kHz	100.00324	99.9562	99.9992	100.0502	V	>10	9	
100.0000 V @ 50 kHz	100.00659	99.9046	100.0090	100.1086	V	>10	2	
100.0000 V @ 100 kHz	100.00878	99.8068	100.0027	100.2108	V	>10	3	
100.0000 V @ 200 kHz	100.03653	99.0262	100.0015	101.0469	V	>10	3	
700.0000 V @ 40 Hz	700.02420	699.4442	699.9892	700.6042	V	>10	6	
700.0000 V @ 20 kHz	700.01940	699.4394	699.7545	700.5994	V	>10	46	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000064	10.005000	Hz	>10	1	
40.00000 Hz @ 1 V		39.996000	40.000514	40.004000	Hz	>10	13	
100.00000 Hz @ 1 V		99.990000	100.001171	100.010000	Hz	>10	12	
1000.0000 Hz @ 1 V		999.90000	1000.00953	1000.10000	Hz	>10	10	
10000.0000 Hz @ 1 V		9999.00000	10000.09823	10001.00000	Hz	>10	10	
20000.0000 Hz @ 1 V		19998.00000	20000.19836	20002.00000	Hz	>10	10	
50000.0000 Hz @ 1 V		49995.00000	50000.49114	50005.00000	Hz	>10	10	
100.00000 kHz @ 1 V		99.990000	100.000982	100.010000	kHz	>10	10	
500.00000 kHz @ 1 V		499.950000	500.004911	500.050000	kHz	>10	10	
1.000000 MHz @ 1 V		0.9999000	1.0000098	1.0001000	MHz	>10	10	
2.000000 MHz @ 1 V		1.9998000	2.0000196	2.0002000	MHz	>10	10	
4.000000 MHz @ 1 V		3.9996000	4.0000393	4.0004000	MHz	>10	10	
6.000000 MHz @ 1 V		5.9994000	6.0000587	6.0006000	MHz	>10	10	
8.000000 MHz @ 1 V		7.9992000	8.0000788	8.0008000	MHz	>10	10	
10.000000 MHz @ 1 V		9.9990000	10.0000992	10.0010000	MHz	>10	10	

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

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:	AS-LEFT
Serial Number:	MY45048371	Calibration Date:	12/17/2018
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
- 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	5/17/2020
44972	Fluke 5725A Amplifier	12/18/2018
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/19/2019
6664630	Fluke 5730A Multifunction Calibrator	3/5/2019
6678754	Fluke 5790A-5 AC Measurement Standard	7/12/2019

Test Results

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

LIMITED CALIBRATION:
   PSL specifications are larger than manufacturer's
   specifications reported in Factory User Manual.
   This is a limitation of the PSL.
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The internal temperature of the 3458A is 36.1 deg.C
DC Volts
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Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99812	100.00009	100.00188	mV	2.26#	5	
-100.00000 mV		-100.00188	-100.00005	-99.99812	mV	2.26#	3	
1.00000000 V		0.99998965	0.99999925	1.00001035	V	2.97#	7	
-1.00000000 V		-1.00001035	-0.99999881	-0.99998965	V	2.97#	12	
-10.0000000 V		-10.0000987	-9.9999992	-9.9999013	V	3.92#	1	
-5.0000000 V		-5.0000501	-4.9999997	-4.9999499	V	3.71#	1	
-2.0000000 V		-2.0000209	-1.9999980	-1.9999791	V	3.24#	10	
2.0000000 V		1.9999791	1.9999996	2.0000209	V	3.24#	2	
5.0000000 V		4.9999499	5.0000005	5.0000501	V	3.71#	1	
10.0000000 V		9.9999013	9.9999985	10.0000987	V	3.92#	2	
100.000000 V		99.998821	100.000049	100.001179	V	3.51#	4	

