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Next Generation Qualification: Quanterra Q330HR Digitizer Evaluation

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Next Generation Qualification: Quanterra Q330HR Digitizer Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated a new digitizer, the Q330HR, manufactured by Quanterra. These digitizers are 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 power consumption, input impedance, sensitivity, full scale, self-noise, dynamic range, system noise, response, passband, and timing. The Q330HR is Quanterra's improved Q330 datalogger with a 26 bits of resolution on channels 1-3 and a 24 bits of resolution on channels 4-6 (26 bit is optional). The Quanterra Q330HR is being evaluated for potential use U.S. Air Force seismic monitoring systems as part of their Next Generation Qualification effort.

ACKNOWLEDGMENTS

The equipment was purchased and setup using funds provided by the United States Department of Defense. The evaluation and generation of the report was funded by the National Nuclear Security Administration's Office of Defense Nuclear Nonproliferation Research and Development (NA-22).

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NOMENCLATURE

BB	Broadband
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
HNM	High Noise Model
Hz	Hertz
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories
SP	Short-period
sps	sample per second

1 INTRODUCTION

The evaluation of the four Quanterra Q330HR digitizers, serial numbers 6162 and 6164, was performed to determine the performance characteristics of the instruments including sensitivity, self-noise, dynamic range, frequency response, and passband.

Figure 1 Quanterra Q330HR Digitizer (photo courtesy of Kinemetrics Inc)

The Q330HR is available as a 3 or 6 channel 26-bit digitizer with variable sample rate and gain level suitable in form-factor for equipment vault style seismic monitoring system deployment.

The evaluation of the two digitizers, serial numbers 6162 and 6164, performed against the digitizer specifications below, has identified that the digitizers' performance are consistent with their manufacturer's specifications. Both units utilized 26 bits of resolution on channels 1 – 3 and 24 bits of resolution on channels 4 – 6.

QUANTERRA

Q330HR

ULTRA-HIGH-RESOLUTION NETWORK-AWARE SEISMIC SYSTEM

A New Performance Standard

The Q330HR sets a new performance standard in seismological instrumentation, building upon the widely praised ultra-low-power Q330. The Q330HR breaks the 24-bit performance barrier to extend the capability of advanced instrumentation for research. The Q330HR remains 100% compatible with our Q330. See Q330 data sheet for a general and functional product description.

FEATURES

- Multiple Network Access for Telemetry and Local Recording
- Internet-Ready Industry Standards
- Comprehensive Sensor Control
- Streamlined Remote Administration

SPECIFICATIONS

Main Channels	3 channels 26-bit and 3 channels 24-bit; option for all 6 channels 26-bit available
Auxiliary Channels	4/8 DI/SE 16-bit 1 sps. Full scale range +50V
Dynamic Range	144-145 dB wideband rms typical
HR Channels	0.02-20Hz 147-148 dB
Input Range	40V P-P at gain=1
Gain	Selectable per channel: 1,20
Filtering	Linear or Minimum Phase FIR.
Sample Rates	200, 100, 50, 40, 20, 10, 1. Independently available any channel.
Time Base	Precision TCXO, phase locked to GPS. No adjustment.

DSP/CPU	ADSP-2189M
Telemetry	Full Duplex, efficient positive acknowledge with advanced error control. Industry-standard IP over serial and Ethernet interfaces. Burst or continuous.
Multiple Access	4 Independent Data Ports. 2 Administration Ports
Format and Protocol	32-bit integer, Level 2 compressed 1-second packets. Published protocols operate with numerous major application software packages.
Temperature	Fully specified -10 to +50° C Operative -40 to +70° C

Continued

Figure 2 Quanterra Q330 HR Specifications, Part 1

QUANTERRA

SPECIFICATIONS

Sensor Control Calibrate step, sine, or random.
Recenter, on-command

Additional State-of-Health Temperature, DC voltage, GPS status, Sensor boom position (6 channels)

Memory 8MB RAM standard

Ethernet Network IEEE 802 10Base-T Ethernet

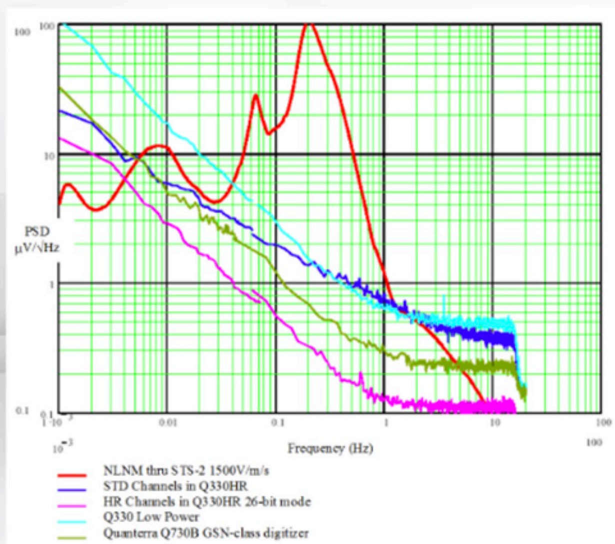
Serial Network 2 serial network and 1 console interface up to 115 kbaud.

Wireless IrDA interface supported.

Power <2.0 W avg. 12VDC 3-channels on
<2.5 W avg. 12VDC 6-channels on

Physical Sealed, Aluminum, 14x4x6 in., 8lbs., rubber endcaps, externally visible status and fault indicators.

High! Resolution



The Q330HR sets a new standard, requiring 26-bit resolution to fully represent its dynamic range. The 'HR exceeds GSN-class standard set by Quanterra nearly 20 years ago. The figure above shows the performance of the HR and standard channels in the Q330HR compared with the ultra-low-power Q330 and Quanterra's GSN-class Q730B. Better by a bit and at very low power!

The Kinemetrics facility in Pasadena, CA has a certified ISO9001 Quality Management System.

USA- 325 Ayer Rd. Harvard, MA
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05-30-17

Figure 3 Quanterra Q330 HR Specifications, Part 2

2 TEST PLAN

2.1 Test Facility

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

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

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

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

Figure 4 FACT Site Bunker

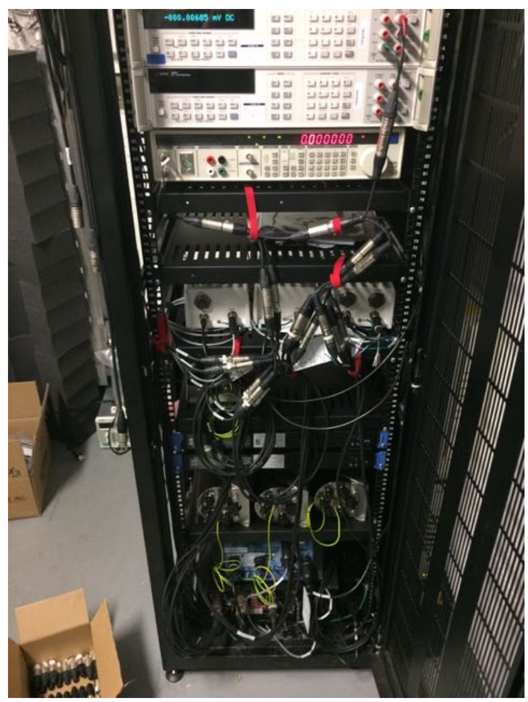

Figure 5 Partial View of Testbed in FACT Site Bunker

The temperature was maintained between 22 and 27 degrees Celsius. The low temperature was maintained with a thermostatically controlled electric heater during the Spring months; temperatures gradually rose through the year, peaking in late Summer.

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

Figure 6 GPS Re-broadcaster

The Quanterra digitizers were powered off of a Protek 3005B laboratory power supply providing approximately 13.6 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 Quanterra digitizer.

Table 1 Tests Performed

Test	Configuration
Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip Total Harmonic Distortion Input Terminated Noise Crosstalk Common Mode Rejection Analog Bandwidth Relative Transfer Function Response Incoherent Noise Time Tag Statistics	**Quanterra Q330HR digitizers SN 6162 and 6164 gain 20x, sample rate 100 sps temperature 23° C**
Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip Total Harmonic Distortion Input Terminated Noise Crosstalk Common Mode Rejection Analog Bandwidth Relative Transfer Function Response Incoherent Noise Time Tag Statistics	**Quanterra Q330HR digitizer SN 6164 SB-1, Environmental Chamber gain 20x, sample rates 4, 20, 40, 100 and 200 sps at 20° C**
Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip Total Harmonic Distortion Input Terminated Noise Crosstalk Common Mode Rejection Analog Bandwidth Relative Transfer Function Response Incoherent Noise Time Tag Statistics	**Quanterra Q330HR digitizer SN 6164 SB-1, Environmental Chamber gain: 20x, sample rate 100 sps temperatures: 46° C, 20° C, -10°C and -20° C *operational check at temperatures of 60° C and -36° C**

2.3 Timeline

Testing of the Q330HR digitizers was performed at Sandia National Laboratories between March and August 2017. Testing was performed using Quanterra digitizers, serial numbers 6162 and 6164 in the bunker. Exposure to low and high temperatures, while recording at select sample rates, was completed with the 6 channel unit, Q330HR 6164.

2.4 Evaluation Frequencies

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

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

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

					0.00315,	0.0040,	0.0050,	0.0063,	0.008,
0.01,	0.0125,	0.016,	0.020,	0.025,	0.0315,	0.040,	0.050,	0.063,	0.08,
0.10,	0.125,	0.16,	0.20,	0.25,	0.315,	0.40,	0.50,	0.63,	0.8,
1.0,	1.25,	1.6,	2.0,	2.5,	3.15,	4.0,	5.0,	6.3,	8.0,
10.0,	12.5,	16.0,	20.0,	25.0,	31.5,	40.0			

3 TEST EVALUATION

3.1 Power Consumption

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

3.1.1 Measurand

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

3.1.2 Configuration

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

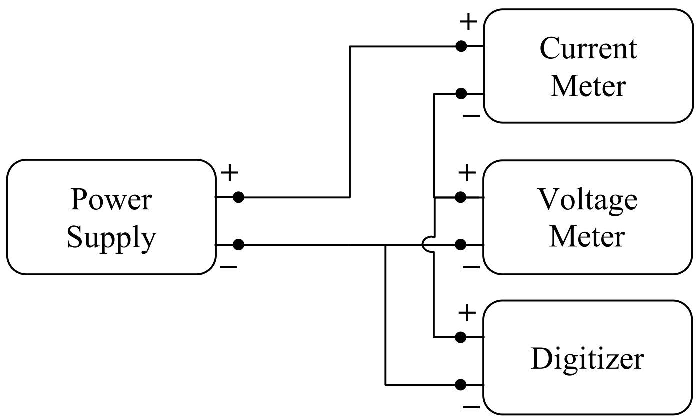

Figure 8 Power Consumption Configuration Diagram

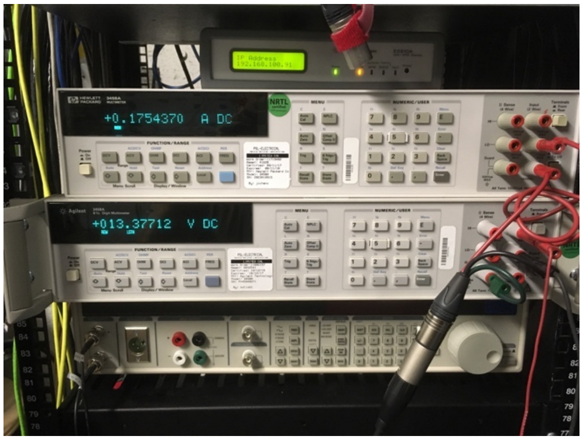

Figure 9 Power Consumption Configuration Picture

Table 2 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Power Supply	Protek 3005B	AC2074	13.5 V
Current Meter	Agilent 3458A	2823A10915	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.

3.1.3 Analysis

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

$$V \text{ and } I$$

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

$$P = V * I$$

3.1.4 Result

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

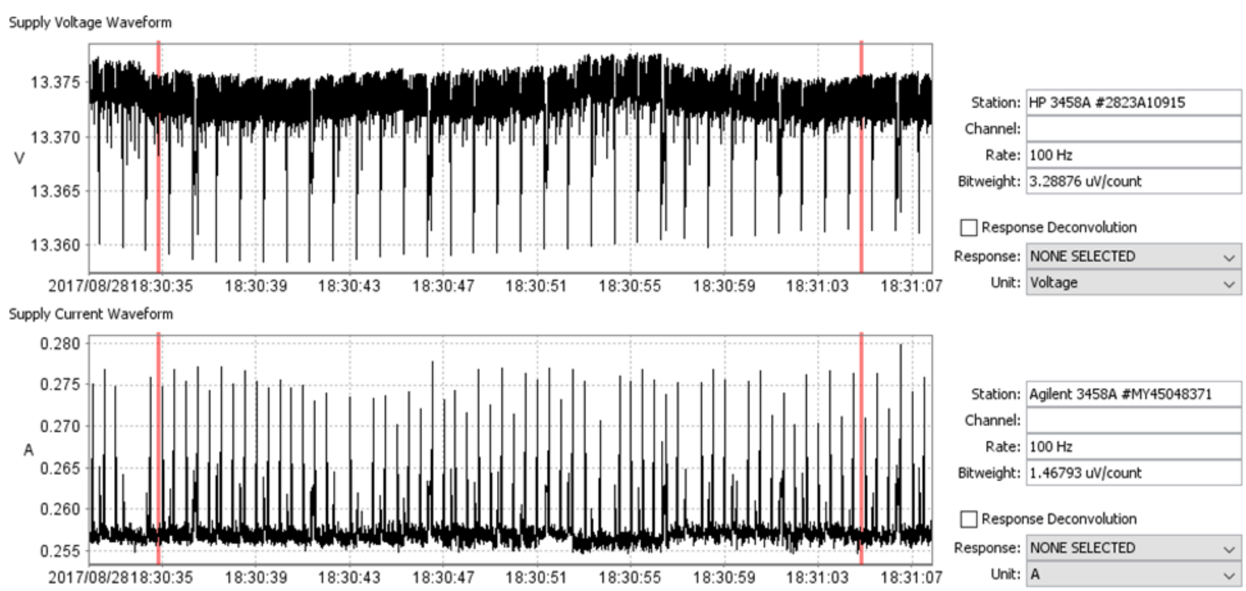

Figure 10 Voltage and Current Recorded Time Series, Q330HR 6162

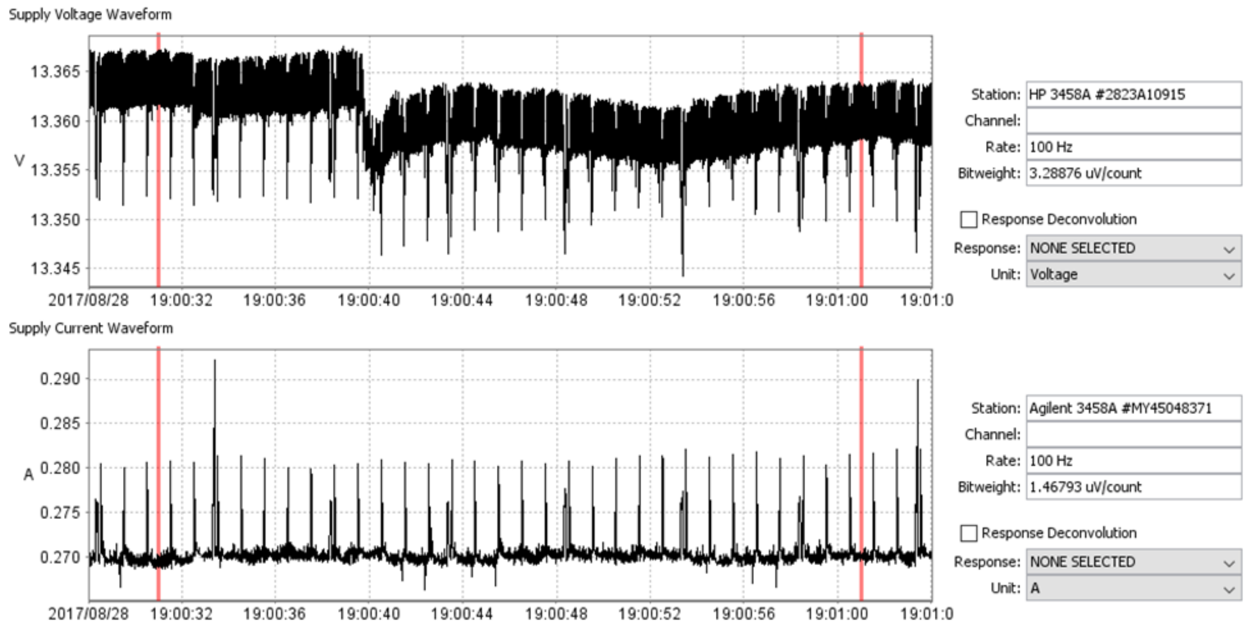

Figure 11 Voltage and Current Recorded Time Series, Q330HR 6164

Table 3 Power Consumption Results

DWR	Supply Voltage	Supply Voltage SD	Supply Current	Supply Current SD	Power Consumption	Power Consumption SD
6162	13.37 V	2.40 mV	0.257 A	2.73 mA	3.44 W	37.11 mW
6164	13.36 V	3.45 mV	0.270 A	1.64 mA	3.61 W	22.78 mW

The six channel Q330HR digitizers were observed to consume between 3.44 watts to 3.61 watts during operation. The relatively short duration time-series illustrate the variation in power required by the Q330HR dataloggers; power requirements likely increase beyond that shown here during if a baler storage unit or field processor are attached.

3.2 Input Impedance

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

3.2.1 Measurand

The quantity being measured is ohms of impedance.