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
1000.00000 V		999.98900	1000.00265	1000.01100	V	2.42#	24	
DC Current								
100.000 nA		91.597	99.978	108.403	nA	1.85#	0	
1.000000 µA		0.969900	0.999950	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999910	10.030100	µA	5.2	0	
100.00000 µA		99.95000	99.99977	100.05000	µA	5.7	0	
1.0000000 mA		0.9997500	0.9999974	1.0002500	mA	7.6	1	
10.000000 mA		9.997500	9.999987	10.002500	mA	8.1	1	
100.00000 mA		99.97500	100.00113	100.02500	mA	6.1	5	
1.0000000 A		0.9995000	1.0000283	1.0005000	A	7.6	6	
Resistance								
10.00000 Ohm	10.000528	9.99943	10.00054	10.00163	Ohm	5.8	1	
100.00000 Ohm	100.005370	99.99987	100.00564	100.01087	Ohm	6.5	5	
1.0000000 kOhm	0.99999750	0.9999465	0.9999962	1.0000485	kOhm	9.1	3	
10.000000 kOhm	9.9998170	9.999307	9.999813	10.000327	kOhm	9.4	1	
100.00000 kOhm	99.998110	99.99301	99.99808	100.00321	kOhm	8.2	1	
1.0000000 MOhm	0.99994470	0.9998427	0.9999461	1.0000467	MOhm	9.3	1	
10.000000 MOhm	9.9979120	9.995812	9.998001	10.000012	MOhm	7.2	4	
100.00000 MOhm	100.012100	99.96109	100.00726	100.06311	MOhm	6.0	10	
1.00117000 GOhm		0.9811366	1.0011724	1.0212034	GOhm	>10	0	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9443	100.1700	µA	7.4	33	
100.0000 µA @ 45 Hz		99.8300	99.9880	100.1700	µA	10.0	7	
100.0000 µA @ 1 kHz		99.8300	99.9874	100.1700	µA	10.0	7	
1.000000 mA @ 20 Hz		0.998300	0.999521	1.001700	mA	10.0	28	
1.000000 mA @ 45 Hz		0.998300	0.999978	1.001700	mA	>10	1	
1.000000 mA @ 5 kHz		0.998300	1.000267	1.001700	mA	6.3	16	
1.000000 mA @ 10 kHz		0.995013	1.000557	1.004987	mA	3.47#	11	
10.00000 mA @ 20 Hz		9.98300	9.99536	10.01700	mA	10.0	27	
10.00000 mA @ 45 Hz		9.98300	9.99982	10.01700	mA	>10	1	
10.00000 mA @ 5 kHz		9.98300	10.00171	10.01700	mA	7.7	10	
10.00000 mA @ 10 kHz		9.94970	10.00294	10.05030	mA	4.0	6	
100.0000 mA @ 20 Hz		99.8300	99.9566	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	100.0354	100.1700	mA	8.5	21	
100.0000 mA @ 10 kHz		99.4800	100.0650	100.5200	mA	5.5	13	
1.000000 A @ 40 Hz		0.998300	0.999955	1.001700	A	6.8	3	
1.000000 A @ 5 kHz		0.998357	1.000978	1.001643	A	3.95#	60	
AC Volts								
10.00000 mV @ 10 Hz	9.997500	9.97730	9.99891	10.01769	mV	7.2	7	
10.00000 mV @ 40 Hz	9.997400	9.99298	9.99825	10.00182	mV	2.94#	19	
10.00000 mV @ 20 kHz	9.998300	9.99388	9.99923	10.00272	mV	2.94#	21	
10.00000 mV @ 50 kHz	9.998800	9.98770	9.99735	10.00990	mV	4.1	13	
10.00000 mV @ 100 kHz	10.002200	9.95109	9.98909	10.05331	mV	>10	26	
10.00000 mV @ 300 kHz	10.002300	9.60021	9.88552	10.40439	mV	>10	29	
100.0000 mV @ 10 Hz	99.99400	99.7920	99.9980	100.1960	mV	>10	2	
100.0000 mV @ 40 Hz	99.99410	99.9471	99.9966	100.0411	mV	>10	5	
100.0000 mV @ 20 kHz	99.99630	99.9493	99.9898	100.0433	mV	>10	14	
100.0000 mV @ 50 kHz	99.99650	99.8945	99.9929	100.0985	mV	>10	3	
100.0000 mV @ 100 kHz	100.00110	99.7991	99.9826	100.2031	mV	>10	9	
100.0000 mV @ 300 kHz	100.01570	99.0055	99.9411	101.0259	mV	>10	7	
1.000000 V @ 10 Hz	1.0000714	0.998051	1.000073	1.002092	V	>10	0	
1.000000 V @ 40 Hz	1.0000144	0.999544	1.000038	1.000484	V	>10	5	
1.000000 V @ 20 kHz	1.0000161	0.999546	0.999924	1.000486	V	>10	20	
1.000000 V @ 50 kHz	1.0000224	0.999002	1.000001	1.001042	V	>10	2	
1.000000 V @ 100 kHz	1.0000400	0.998020	1.000131	1.002060	V	>10	4	
1.000000 V @ 300 kHz	1.0002407	0.990138	1.001517	1.010343	V	>10	13	
10.00000 V @ 10 Hz	10.000778	9.98058	10.00051	10.02098	V	>10	1	
10.00000 V @ 40 Hz	10.000202	9.99550	10.00038	10.00490	V	>10	4	
10.00000 V @ 20 kHz	10.000220	9.99552	9.99997	10.00492	V	>10	5	
10.00000 V @ 50 kHz	10.000472	9.99027	10.00085	10.01067	V	>10	4	