3.2.2 Configuration

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

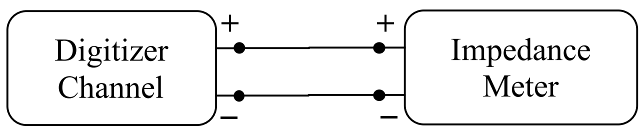

Figure 12 Input Impedance Configuration Diagram

Figure 13 Input Impedance Configuration Picture

Table 4 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Impedance Meter - Bunker	Agilent 3458A	MY45048372	DC Impedance
Impedance Meter – SB1	Agilent 3458A	2823A10915	DC Impedance

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

3.2.3 Analysis

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

3.2.4 Result

Table 5 Impedance of Q330HR 6164 at Select Temperatures

Temp.	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
46° C	65.3289 Kohm	65.2337 Kohm	65.1866 Kohm	65.1986 Kohm	65.1896 Kohm	65.2800 Kohm
20° C	67.2849 Kohm	67.1923 Kohm	67.1488 Kohm	67.1687 Kohm	67.1651 Kohm	67.2614 Kohm
-10° C	69.4866 Kohm	69.4866 Kohm	69.0591 Kohm	69.1196 Kohm	69.1242 Kohm	69.2209 Kohm
-20° C	69.4866 Kohm	69.3952 Kohm	69.3726 Kohm	69.3747 Kohm	69.4278 Kohm	69.5266 Kohm

Over the range of temperatures at which impedance was measured (-20° C to 46° C), impedance values measured increased as temperature decreased. Average impedance measured over the temperatures of evaluation is 67.7800 Kohm.

Table 6 Impedance Variation with Sample Rate, Q330HR 6164, 20°C

Sample Rate	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
5 sps	67.2849 Kohm	67.1923 Kohm	67.1488 Kohm	67.1687 Kohm	67.1651 Kohm	67.2614 Kohm
20 sps	67.2849 Kohm	67.1923 Kohm	67.1488 Kohm	67.1687 Kohm	67.1651 Kohm	67.2614 Kohm
40 sps	67.2849 Kohm	67.1923 Kohm	67.1488 Kohm	67.1687 Kohm	67.1651 Kohm	67.2614 Kohm
200 sps	67.2849 Kohm	67.1923 Kohm	67.1488 Kohm	67.1687 Kohm	67.1651 Kohm	67.2614 Kohm

One impedance measurement per channel was made as all sample rates were recorded simultaneously.

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.

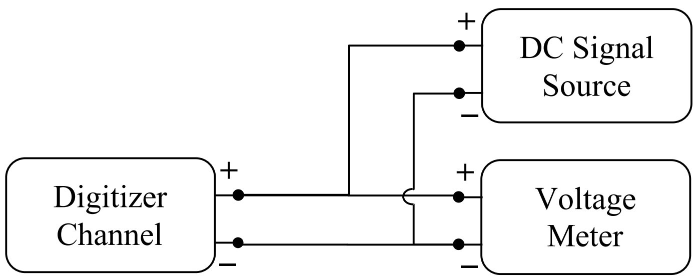

Figure 14 DC Accuracy Configuration Diagram

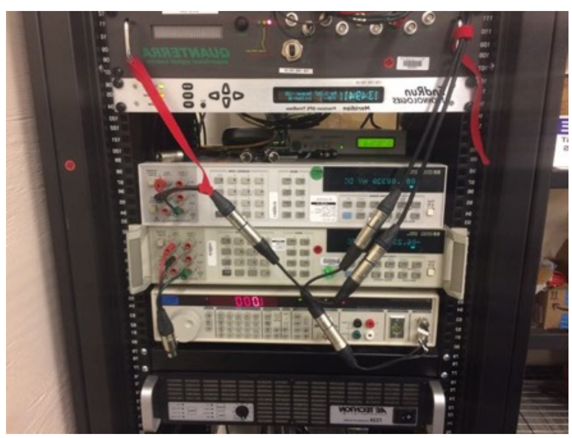

Figure 15 DC Accuracy Configuration

Table 7 DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - Bunker	Agilent 3458A	MY45048372	1 V full scale
DC Signal Source - SB1	Stanford Research Systems DS360	123669	+1V / - 1 V
Voltage Meter - SB1	Agilent 3458A	2823A10915	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 sps.

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:

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

The digitizer DC offset is computed:

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

3.3.4 Result

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

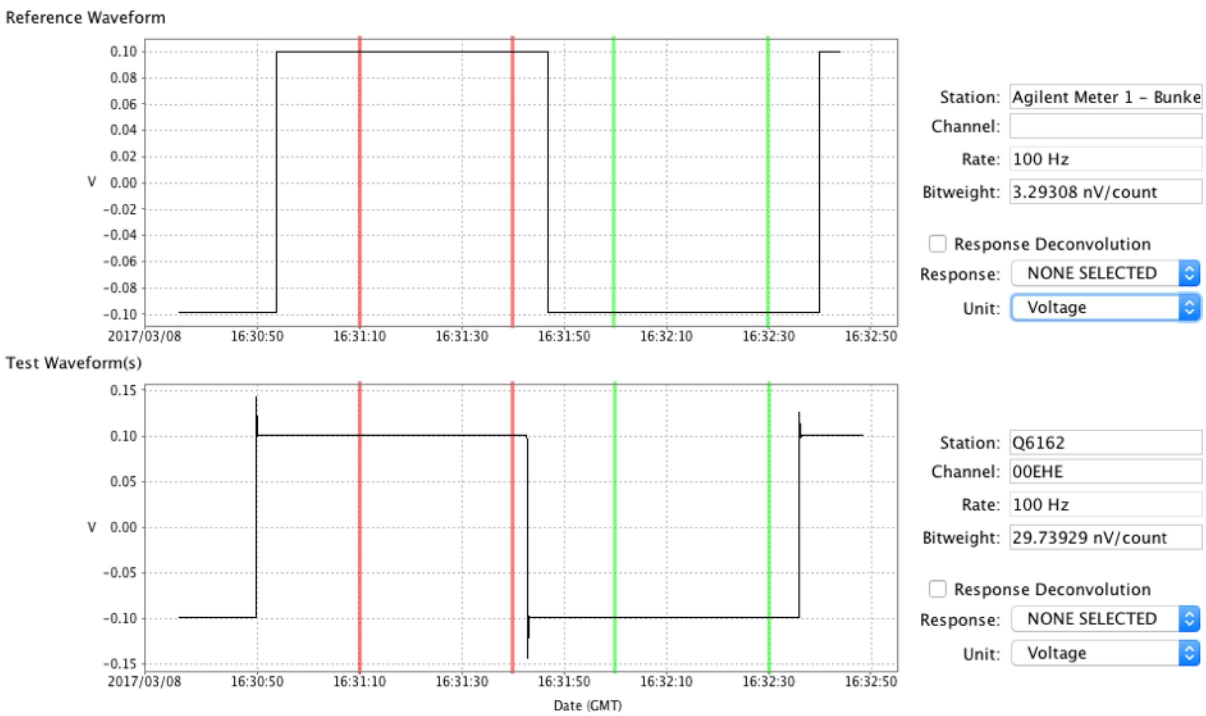

Figure 16 DC Accuracy Test Time series, Q330HR 6162, Channel 00 EHE (3)

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

Table 8 DC Accuracy Bitweight, All Q330HR DWR at 23° C

DWR	00EHE (Channel 3)	00EHN (Channel 2)	00EHZ (Channel 1)	10EHE (Channel 6)	10EHN (Channel 5)	10EHZ (Channel 4)
6162	29.7628 nV/cts	29.7548 nV/cts	29.7477 nV/cts	118.86 nV/cts	118.85 nV/cts	118.88 nV/cts
6164	29.7459 nV/cts	29.7625 nV/cts	29.7469 nV/cts	118.83 nV/cts	118.90 nV/cts	118.82 nV/cts

The nominal bit weights provided by Quanterra were specified to be: 29.8 nV/count and 119 nV/count, for the 26 bit (channels 1-3) and 24 bit (channels 4-6) digitizers, respectively.

The differences between the observed bit weights at 23° C and the nominal values provided by the manufacturer ranged from 0.12% to 0.18%.

Table 9 DC Accuracy Bitweight, Q330HR 6164 at Select Temperatures

Temp.	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
46° C	29.7575 nV/cts	29.7474 nV/cts	29.7598 nV/cts	118.89 nV/cts	118.86 nV/cts	118.89 nV/cts
20° C	29.6925 nV/cts	29.6812 nV/cts	29.6933 nV/cts	118.61 nV/cts	118.58 nV/cts	118.61 nV/cts
-10° C	29.7396 nV/cts	29.7545 nV/cts	29.7380 nV/cts	118.78 nV/cts	118.86 nV/cts	118.88 nV/cts
-20° C	29.7448 nV/cts	29.7307 nV/cts	29.7421 nV/cts	118.79 nV/cts	118.76 nV/cts	118.77 nV/cts

Over the selected temperature range, the bitweights of Q330HR 6164, varied from 0.09% to more than 0.40% from the nominal bit weights.

Table 10 DC Accuracy Bitweight, Q330HR 6164 at Select Sample Rates, 20° C

Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
10 sps	29.6945 nV/cts	29.6833 nV/cts	29.6953 nV/cts	118.62 nV/cts	118.59 nV/cts	118.61 nV/cts
20 sps	29.6954 nV/cts	29.6842 nV/cts	29.6962 nV/cts	118.62 nV/cts	118.59 nV/cts	118.62 nV/cts
40 sps	29.6963 nV/cts	29.6851 nV/cts	29.6972 nV/cts	118.63 nV/cts	118.59 nV/cts	118.62 nV/cts
100 sps	29.6925 nV/cts	29.6812 nV/cts	29.6933 nV/cts	118.61 nV/cts	118.58 nV/cts	118.61 nV/cts
200 sps	29.6929 nV/cts	29.6817 nV/cts	29.6938 nV/cts	118.61 nV/cts	118.58 nV/cts	118.61 nV/cts

Across the selected sample rates, bit weights varied little; from as low as 0.33% to 0.40% of the nominal bit weights.

Over all, across selected sample rates and temperatures, bit weights remained relatively stable, and varying no more than 0.40% from nominal.

3.4 AC Accuracy

The AC Accuracy test is used to measure the bitweight 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 bitweight 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.

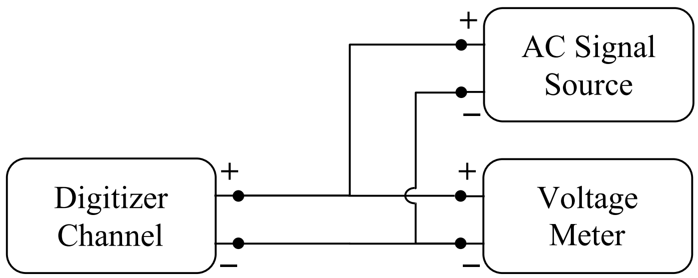

Figure 17 AC Accuracy Configuration Diagram

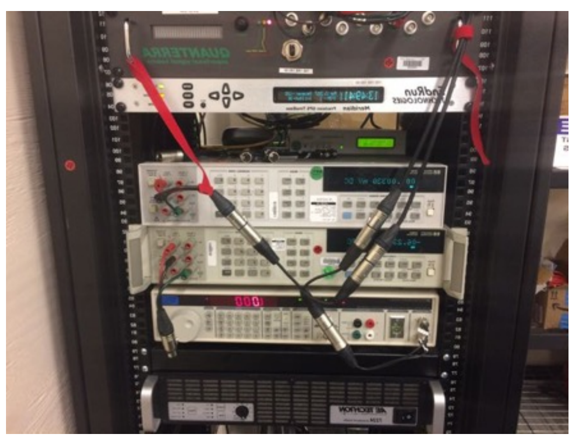

Figure 18 AC Accuracy Configuration Picture

Table 11 AC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - Bunker	Agilent 3458A	MY45048372	1 V full scale
DC Signal Source - SB1	Stanford Research Systems DS360	123669	+1V / - 1 V
Voltage Meter - SB1	Agilent 3458A	2823A10915	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 sps, 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.

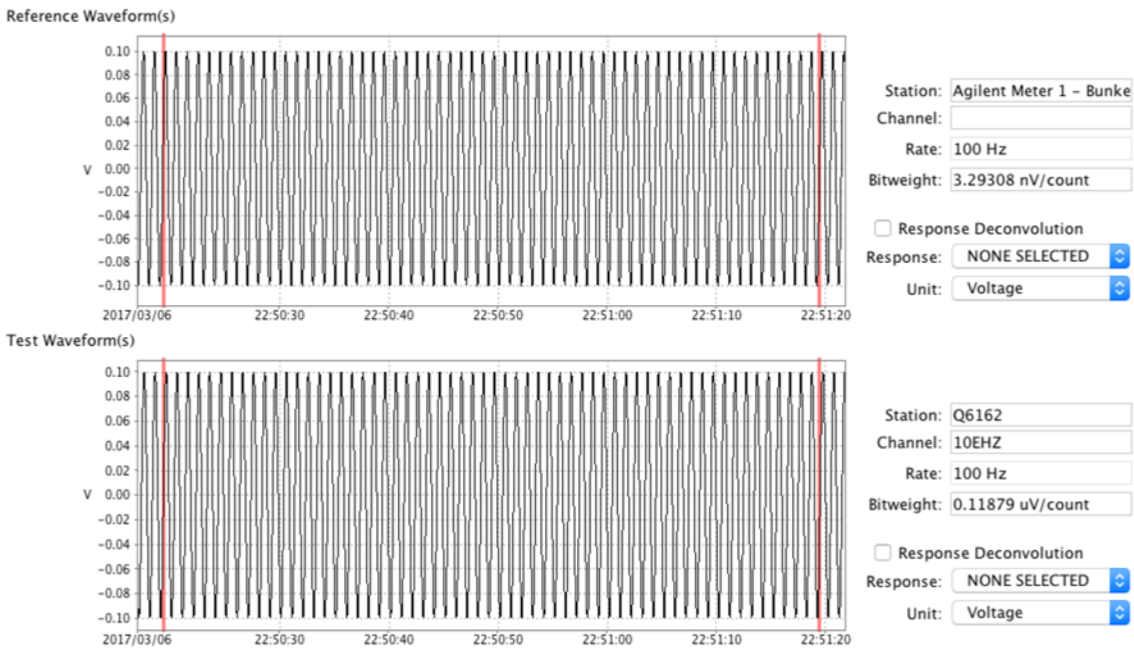

Figure 19 AC Accuracy Time Series

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

Table 12 AC Accuracy Bitweight, Both Q330HRs at 23° C

DWR	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	29.7393 nV/cts	29.7313 nV/cts	29.7241 nV/cts	118.77 nV/cts	118.76 nV/cts	118.79 nV/cts
6164	29.7228 nV/cts	29.7393 nV/cts	29.7237 nV/cts	118.73 nV/cts	118.81 nV/cts	118.72 nV/cts

Table 13 AC Accuracy Bitweight, Q330HR 6164, at Select Temperatures

Temp.	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
60° C	29.7342 nV/cts	29.7241 nV/cts	29.7365 nV/cts	118.80 nV/cts	118.76 nV/cts	118.80 nV/cts
20° C	29.6693 nV/cts	29.6581 nV/cts	29.6701 nV/cts	118.52 nV/cts	118.49 nV/cts	118.51 nV/cts
-10° C	29.7163 nV/cts	29.7312 nV/cts	29.7147 nV/cts	118.68 nV/cts	118.77 nV/cts	118.78 nV/cts
-20° C	29.7211 nV/cts	29.7071 nV/cts	29.7185 nV/cts	118.70 nV/cts	118.67 nV/cts	118.68 nV/cts

Table 14 AC Accuracy Bitweight, Q330HR 6164, at Select Sample Rates, 20° C

Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
10 sps	29.4772 nV/cts	29.4660 nV/cts	29.4780 nV/cts	117.75 nV/cts	117.72 nV/cts	117.75 nV/cts
20 sps	29.5006 nV/cts	29.4894 nV/cts	29.5014 nV/cts	117.85 nV/cts	117.81 nV/cts	117.84 nV/cts
40 sps	29.5074 nV/cts	29.4962 nV/cts	29.5082 nV/cts	117.87 nV/cts	117.84 nV/cts	117.87 nV/cts
100 sps	29.6693 nV/cts	29.6581 nV/cts	29.6701 nV/cts	118.52 nV/cts	118.49 nV/cts	118.51 nV/cts
200 sps	29.6884 nV/cts	29.6772 nV/cts	29.6893 nV/cts	118.60 nV/cts	118.56 nV/cts	118.59 nV/cts

AC Accuracy Test results varied more than with DC Accuracy Tests results; as little as 0.17% for the 100 sps 46° C test to as high as 1.12% at 10 sps sampling rate (perhaps due to undersampling the waveform).

When reviewing the AC accuracy results averaged over the channels for each test, AC accuracy improves slightly as sample rate increases (oversampling improves characterization of the waveform) and also improves as temperature increases.

3.5 Input Shorted Offset

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

3.5.1 Measurand

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

3.5.2 Configuration

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

Figure 20 Input Shorted Offset Configuration Diagram

Figure 21 Input Shorted Offset Configuration Picture

Table 15 Input Shorted Offset Testbed Equipment

Digitizer	Resistor load
Quanterra Q330HR	300 Ohm (2x150 Ohm)

Approximately 7 hours of data are recorded for tests of all units at 23° C, while at select temperatures 1 hour of data is recorded.

3.5.3 Analysis

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

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

The mean value, in volts, is evaluated:

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

3.5.4 Result

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

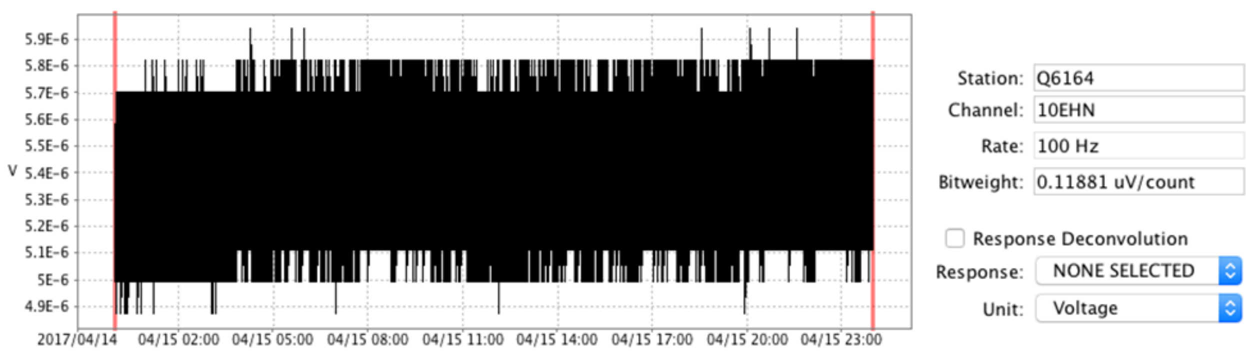

Figure 22 Input Shorted Offset Time Series

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

Table 16 Input Shorted Offset, Both Q330HRs, 23° C

DWR	00EHE (Channel 3)	00EHN (Channel 2)	00EHZ (Channel 1)	10EHE (Channel 6)	10EHN (Channel 5)	10EHZ (Channel 4)
6162	7.111 uV	4.514 uV	7.284 uV	2.749 uV	2.103 uV	5.597 uV
6164	4.997 uV	3.609 uV	4.552 uV	3.178 uV	4.683 uV	3.383 uV

Table 17 Input Shorted Offset, Q330HR 6164, at Select Temperatures

Temp.	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
46° C	-6.560 uV	-8.704 uV	-3.681 uV	-4.561 uV	-5.806 uV	-4.527 uV
20° C	5.831 uV	5.245 uV	5.443 uV	4.766 uV	5.453 uV	4.578 uV
-10° C	38.10 uV	39.69 uV	39.25 uV	42.1 uV	18.07 uV	34.94 uV
-20° C	-2.633 uV	-2.735 uV	-1.238 uV	-3.059 uV	6.431 uV	-4.978 uV

Over varying temperatures the input shorted offset appears to be at a maximum voltage at -10° C; on either side of -10° C the terminated voltage drops. The maximum differential over the temperatures at which tests were conducted is 46. uV, observed on channel 6.

Table 18 Input Shorted Offset Q330HR 6164 at Select Sample Rates, 20° C

Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
5 sps	5.829 uV	5.243 uV	5.440 uV	4.762 uV	5.452 uV	4.576 uV
20 sps	5.829 uV	5.243 uV	5.440 uV	4.763 uV	5.451 uV	4.576 uV
40 sps	5.829 uV	5.243 uV	5.440 uV	4.763 uV	5.451 uV	4.575 uV
100 sps	5.831 uV	5.245 uV	5.443 uV	4.766 uV	5.453 uV	4.578 uV
200 sps	5.831 uV	5.245 uV	5.442 uV	4.766 uV	5.453 uV	4.578 uV

Not surprisingly, input shorted offsets did not vary appreciably over the selected sample rates.

3.6 AC Full Scale

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

3.6.1 Measurand

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

3.6.2 Configuration

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

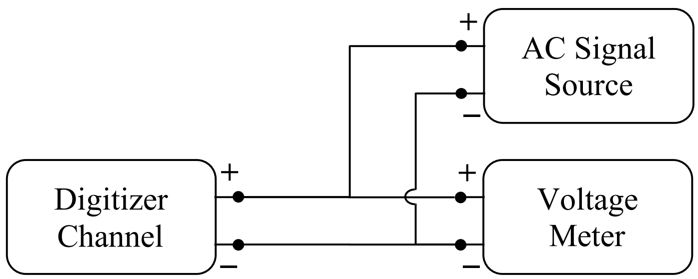

Figure 23 AC Full Scale Configuration Diagram

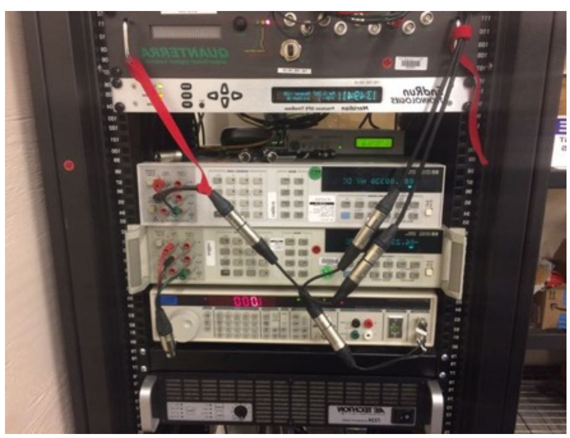

Figure 24 AC Full Scale Configuration Picture

Table 19 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter Bunker	Agilent 3458A	MY45048372	1 V full scale
DC Signal Source SB1	Stanford Research Systems DS360	123669	+1V / - 1 V
Voltage Meter SB1	Agilent 3458A	2823A10915	1 V full scale

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

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

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

3.6.3 Analysis

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

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

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

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

3.6.4 Result

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

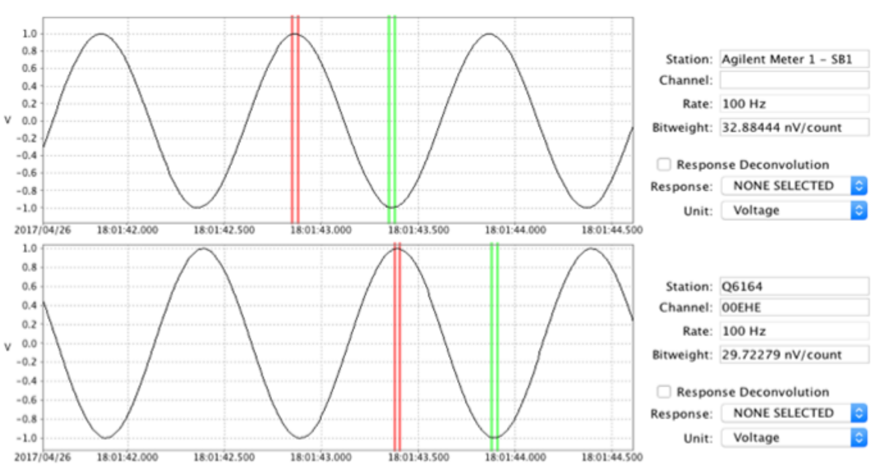

Figure 25 AC Full Scale Time Series, Q330HR 6164

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

Table 20 AC Full Scale Positive Peak

DWR	Temperature/ Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	23° C, 100 sps	0.9939 V	0.9939 V	0.9939 V	0.9939 V	0.9939 V	0.9939 V
6164	23° C, 100 sps	0.9939 V	0.9939 V	0.9939 V	0.9939 V	0.9939 V	0.9939 V
6164	46° C, 100 sps	0.9948 V	0.9957 V	0.9948 V	0.9946 V	0.9956 V	0.9946 V
6164	20° C, 10 sps	0.9624 V	0.9632 V	0.9624 V	0.9623 V	0.9632 V	0.9623 V
6164	20° C, 20 sps	1.0017 V	1.0026 V	1.0017 V	1.0017 V	1.0026 V	1.0016 V
6164	20° C, 40 sps	1.0015 V	1.0024 V	1.0015 V	1.0014 V	1.0024 V	1.0014 V
6164	20° C, 100 sps	0.9947 V	0.9956 V	0.9947 V	0.9947 V	0.9956 V	0.9946 V
6164	20° C, 200 sps	0.9942 V	0.9951 V	0.9942 V	0.9941 V	0.9950 V	0.9942 V
6164	-10° C, 100 sps	0.9955 V	0.9955 V	0.9956 V	0.9956 V	0.9956 V	0.9947 V
6164	-20° C, 100 sps	0.9955 V	0.9965 V	0.9956 V	0.9957 V	0.9967 V	0.9958 V

Table 21 AC Full Scale Negative Peak

DWR	Temperature/ Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	23° C, 100 sps	-0.9947 V	-0.9956 V	-0.9956 V	-0.9956 V	-0.9956 V	-0.9956 V
6164	23° C, 100 sps	-0.9956 V	-0.9956 V	-0.9956 V	-0.9956 V	-0.9956 V	-0.9956 V
6164	46° C, 100 sps	-0.9967 V	-0.9976 V	-0.9955 V	-0.9965 V	-0.9975 V	-0.9964 V
6164	20° C, 10 sps	-0.9663 V	-0.9672 V	-0.9663 V	-0.9663 V	-0.9672 V	-0.9663 V
6164	20° C, 20 sps	-1.0034 V	-1.0044 V	-1.0034 V	-1.0034 V	-1.0043 V	-1.0033 V
6164	20° C, 40 sps	-1.0032 V	-1.0041 V	-1.0032 V	-1.0032 V	-1.0041 V	-1.0031 V
6164	20° C, 100 sps	-0.9962 V	-0.9978 V	-0.9962 V	-0.9961 V	-0.9977 V	-0.9961 V
6164	20° C, 200 sps	-0.9962 V	-0.9972 V	-0.9962 V	-0.9962 V	-0.9970 V	-0.9961 V
6164	-10° C, 100 sps	-0.9969 V	-0.9968 V	-0.9970 V	-0.9970 V	-0.9970 V	-0.9961 V
6164	-20° C, 100 sps	-0.9970 V	-0.9980 V	-0.9971 V	-0.9965 V	-0.9974 V	-0.9966 V

Table 22 AC Full Scale Peak-to-Peak

DWR	Temperature/ Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	23° C, 100 sps	1.9895 V	1.9895 V	1.9895 V	1.9895 V	1.9895 V	1.9896 V
6164	23° C, 100 sps	1.9895 V	1.9895 V	1.9895 V	1.9895 V	1.9896 V	1.9895 V
6164	46° C, 100 sps	1.9915 V	1.9933 V	1.9903 V	1.9911 V	1.9931 V	1.9910 V
6164	20° C, 10 sps	1.9287 V	1.9305 V	1.9287 V	1.9286 V	1.9304 V	1.9285 V
6164	20° C, 20 sps	2.0051 V	2.0070 V	2.0052 V	2.0050 V	2.0069 V	2.0050 V
6164	20° C, 40 sps	2.0047 V	2.0066 V	2.0047 V	2.0046 V	2.0065 V	2.0045 V
6164	20° C, 100 sps	1.9909 V	1.9934 V	1.9909 V	1.9908 V	1.9933 V	1.9907 V
6164	20° C, 200 sps	1.9904 V	1.9922 V	1.9904 V	1.9903 V	1.9920 V	1.9903 V
6164	-10° C, 100 sps	1.9924 V	1.9924 V	1.9925 V	1.9927 V	1.9926 V	1.9909 V
6164	-20° C, 100 sps	1.9925 V	1.9945 V	1.9927 V	1.9922 V	1.9940 V	1.9923 V

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

3.7 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.

3.7.1 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.

3.7.2 Configuration

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

Figure 26 Self Noise Configuration Diagram

Figure 27 Self Noise Configuration Picture

Table 23 Self Noise Testbed Equipment

	Impedance
Resistor	440 ohm (2 x 220 Ohm)

24 hours of data are generally utilized for this test.

3.7.3 Analysis

The measured bitweights at 1 Hz, from section 3.4, AC Accuracy, appropriate to the gain setting utilized, are 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 32K-sample Hann window. The window length and data duration were chosen such that there were several points below the lower limit of the lower evaluation pass-band of 0.02 Hz and the 90% confidence interval to be approximately 0.5 dB. The resulting 90% confidence intervals determined for the analysis is as follows: 0.43 dB for data logger comparisons at 23° C (24 hour window), less than 0.48 dB for the sample rate comparisons (12-24 hours duration).

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

Over frequencies (in Hertz):

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

In addition, the total RMS noise over the application pass-bands of 0.02 Hz to 16 Hz, 0.02 Hz to 1 Hz and 0.5 Hz to 16 Hz are 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

3.7.4 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.

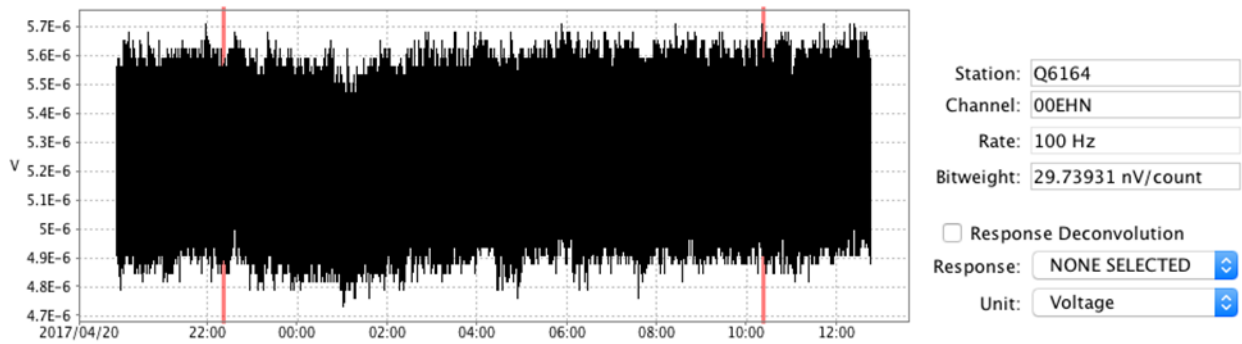

Figure 28 Self Noise Time Series Example, Q330HR 6164, 00 EHN (channel 2)

Plots of power spectra and tables of RMS noise levels are organized as follows:

- each datalogger recording at 100 sps at a temperature of 23° C, 24 hour data window.
- SN 6164 at varying sample rates (10, 20, 40, 100 and 200) while exposed to 20° C, recording for 12 hours.
- SN6164 recording at 100 sps, while exposed at temperatures of 46° C, 20° C, -10° C and -20° C, recording for 12 - 24 hours.

Recall the Q330HR units tested have 26-bit digitization on channels 1 through 3 and 24-bit digitization on channels 4-6.