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 100 kHz	10.000988	9.98079	10.00019	10.02119	V	>10	4	
10.00000 V @ 300 kHz	10.002562	9.90154	10.00012	10.10359	V	>10	2	
100.0000 V @ 10 Hz	100.00636	99.8043	100.0037	100.2084	V	>10	1	
100.0000 V @ 40 Hz	100.00182	99.9548	100.0020	100.0488	V	>10	0	
100.0000 V @ 20 kHz	100.00325	99.9562	99.9978	100.0503	V	>10	12	
100.0000 V @ 50 kHz	100.00681	99.9048	100.0077	100.1088	V	>10	1	
100.0000 V @ 100 kHz	100.00938	99.8074	100.0005	100.2114	V	>10	4	
100.0000 V @ 200 kHz	100.03625	99.0259	100.0052	101.0466	V	>10	3	
700.0000 V @ 40 Hz	700.02260	699.4426	699.9753	700.6026	V	>10	8	
700.0000 V @ 20 kHz	700.01930	699.4393	699.7303	700.5993	V	>10	50	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000052	10.005000	Hz	>10	1	
40.00000 Hz @ 1 V		39.996000	40.000453	40.004000	Hz	>10	11	
100.00000 Hz @ 1 V		99.990000	100.000885	100.010000	Hz	>10	9	
1000.0000 Hz @ 1 V		999.90000	1000.00991	1000.10000	Hz	>10	10	
10000.0000 Hz @ 1 V		9999.00000	10000.09823	10001.00000	Hz	>10	10	
20000.0000 Hz @ 1 V		19998.00000	20000.19455	20002.00000	Hz	>10	10	
50000.0000 Hz @ 1 V		49995.00000	50000.48637	50005.00000	Hz	>10	10	
100.00000 kHz @ 1 V		99.990000	100.000982	100.010000	kHz	>10	10	
500.00000 kHz @ 1 V		499.950000	500.004911	500.050000	kHz	>10	10	
1.000000 MHz @ 1 V		0.9999000	1.0000098	1.0001000	MHz	>10	10	
2.000000 MHz @ 1 V		1.9998000	2.0000196	2.0002000	MHz	>10	10	
4.000000 MHz @ 1 V		3.9996000	4.0000391	4.0004000	MHz	>10	10	
6.000000 MHz @ 1 V		5.9994000	6.0000587	6.0006000	MHz	>10	10	
8.000000 MHz @ 1 V		7.9992000	8.0000786	8.0008000	MHz	>10	10	
10.000000 MHz @ 1 V		9.9990000	10.0000973	10.0010000	MHz	>10	10	

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limitations

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

Equipment (Standard) Used

Asset #	Description	Model #	Expires
6678754	Standard,Measurement	5790B-5	July 12, 2019
6664630	Calibrator,Multifunction	5730A/05	August 20, 2020
6651332	Generator,Function	33250A	February 20, 2019
44972	Amplifier	5725A	December 19, 2018
11123	Resistor,Standard	5155-9	May 17, 2020

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

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 the SI;
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 results reported above relate only to the items tested or calibrated.

NOTE 4: The Decision Rule for the As-Found condition is Simple Acceptance, where the measured value is within the previous certification limits.

Authorization

Calibrated By:

Liddle, Brian David
Metrologist

Approved By:

Espino Flores, Oscar

End-of-Document

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