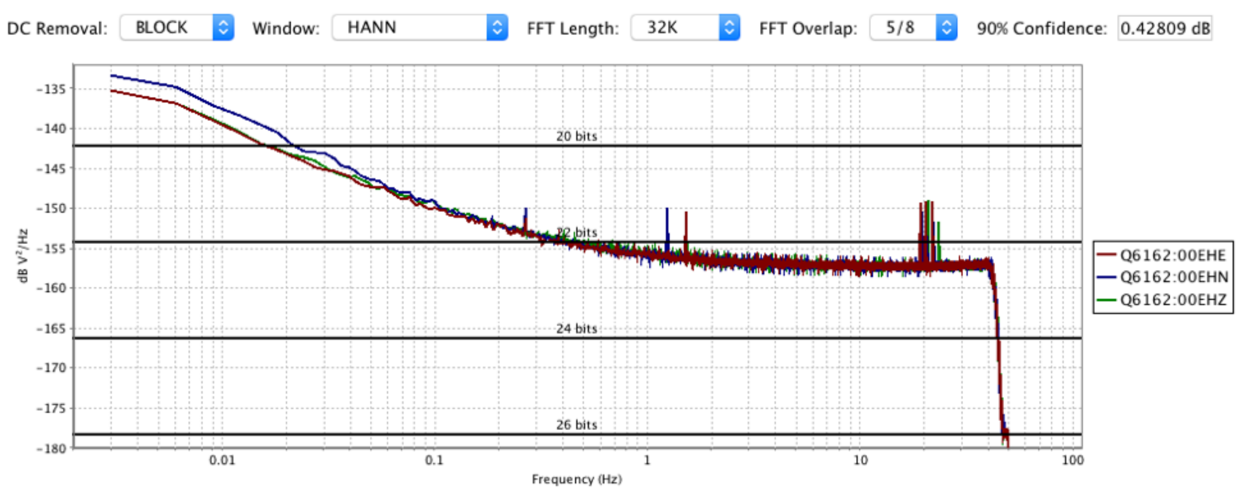

Figure 29 Self Noise Power Spectra Q330HR 6162, Channels 1 - 3, 100 sps, 23° C

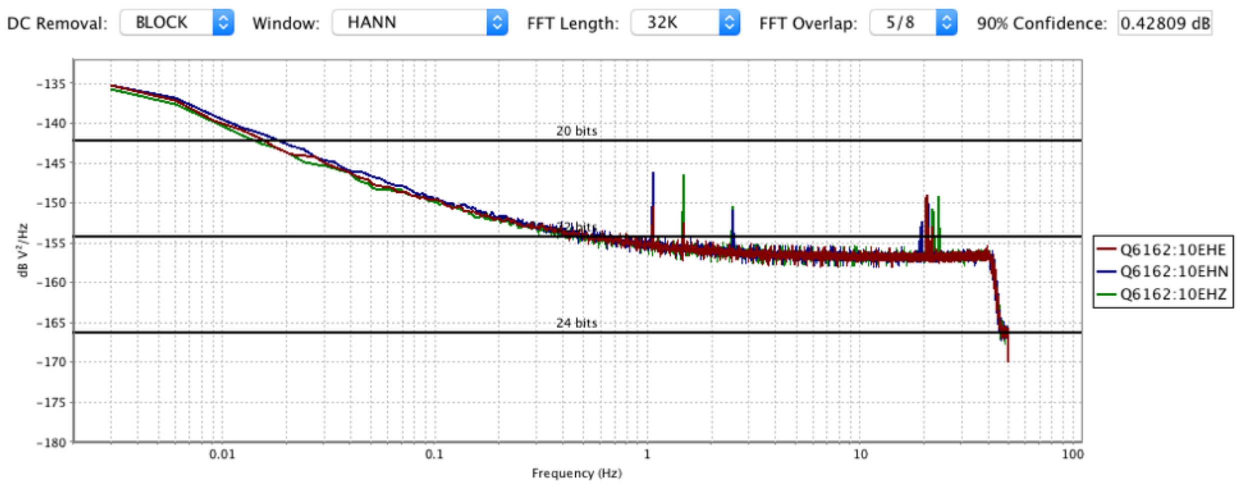

Figure 30 Self Noise Power Spectra Q330HR 6162, Channels 4 - 6, 100 sps, 23° C

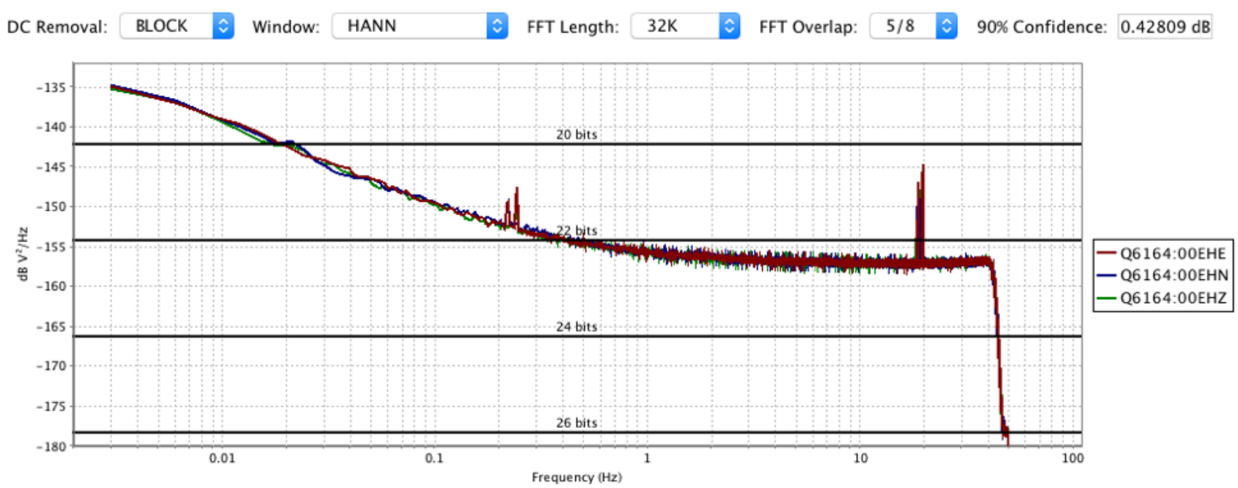

Figure 31 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 100 sps, 23° C

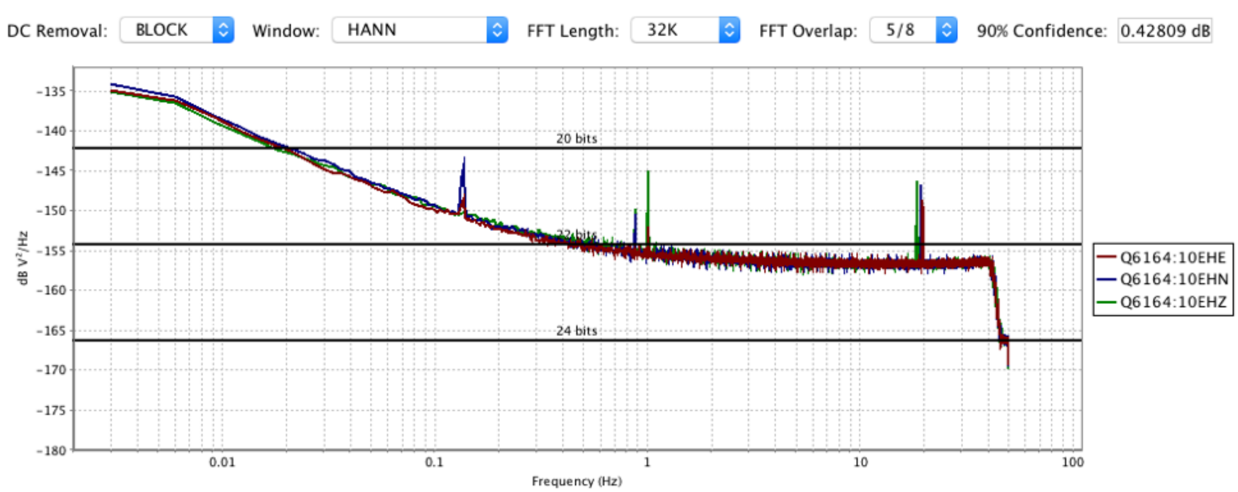

Figure 32 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 100 sps, 23° C

A visual inter-comparison of the noise spectra of the dataloggers does not show any strong correlation with respect to elevated noise on any specific channel. The lower frequency peaks in the spectra are not consistent across groups of channels, however the peaks near 20 Hz appear in both groups of channels (1-3 and 4-6), though not consistently on 1 and 4, or 2 and 5, or 3 and 6.

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

Table 24 Self Noise RMS over 0.02 Hz – 1 Hz at 23° C, both Q330HRs

DWR	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	22.24 nV rms	23.48 nV rms	23.14 nV rms	23.15 nV rms	23.92 nV rms	22.65 nV rms
	0.75 cts rms	0.79 cts rms	0.78 cts rms	0.19 cts rms	0.20 cts rms	0.19 cts rms
6164	23.28 nV rms	23.36 nV rms	22.74 nV rms	23.02 nV rms	24.19 nV rms	24.14 nV rms
	0.78 cts rms	2.00 cts rms	1.89 cts rms	0.19 cts rms	0.20 cts rms	0.20 cts rms

Table 25 Self Noise RMS over 0.5 Hz – 16 Hz at 23° C, both Q330HRs

DWR	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	55.24 nV rms	55.02 nV rms	55.56 nV rms	58.34 nV rms	58.56 nV rms	58.52 nV rms
	1.86 cts rms	1.85 cts rms	1.87 cts rms	0.49 cts rms	0.49 cts rms	0.49 cts rms
6164	56.21 nV rms	56.19 nV rms	55.91 nV rms	59.04 nV rms	58.63 nV rms	58.93 nV rms
	0.77 cts rms	1.99 cts rms	1.88 cts rms	0.50 cts rms	0.49 cts rms	0.50 cts rms

Table 26 Self Noise RMS over 0.02 Hz – 16 Hz at 23° C, both Q330HRs

DWR	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	58.33 nV rms	58.61 nV rms	58.87 nV rms	61.44 nV rms	61.91 nV rms	61.47 nV rms
	1.96 cts rms	1.97 cts rms	1.98 cts rms	0.52 cts rms	0.52 cts rms	0.52 cts rms
6164	59.59 nV rms	59.60 nV rms	59.15 nV rms	62.13 nV rms	62.14 nV rms	62.29 nV rms
	0.79 cts rms	2.00 cts rms	1.89 cts rms	0.52 cts rms	0.52 cts rms	0.52 cts rms

A review of the RMS noise values measured at 23° C shows little correlation of self noise (high or low) consistent across dataloggers. In all instances observed noise was below 62.29 nV rms. Across the low passband noise values varied from 22.24 nV rms to 24.19 nV rms; across the high passband from 55.02 nV rms to 59.04 nV rms; and across the broad passband 58.33 nV rms to 62.29 nV rms.

Self noise spectra plots and tables, containing the computed RMS noise levels in both volts and counts, follow for each of the evaluated temperatures. Passbands consistent with the requirements for seismic applications were selected.

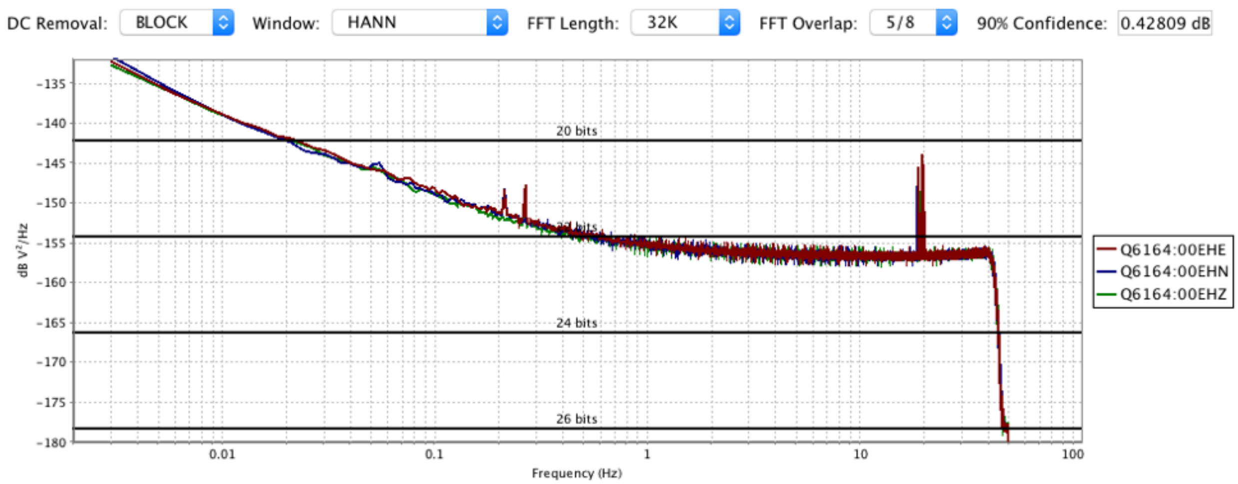

Figure 33 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 46° C

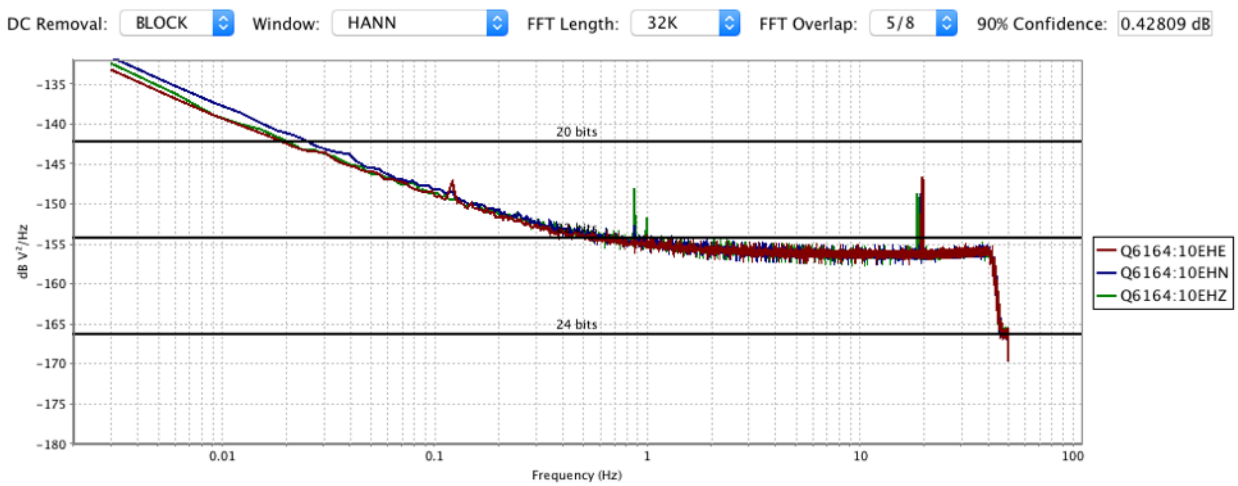

Figure 34 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 46° C

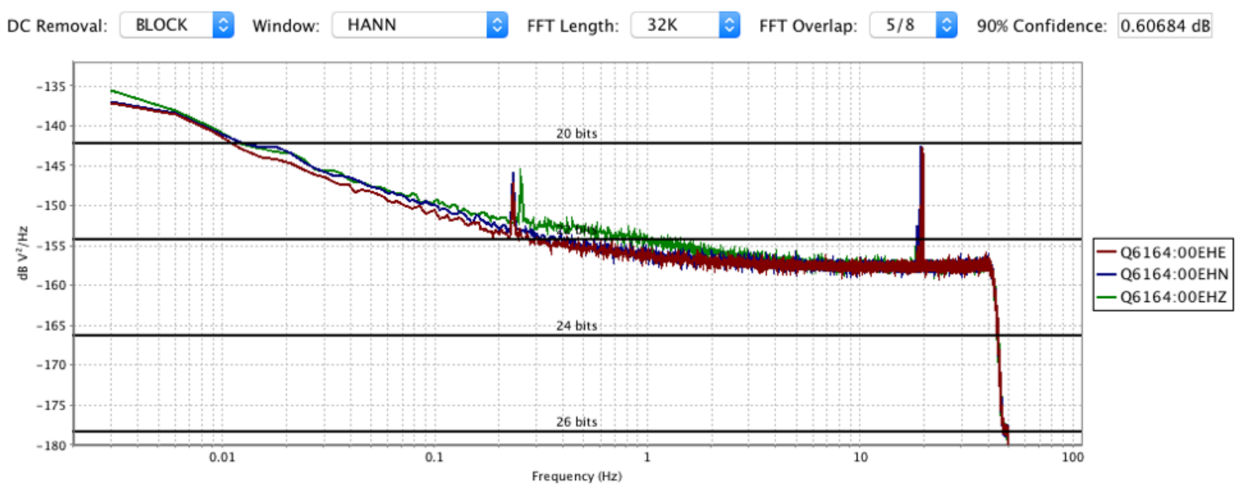

Figure 35 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, -10° C

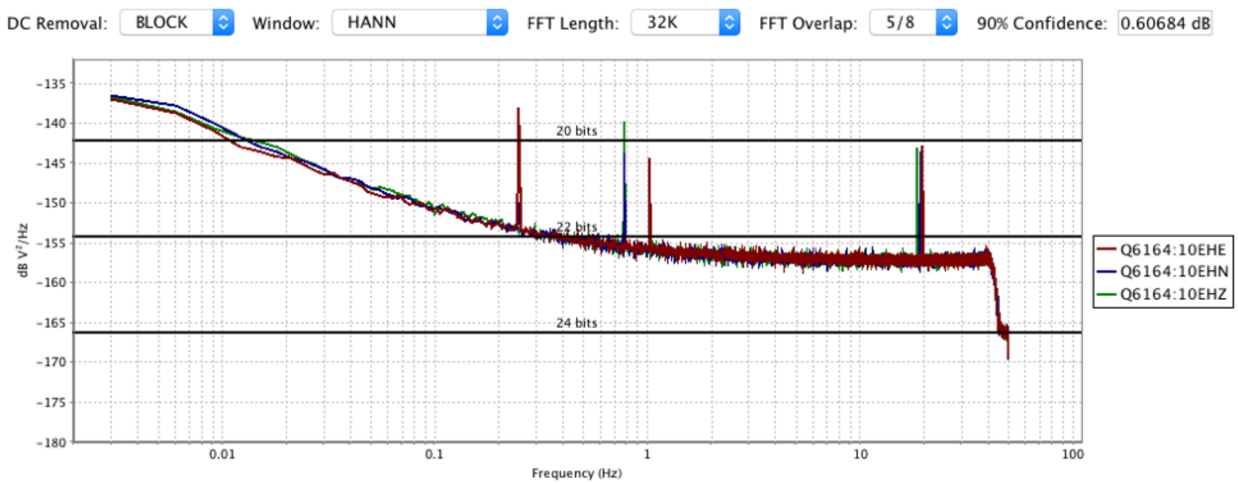

Figure 36 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, -10° C

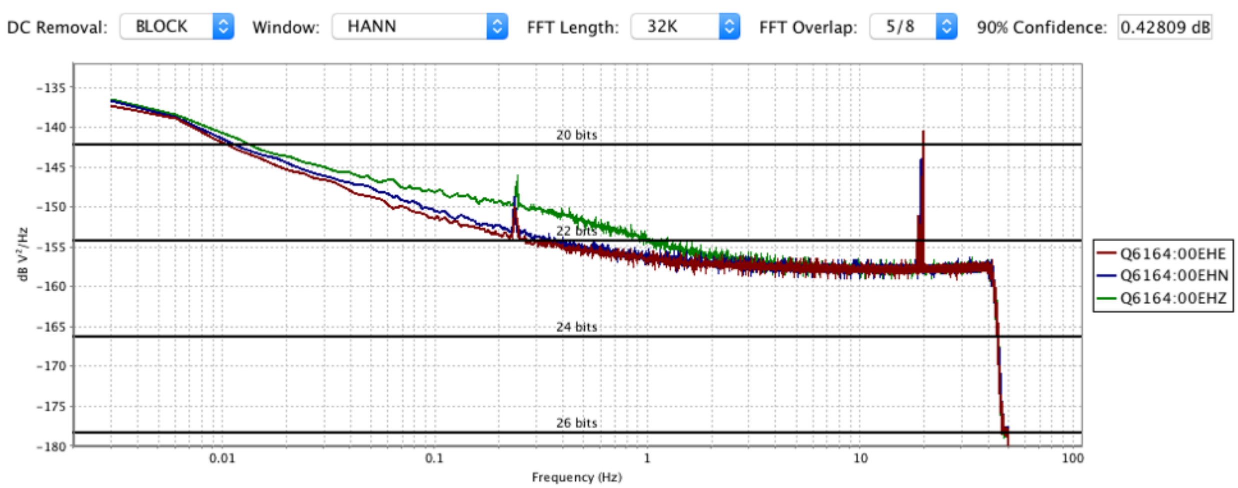

Figure 37 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, -20° C

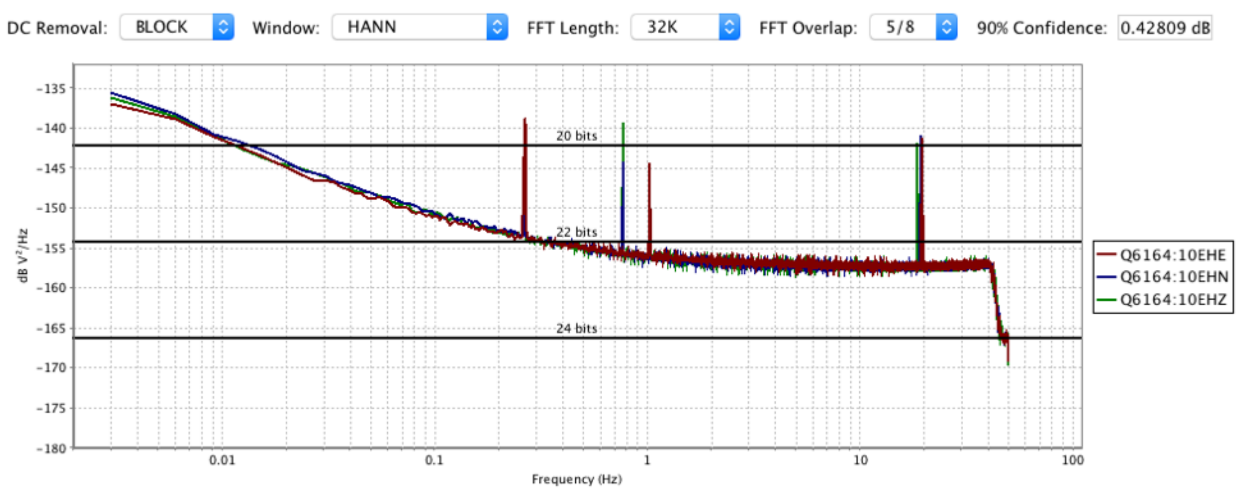

Figure 38 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, -20° C

Table 27 Self Noise RMS, Q330HR 6164, 0.02 Hz–1.0 Hz, at Select Temperatures

Temperature	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
46° C	25.53 nV rms	24.96 nV rms	24.40 nV rms	24.81 nV rms	26.31 nV rms	25.56 nV rms
	0.86 cts rms	0.84 cts rms	0.82 cts rms	0.21 cts rms	0.22 cts rms	0.22 cts rms
20° C	22.46 nV rms	23.01 nV rms	22.67 nV rms	23.72 nV rms	23.72 nV rms	24.86 nV rms
	0.76 cts rms	0.77 cts rms	0.76 cts rms	0.20 cts rms	0.20 cts rms	0.21 cts rms
-10° C	20.28 nV rms	21.93 nV rms	24.97 nV rms	22.68 nV rms	21.85 nV rms	22.79 nV rms
	0.68 cts rms	0.74 cts rms	0.84 cts rms	0.19 cts rms	0.18 cts rms	0.19 cts rms
-20° C	19.81 nV rms	21.28 nV rms	28.66 nV rms	22.10 nV rms	21.52 nV rms	21.97 nV rms
	0.67 cts rms	0.72 cts rms	0.96 cts rms	0.19 cts rms	0.18 cts rms	0.19 cts rms

Table 28 Self Noise RMS, Q330HR 6164, 0.5 Hz – 16 Hz, at Select Temperatures

Temperature	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
46° C	59.21 nV rms	58.90 nV rms	58.46 nV rms	61.35 nV rms	61.41 nV rms	61.39 nV rms
	1.99 cts rms	1.98 cts rms	1.97 cts rms	0.52 cts rms	0.52 cts rms	0.52 cts rms
20° C	58.07 nV rms	58.46 nV rms	58.29 nV rms	58.40 nV rms	58.40 nV rms	58.92 nV rms
	1.95 cts rms	1.97 cts rms	1.96 cts rms	0.49 cts rms	0.49 cts rms	0.50 cts rms
-10° C	52.46 nV rms	52.97 nV rms	55.50 nV rms	56.10 nV rms	55.62 nV rms	55.74 nV rms
	1.77 cts rms	1.78 cts rms	1.87 cts rms	0.47 cts rms	0.47 cts rms	0.47 cts rms
-20° C	51.56 nV rms	52.00 nV rms	54.63 nV rms	55.26 nV rms	54.60 nV rms	54.58 nV rms
	1.73 cts rms	1.75 cts rms	1.84 cts rms	0.47 cts rms	0.46 cts rms	0.46 cts rms

Table 29 Self Noise RMS, Q330HR 6164, 0.02 Hz – 16 Hz, at Select Temperatures

Temperature	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
46° C	63.15 nV rms	62.64 nV rms	62.08 nV rms	64.86 nV rms	65.43 nV rms	65.05 nV rms
	2.12 cts rms	2.11 cts rms	2.09 cts rms	0.55 cts rms	0.55 cts rms	0.55 cts rms
20° C	58.79 nV rms	59.18 nV rms	59.08 nV rms	61.62 nV rms	61.62 nV rms	62.14 nV rms
	1.98 cts rms	1.99 cts rms	1.99 cts rms	0.52 cts rms	0.52 cts rms	0.52 cts rms
-10° C	55.10 nV rms	56.11 nV rms	59.09 nV rms	59.32 nV rms	58.37 nV rms	58.55 nV rms
	1.85 cts rms	1.89 cts rms	1.99 cts rms	0.50 cts rms	0.49 cts rms	0.49 cts rms
-20° C	54.10 nV rms	54.99 nV rms	59.62 nV rms	58.34 nV rms	57.36 nV rms	57.24 nV rms
	1.82 cts rms	1.85 cts rms	2.01 cts rms	0.49 cts rms	0.48 cts rms	0.48 cts rms

Noise levels generally appear to be a minimum at -20° C; at the lower temperature ranges, especially at -20° C, there is a broader spread of computed noise levels. The computed self noise in the low passband for channel 1 (00EHZ) is 23% greater than channel 3 (00 EHE) at -10° C and 45% greater at -20° C. Note in Figure 46 and Figure 48 channel 1 (00 EHZ) has an increase in self noise relative to the other channels.

Next are the power spectra of the data collected at varying sample rates, from high to low sample, for SN 6164.

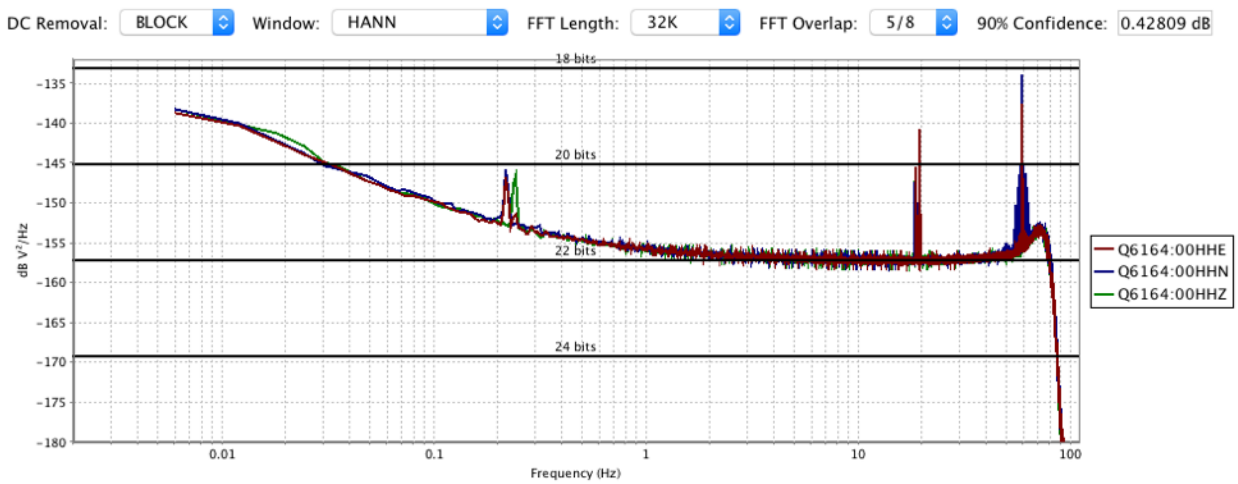

Figure 39 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 200 sps, 20° C

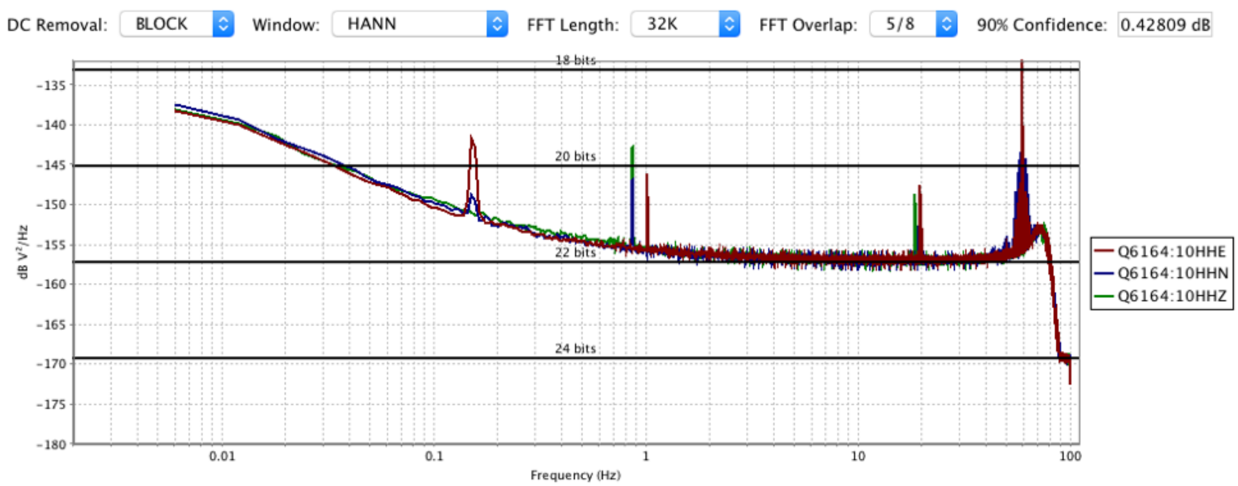

Figure 40 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 200 sps, 20° C

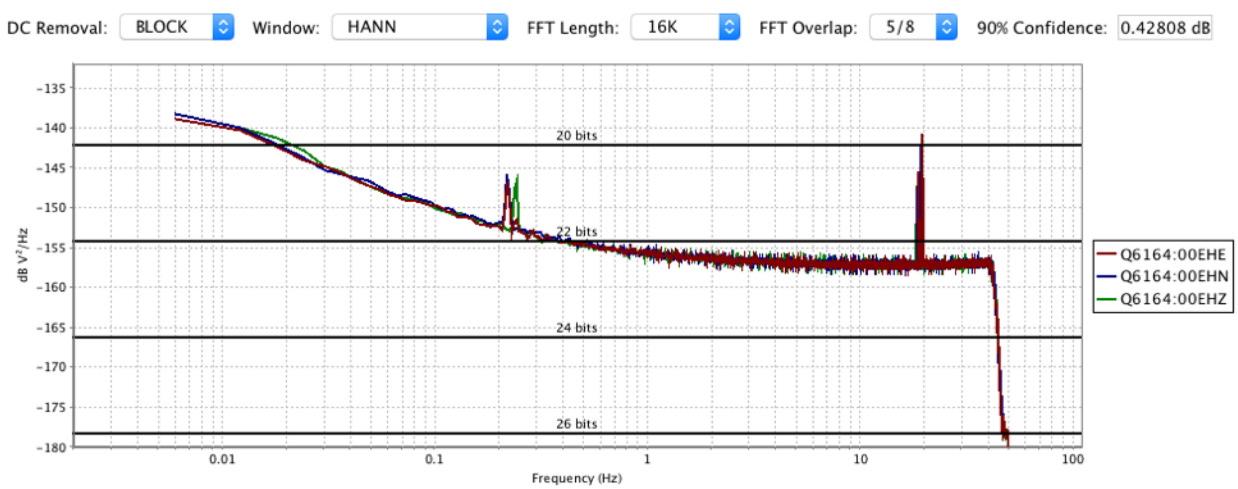

Figure 41 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 100 sps, 20° C

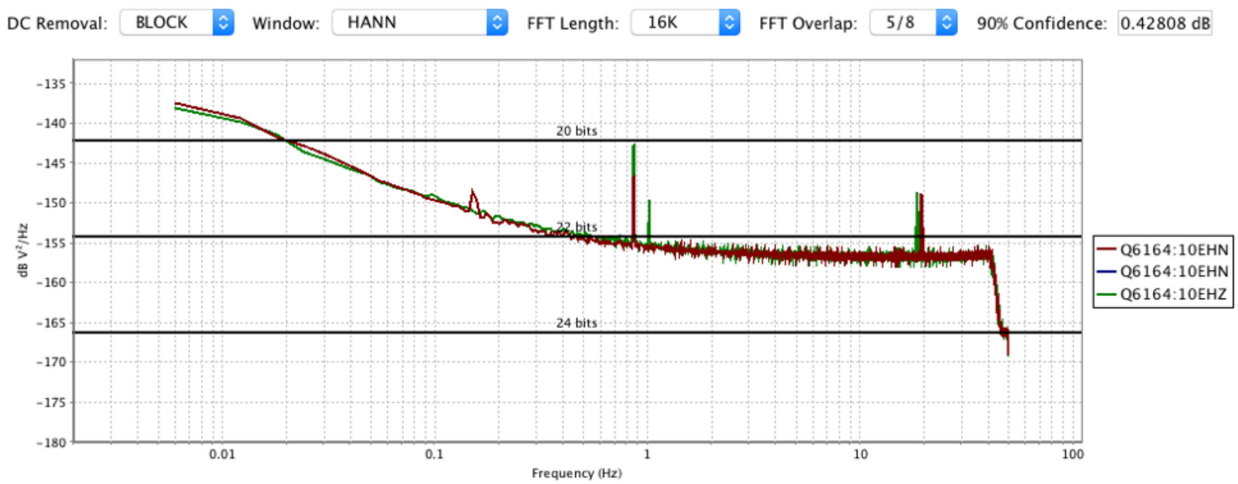

Figure 42 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 100 sps, 20° C

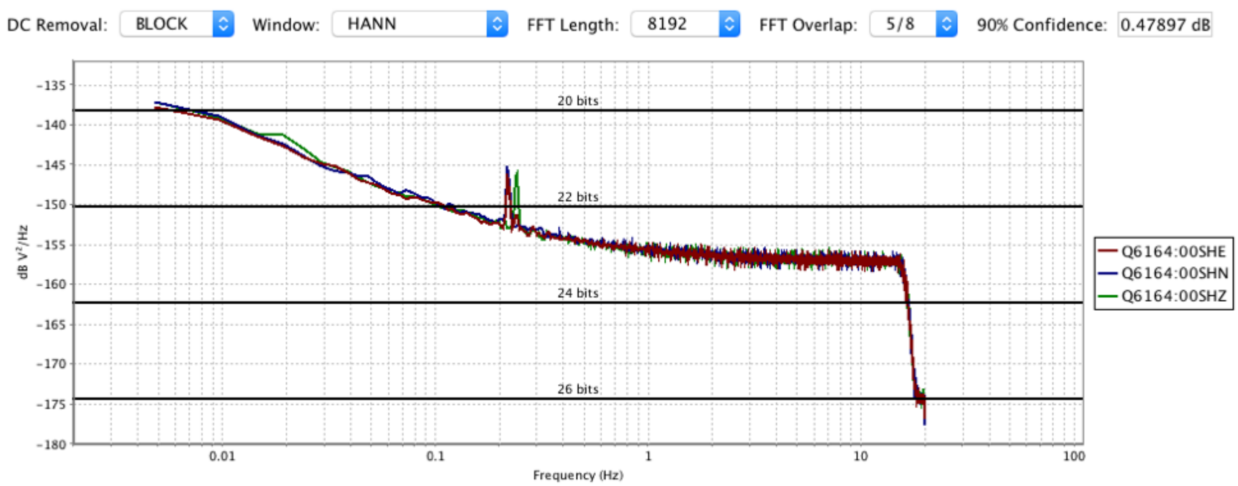

Figure 43 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 40 sps, 20° C

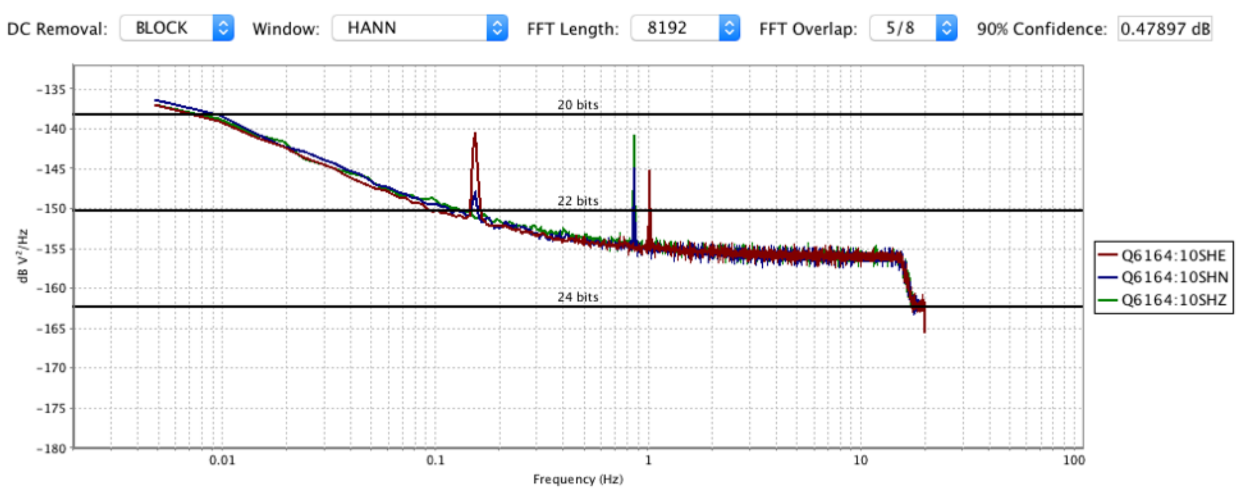

Figure 44 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 40 sps, 20° C

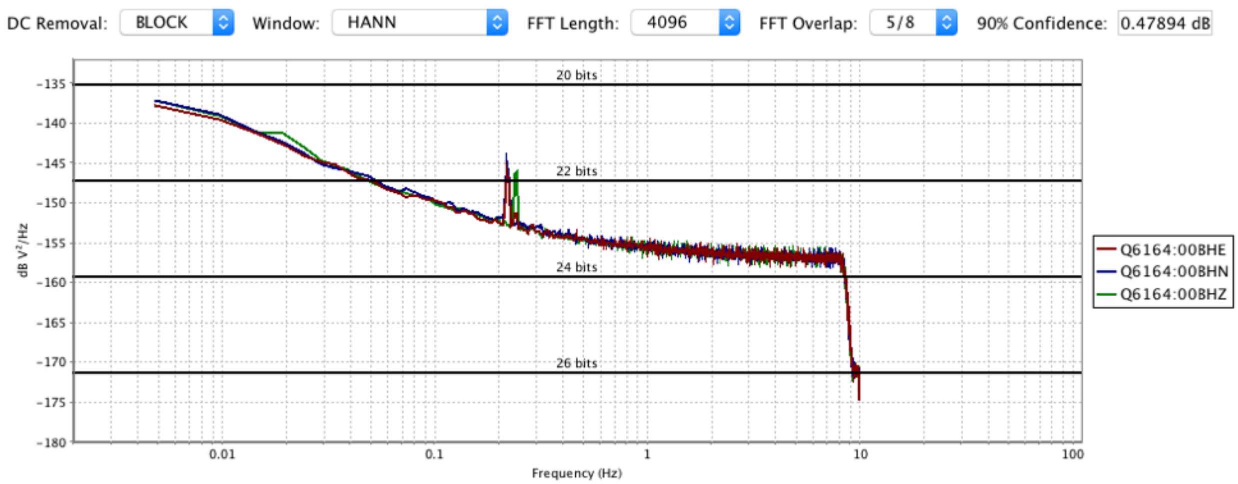

Figure 45 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 20 sps, 20° C

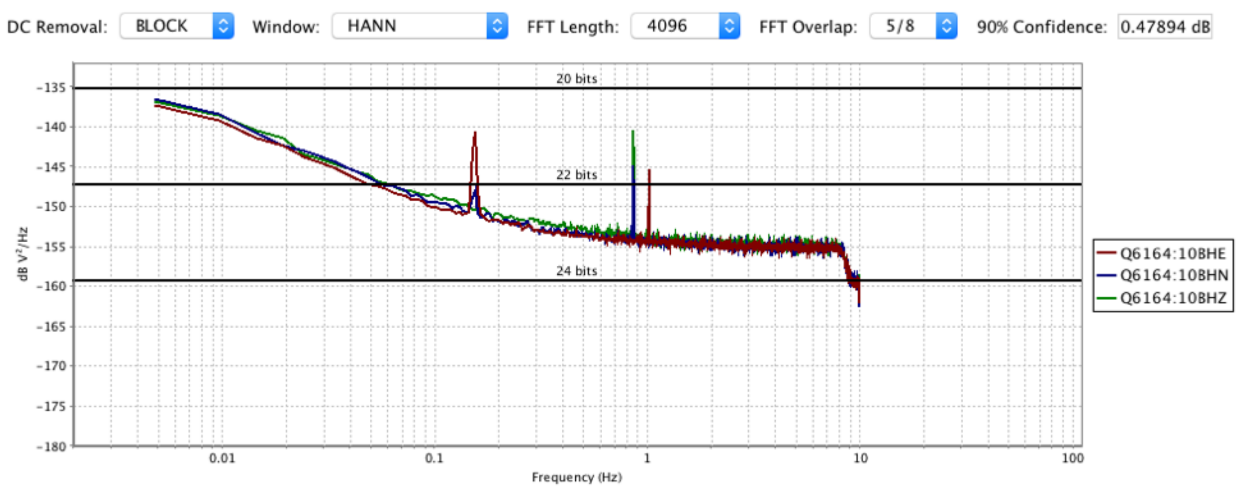

Figure 46 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 20 sps, 20° C

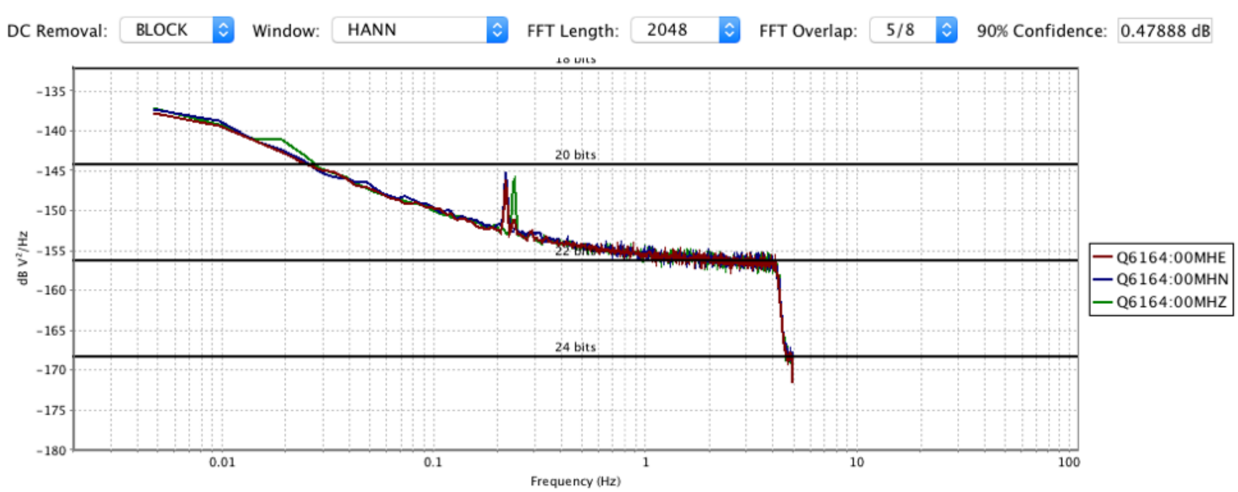

Figure 47 Self Noise Power Spectra Q330HR 6164, Channels 1 - 3, 10 sps, 20° C

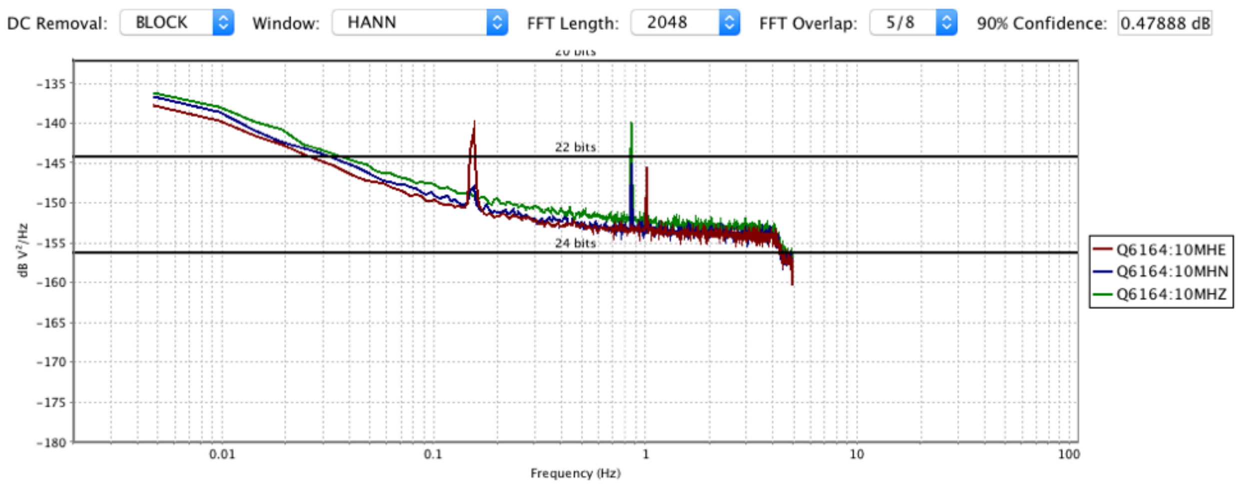

Figure 48 Self Noise Power Spectra Q330HR 6164, Channels 4 - 6, 10 sps, 20° C

Notice the spike in the at 60 Hz in Figure 39. Possible 60 Hz noise sources are numerous, including the 220 V AC powered environmental chamber in which all 20° C tests occurred. As was observed with the spectra computed for the 23° C test the lower frequency peaks in the spectra are not consistent across groups of channels, however the peaks near 20 Hz appear both groups of channels (1-3 and 4-6), though not consistently on 1 and 4 or 2 and 5 or 3 and 6.

Table 30 Self Noise RMS, Q330HR 6164, 0.02 Hz – 1 Hz, at Select Sample Rates

Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
10 sps	22.75 nV rms	23.30 nV rms	22.90 nV rms	26.35 nV rms	26.99 nV rms	31.27 nV rms
	0.77 cts rms	0.78 cts rms	0.77 cts rms	0.22 cts rms	0.23 cts rms	0.26 cts rms
20 sps	22.54 nV rms	23.09 nV rms	22.72 nV rms	25.11 nV rms	25.28 nV rms	27.36 nV rms
	0.76 cts rms	0.78 cts rms	0.76 cts rms	0.21 cts rms	0.21 cts rms	0.23 cts rms
40 sps	22.46 nV rms	23.01 nV rms	22.61 nV rms	24.39 nV rms	24.37 nV rms	25.56 nV rms
	0.76 cts rms	0.77 cts rms	0.76 cts rms	0.21 cts rms	0.21 cts rms	0.22 cts rms
100 sps	22.46 nV rms	23.01 nV rms	22.67 nV rms	23.72 nV rms	23.72 nV rms	24.86 nV rms
	0.76 cts rms	0.77 cts rms	0.76 cts rms	0.20 cts rms	0.20 cts rms	0.21 cts rms
200 sps	22.43 nV rms	23.00 nV rms	22.63 nV rms	23.65 nV rms	23.43 nV rms	24.68 nV rms
	0.75 cts rms	0.77 cts rms	0.76 cts rms	0.20 cts rms	0.20 cts rms	0.21 cts rms

Table 31 Self Noise RMS, Q330HR 6164, 0.5 Hz – 16 Hz, at Select Sample Rates

Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
10 sps	34.97 nV rms	35.43 nV rms	35.02 nV rms	40.98 nV rms	41.69 nV rms	46.79 nV rms
	1.18 cts rms	1.19 cts rms	1.18 cts rms	0.35 cts rms	0.35 cts rms	0.39 cts rms
20 sps	42.17 nV rms	42.41 nV rms	42.37 nV rms	52.22 nV rms	52.33 nV rms	54.74 nV rms
	1.42 cts rms	1.43 cts rms	1.43 cts rms	0.44 cts rms	0.44 cts rms	0.46 cts rms
40 sps	58.37 nV rms	58.74 nV rms	58.58 nV rms	63.17 nV rms	62.77 nV rms	63.54 nV rms
	1.96 cts rms	1.98 cts rms	1.97 cts rms	0.53 cts rms	0.53 cts rms	0.54 cts rms
100 sps	58.07 nV rms	58.46 nV rms	58.29 nV rms	58.40 nV rms	58.40 nV rms	58.92 nV rms
	1.95 cts rms	1.97 cts rms	1.96 cts rms	0.49 cts rms	0.49 cts rms	0.50 cts rms
200 sps	57.92 nV rms	58.32 nV rms	58.13 nV rms	60.13 nV rms	59.08 nV rms	59.91 nV rms
	1.95 cts rms	1.96 cts rms	1.96 cts rms	0.51 cts rms	0.50 cts rms	0.50 cts rms

Table 32 Self Noise RMS, Q330HR 6164, 0.02 Hz – 16 Hz, at Select Sample Rates

Sample Rate	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
10 sps	36.09 nV rms	36.56 nV rms	36.23 nV rms	46.25 nV rms	46.94 nV rms	52.66 nV rms
	1.21 cts rms	1.23 cts rms	1.22 cts rms	0.39 cts rms	0.40 cts rms	0.44 cts rms
20 sps	46.22 nV rms	46.68 nV rms	46.51 nV rms	56.24 nV rms	56.21 nV rms	58.77 nV rms
	1.55 cts rms	1.57 cts rms	1.56 cts rms	0.47 cts rms	0.47 cts rms	0.50 cts rms
40 sps	59.04 nV rms	59.43 nV rms	59.31 nV rms	66.43 nV rms	65.88 nV rms	66.65 nV rms
	1.99 cts rms	2.00 cts rms	2.00 cts rms	0.56 cts rms	0.55 cts rms	0.58 cts rms
100 sps	58.79 nV rms	59.18 nV rms	59.08 nV rms	61.62 nV rms	61.62 nV rms	62.14 nV rms
	1.98 cts rms	1.99 cts rms	1.99 cts rms	0.52 cts rms	0.52 cts rms	0.52 cts rms
200 sps	58.64 nV rms	59.05 nV rms	58.91 nV rms	60.87 nV rms	59.95 nV rms	60.68 nV rms
	1.97 cts rms	1.99 cts rms	1.98 cts rms	0.51 cts rms	0.50 cts rms	0.51 cts rms

While computed noise varied across the sample rates within the individual passbands, rms noise values did not exceed the equivalent of 2 count rms, on the 26 bit channels, and 1 count rms, on the 24 bit channels. RMS noise values varied no more than 5.33% across channels for any given sample rate.

Over all temperatures and sample rates over which the Q330HR was evaluated, self noise did not exceed 3 counts and 1 counts, for the 26 bit and 24 bit channels, respectively.

3.8 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.

3.8.1 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).

3.8.2 Configuration

There is no test configuration for the dynamic range test.

The full scale value used for the largest signal comes from the manufacturer's nominal specifications, validated in section 3.6

AC Full Scale. The value for the smallest signal comes from the evaluated digitizer channel self noise determined in section 3.7 Self-Noise.

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

3.8.4 Result

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

Table 33 Dynamic Range, 20x Gain, at 23°C, Both Q330HRs

DWR	Passband	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
6162	20 mHz - 1 Hz	150.05 dB	149.58 dB	149.70 dB	149.70 dB	149.42 dB	149.89 dB
	20 mHz - 16 Hz	141.67 dB	141.63 dB	141.59 dB	141.22 dB	141.15 dB	141.22 dB
	0.5 Hz - 16 Hz	142.14 dB	142.18 dB	142.10 dB	141.67 dB	141.64 dB	141.64 dB
6164	20 mHz - 1 Hz	149.65 dB	149.62 dB	149.85 dB	149.75 dB	149.32 dB	149.33 dB
	20 mHz - 16 Hz	141.49 dB	141.48 dB	141.55 dB	141.12 dB	141.12 dB	141.10 dB
	0.5 Hz - 16 Hz	141.99 dB	142.00 dB	142.04 dB	141.57 dB	141.63 dB	141.58 dB

The observed dynamic range values across all dataloggers, recording at a gain of 20x while exposed to 23° C, averaged across common resolution channels for the 26 bit channels were: 149.74 dB, 142.08 dB and 141.57 dB for the low, high and broad passbands respectively; for the 24 bit channel averages were 149.57 dB, 141.62 dB and 141.16 dB for the low, high and broad passbands respectively.

Table 34 Dynamic Range Q330HR 6164, at Select Temperatures

Temp	Passband	00HHE Channel 3	00HHN Channel 2	00HHZ Channel 1	10HHE Channel 6	10HHN Channel 5	10HHZ Channel 4
46°C	20 mHz - 1 Hz	148.85 dB	149.05 dB	149.24 dB	149.10 dB	148.59 dB	148.84 dB
	20 mHz - 16 Hz	140.98 dB	141.05 dB	141.13 dB	140.75 dB	140.67 dB	140.73 dB
	0.5 Hz - 16 Hz	141.54 dB	141.59 dB	141.65 dB	141.23 dB	141.23 dB	141.23 dB
20°C	20 mHz - 1 Hz	149.96 dB	149.75 dB	149.88 dB	149.49 dB	149.49 dB	149.08 dB
	20 mHz - 16 Hz	141.60 dB	141.55 dB	141.56 dB	141.19 dB	141.19 dB	141.12 dB
	0.5 Hz - 16 Hz	141.71 dB	141.65 dB	141.68 dB	141.66 dB	141.66 dB	141.59 dB
-10°C	20 mHz - 1 Hz	150.85 dB	150.17 dB	149.04 dB	149.88 dB	150.20 dB	149.83 dB
	20 mHz - 16 Hz	142.17 dB	142.01 dB	141.56 dB	141.53 dB	141.67 dB	141.64 dB
	0.5 Hz - 16 Hz	142.59 dB	142.51 dB	142.10 dB	142.01 dB	142.08 dB	142.07 dB
-20°C	20 mHz - 1 Hz	151.05 dB	150.43 dB	147.84 dB	150.10 dB	150.33 dB	150.15 dB
	20 mHz - 16 Hz	142.33 dB	142.18 dB	141.48 dB	141.67 dB	141.82 dB	141.84 dB
	0.5 Hz - 16 Hz	142.74 dB	142.67 dB	142.24 dB	142.14 dB	142.25 dB	142.25 dB

Performance generally improves slightly as temperatures decrease, except for dynamic ranges observed on channel 1 (00 HHZ), where dynamic ranges computed over the low and broad pass bands decreased slightly below 20° C with a temperature drop.

In the low passband, over all temperatures, while recording at a gain of 20x, each channel remained between 1.46% of the respective channel’s maximum dynamic range in the passband. Similarly, in the high passband, at all temperatures, each channel remained between 0.84% of the respective channel’s maximum dynamic range in the passband; and finally in the broad passband, each channel remained within 0.94% of the respective channel’s maximum dynamic range in the passband.

Table 35 Dynamic Range Q330HR 6164, at Select Sample Rates

Rate	Passband	00HHE (Channel 3)	00HHN (Channel 2)	00HHZ (Channel 1)	10HHE (Channel 6)	10HHN (Channel 5)	10HHZ (Channel 4)
10 sps	20 mHz - 1 Hz	149.85 dB	149.64 dB	149.79 dB	148.57 dB	148.36 dB	147.09 dB
	20 mHz - 16 Hz	145.84 dB	145.73 dB	145.81 dB	143.69 dB	143.56 dB	142.56 dB
	0.5 Hz - 16 Hz	146.12 dB	146.00 dB	146.10 dB	144.74 dB	144.59 dB	143.59 dB
20 sps	20 mHz - 1 Hz	149.93 dB	149.72 dB	149.86 dB	148.99 dB	148.93 dB	148.25 dB
	20 mHz - 16 Hz	143.69 dB	143.61 dB	143.64 dB	141.99 dB	141.99 dB	141.61 dB
	0.5 Hz - 16 Hz	144.49 dB	144.44 dB	144.45 dB	142.63 dB	142.61 dB	142.22 dB
40 sps	20 mHz - 1 Hz	149.96 dB	149.75 dB	149.90 dB	149.24 dB	149.25 dB	148.84 dB
	20 mHz - 16 Hz	141.57 dB	141.51 dB	141.53 dB	140.54 dB	140.61 dB	140.51 dB
	0.5 Hz - 16 Hz	141.67 dB	141.61 dB	141.63 dB	140.98 dB	141.03 dB	140.93 dB
100 sps	20 mHz - 1 Hz	149.96 dB	149.75 dB	149.88 dB	149.49 dB	149.49 dB	149.08 dB
	20 mHz - 16 Hz	141.60 dB	141.55 dB	141.56 dB	141.19 dB	141.19 dB	141.12 dB
	0.5 Hz - 16 Hz	141.71 dB	141.65 dB	141.68 dB	141.66 dB	141.66 dB	141.59 dB
200 sps	20 mHz - 1 Hz	149.97 dB	149.76 dB	149.89 dB	149.51 dB	149.60 dB	149.14 dB
	20 mHz - 16 Hz	141.63 dB	141.57 dB	141.59 dB	141.30 dB	141.43 dB	141.33 dB
	0.5 Hz - 16 Hz	141.73 dB	141.67 dB	141.70 dB	141.41 dB	141.56 dB	141.44 dB

Over the sample rates at which dynamic ranges were evaluated, dynamic ranges remained relatively stable across channels. For the 26 bit channels, dynamic range values were all within 0.21% for the 0.02 – 1 Hz passband, 0.11% in the 0.5 – 16 Hz passband, and 0.08% in the 0.02 – 16 Hz passband. For the 24 bit channels, dynamic ranges values were all within 0.8% for the 0.02 – 1 Hz passband, 1.0% in the 0.5 – 16 Hz passband, and 0.78% in the 0.02 – 16 Hz passband.

Dynamic Ranges over all tested conditions and passbands varied from as low 141 dB to as much as 151 dB.

3.9 System Noise

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

3.9.1 Measurand

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

3.9.2 Configuration

There is no test configuration for the dynamic range test.

The time-series data and PSD are obtained from the evaluated digitizer channel self noise determined in section 3.7 Self-Noise.

3.9.3 Analysis

The time-series data and PSD computed in section 3.7 Self-Noise are corrected for a desired sensor's amplitude response model. The resulting PSD in the sensor's geophysical unit is then compared against an application requirement or background noise model to determine whether the resulting system noise meets the requirement.

3.9.4 Result

The PSD of the system noise is shown in the plots below. Where available, reference sensor and background noise models are provided for comparison.

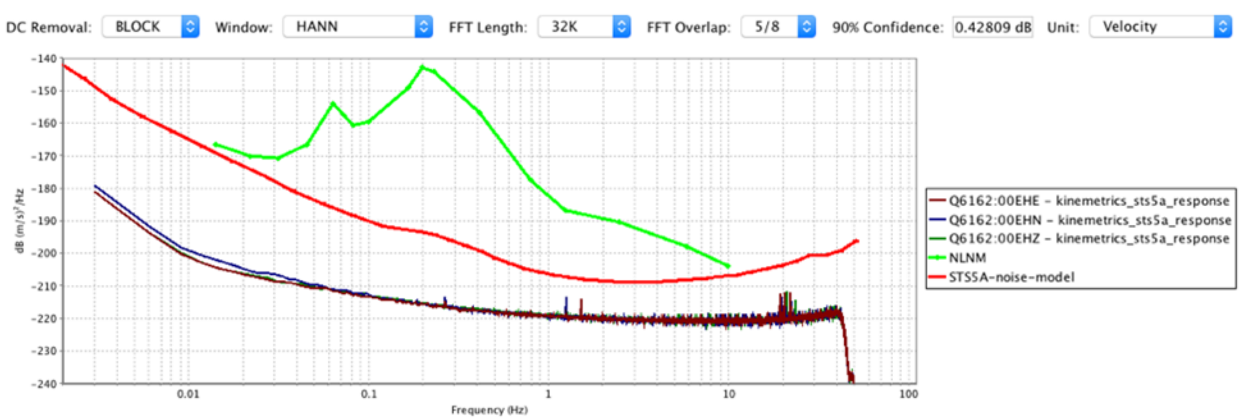

Figure 49 Seismic System Noise Q330HR 6162, Channels 1 - 3, 23° C

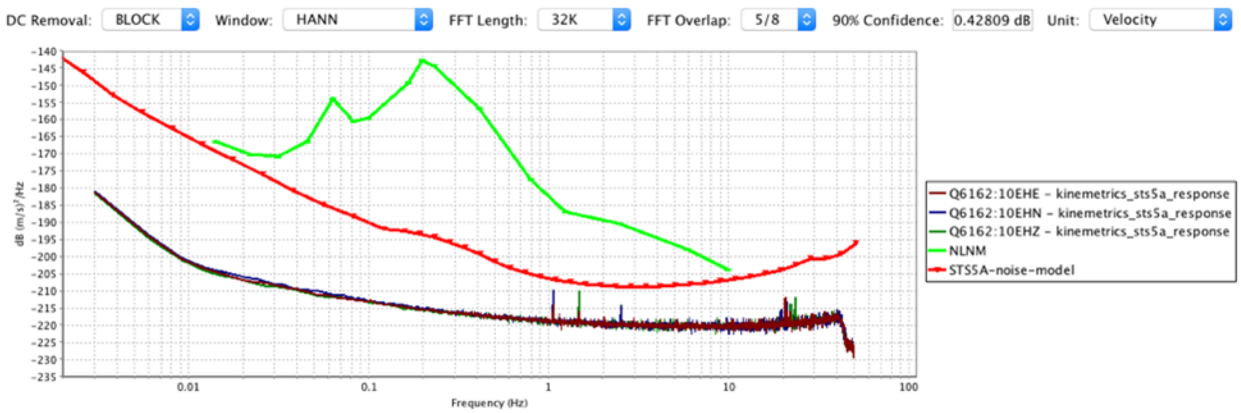

Figure 50 Seismic System Noise Q330HR 6162, Channels 4 - 6, 23° C

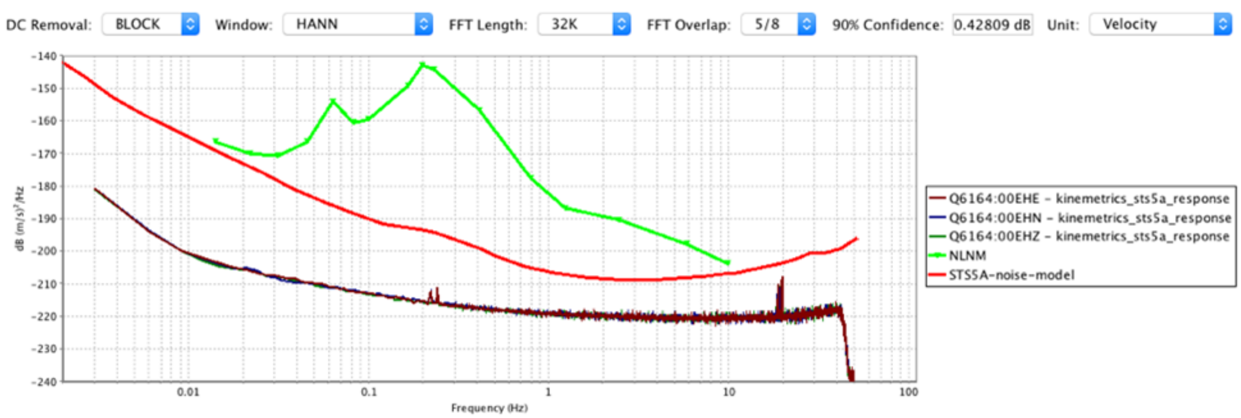

Figure 51 Seismic System Noise Q330HR 6162, Channels 1 - 3, 23° C

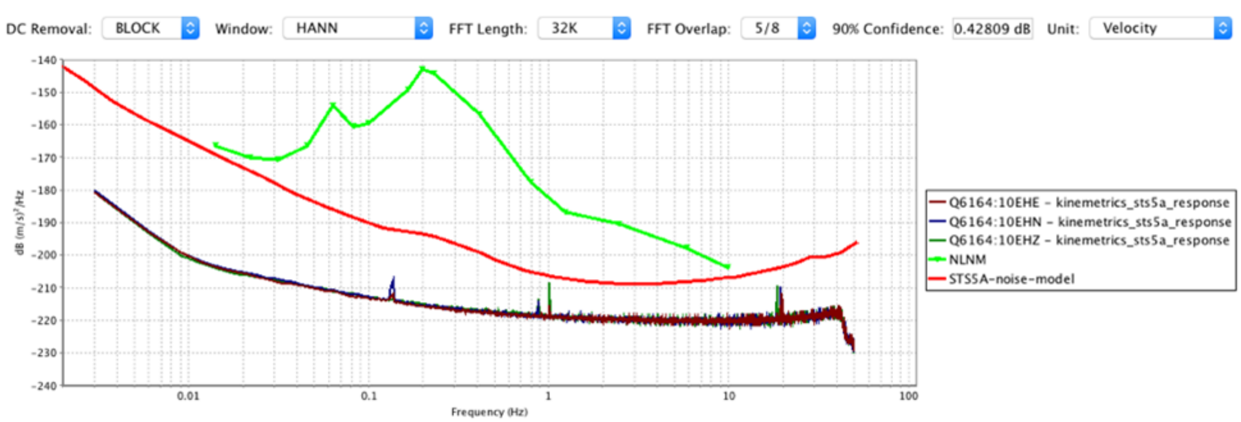

Figure 52 Seismic System Noise Q330HR 6164, Channels 1 - 3, 23° C

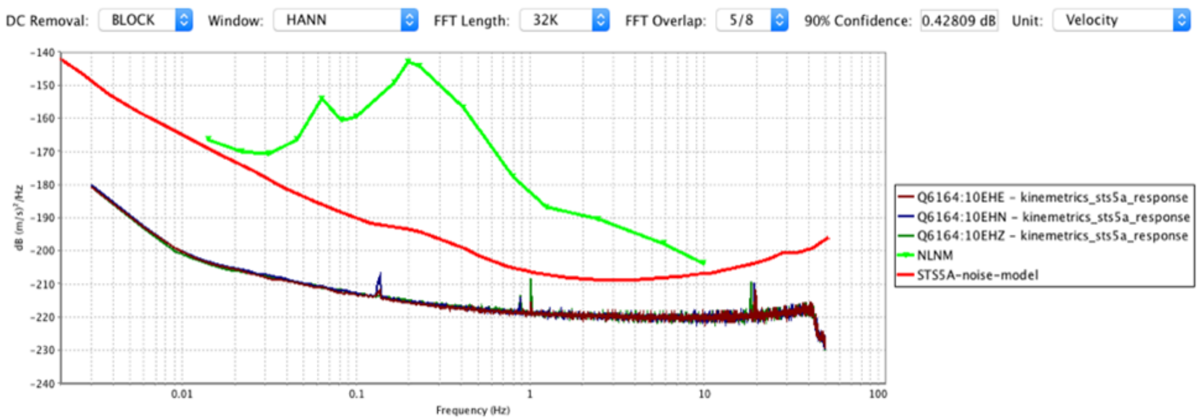

Figure 53 Seismic System Noise Q330HR 6164, Channels 4 - 6, 60° C

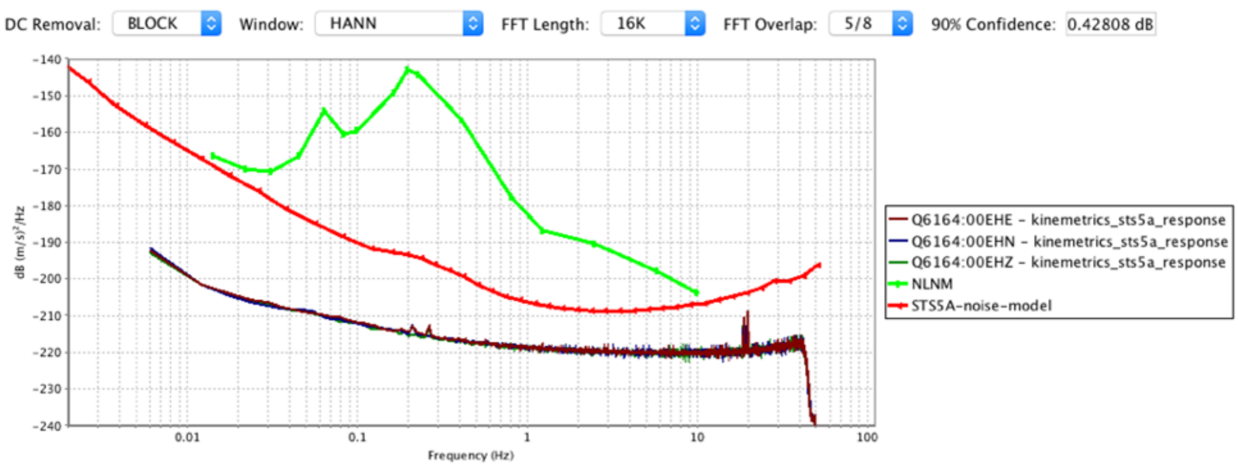

Figure 54 Seismic System Noise Q330HR 6164, Channels 1 - 3, 46° C

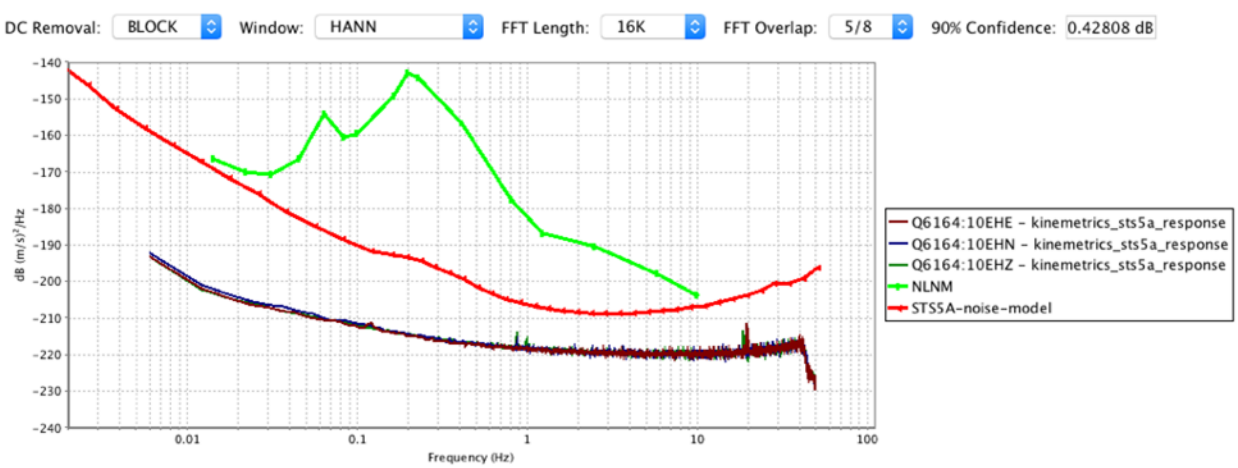

Figure 55 Seismic System Noise Q330HR 6164, Channels 4 - 6, 46° C

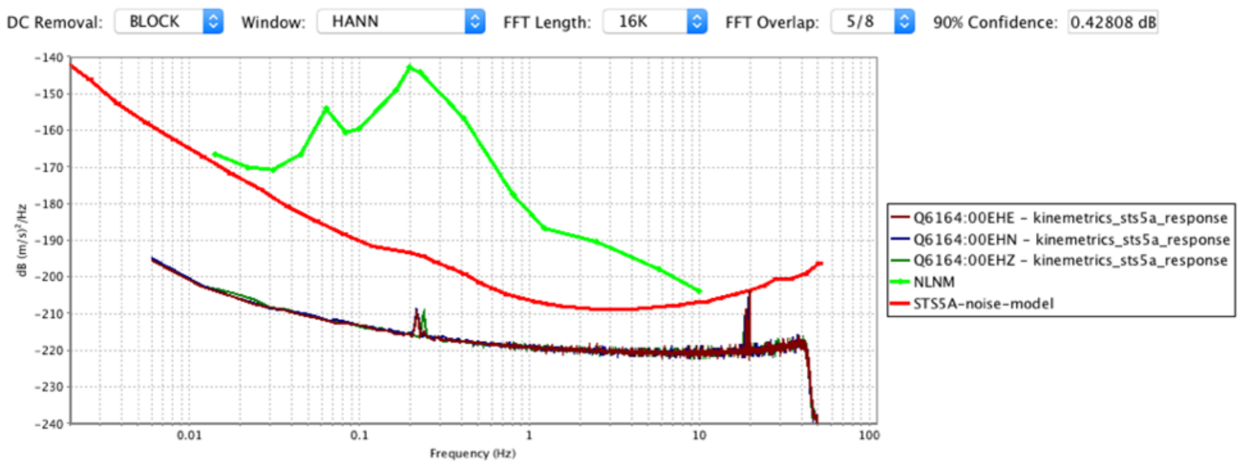

Figure 56 Seismic System Noise Q330HR 6164, Channels 1 - 3, 20° C

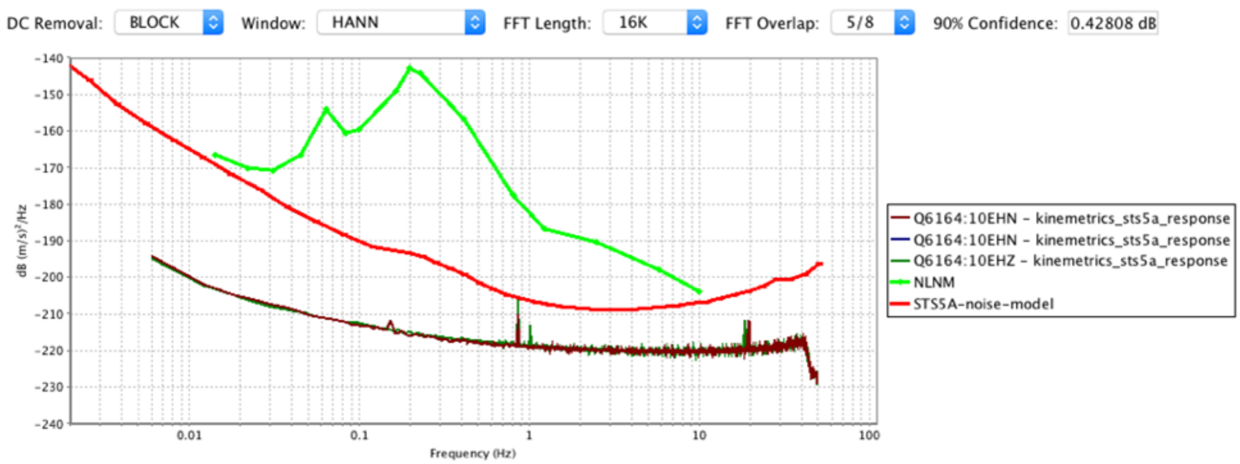

Figure 57 Seismic System Noise Q330HR 6164, Channels 4 - 6, 20° C

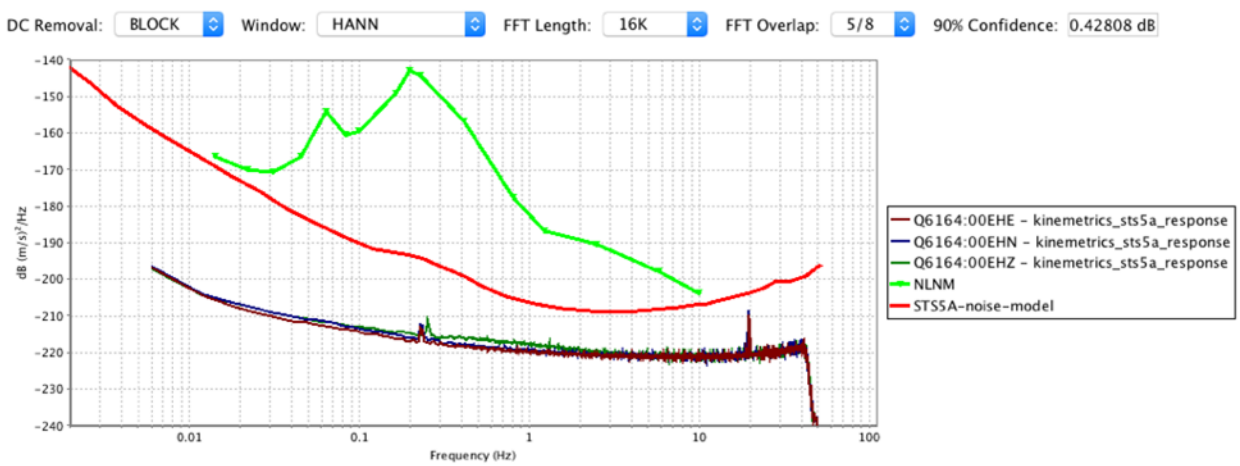

Figure 58 Seismic System Noise Q330HR 6164, Channels 1 - 3, -10° C

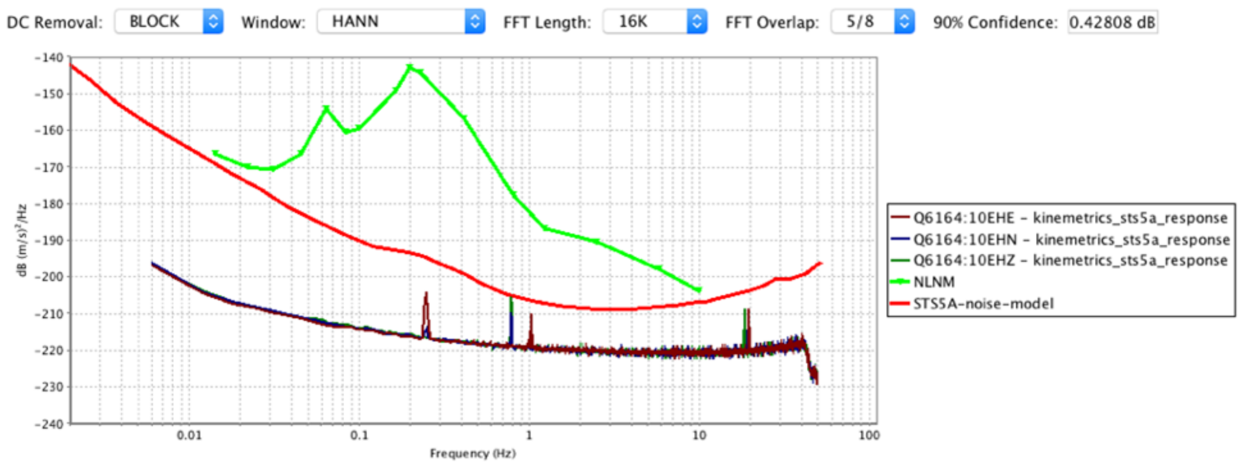

Figure 59 Seismic System Noise Q330HR 6164, Channels 4 - 6, -10° C

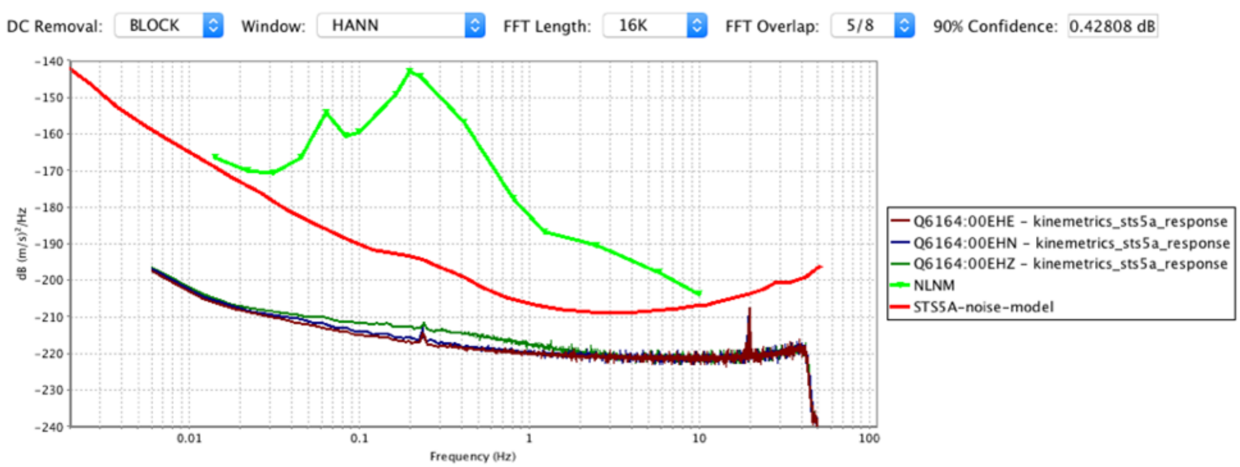

Figure 60 Seismic System Noise Q330HR 6164, Channels 1 - 3, -20° C

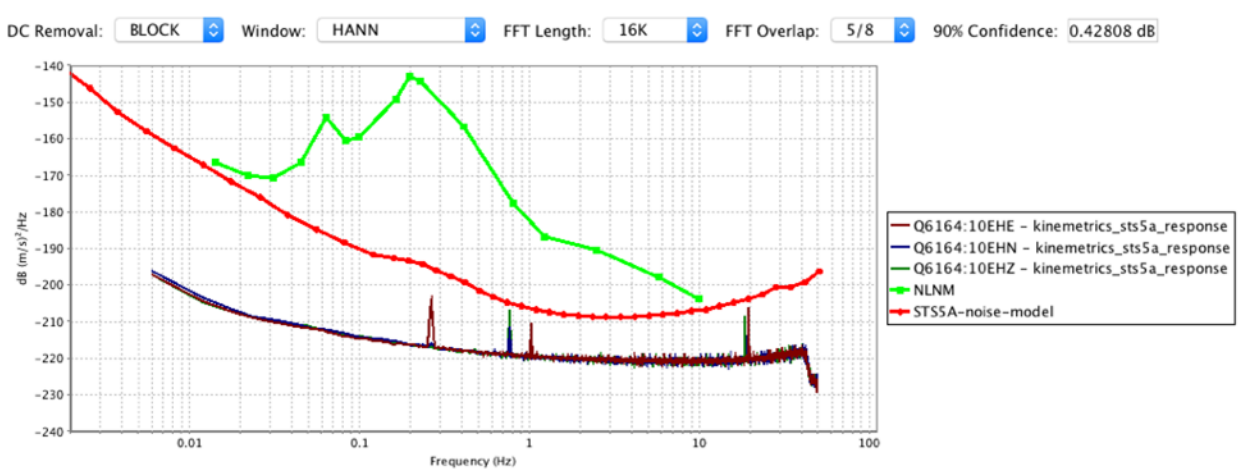

Figure 61 Seismic System Noise Q330HR 6164, Channels 4 - 6, -20° C

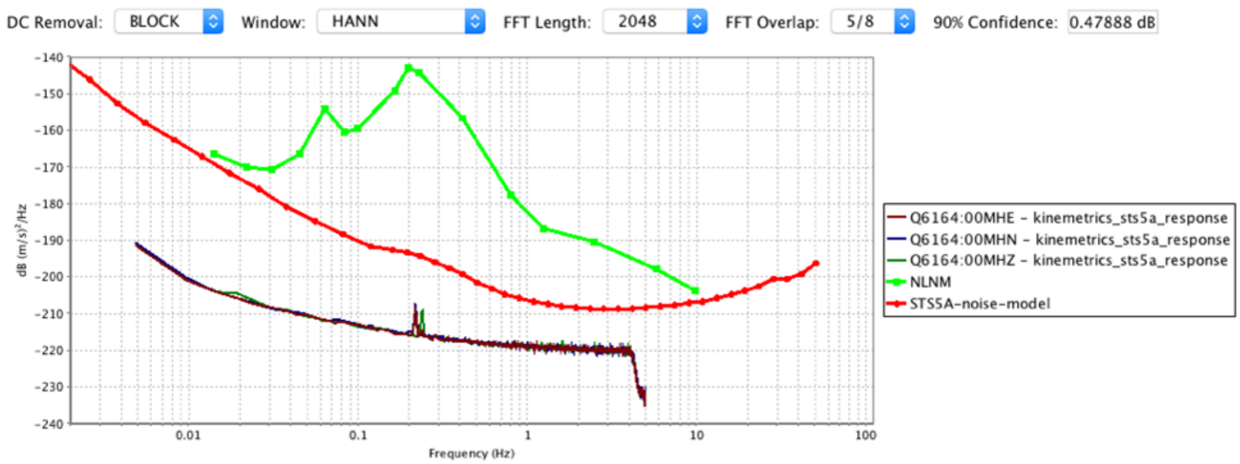

Figure 62 Seismic System Noise Q330HR 6164, Channels 1 - 3, 10 sps

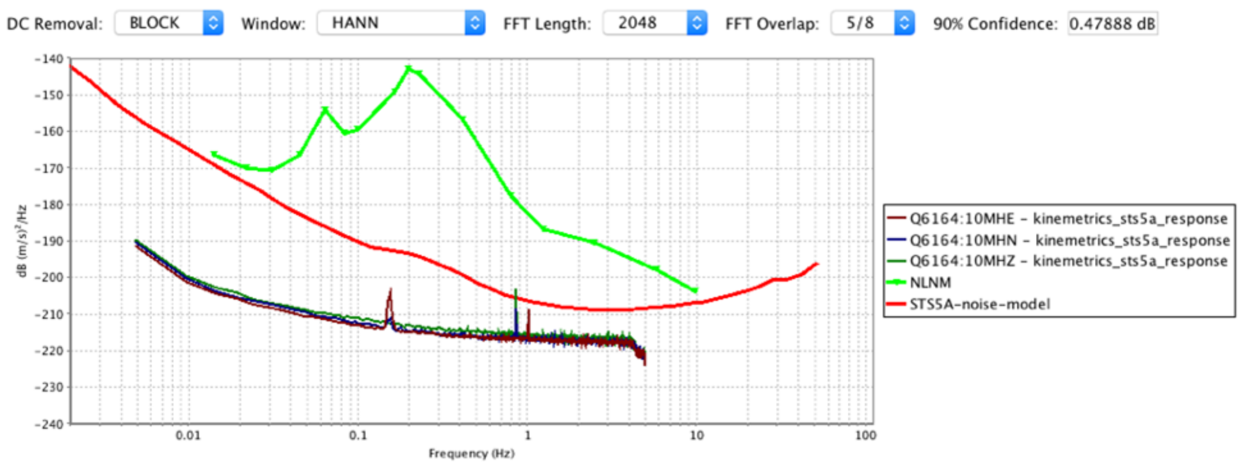

Figure 63 Seismic System Noise Q330HR 6164, Channels 4 - 6, 10 sps

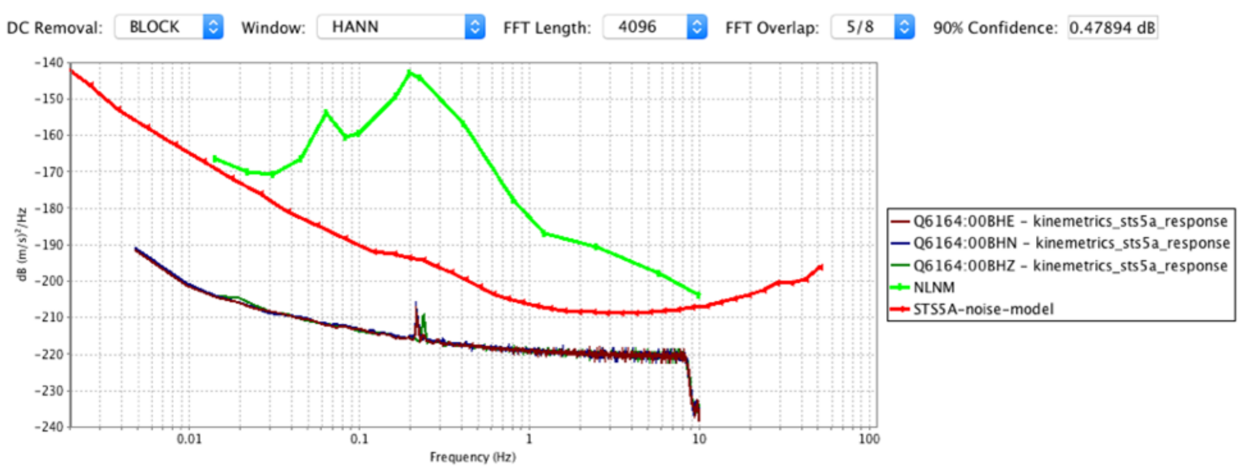

Figure 64 Seismic System Noise Q330HR 6164, Channels 1 - 3, 20 sps

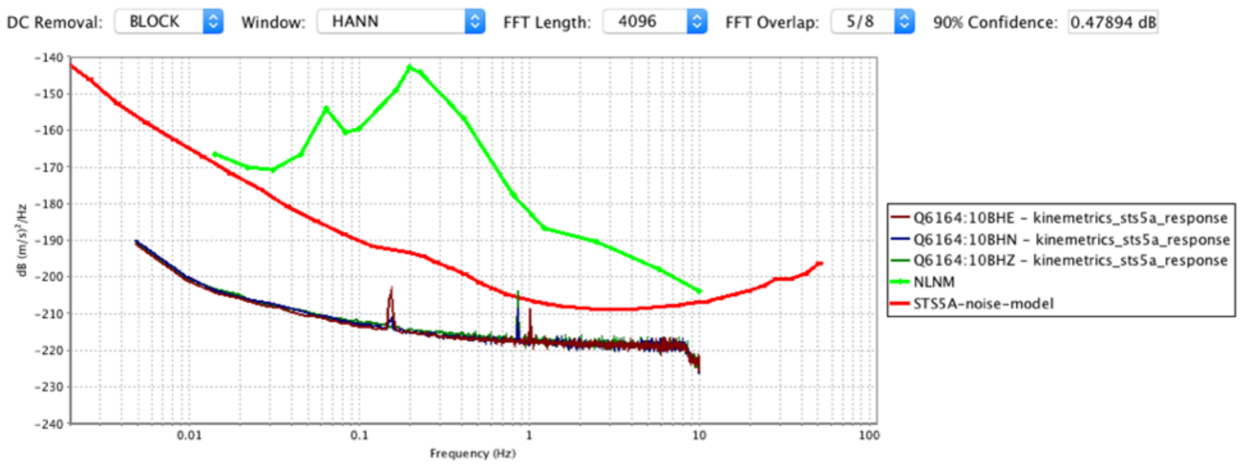

Figure 65 Seismic System Noise Q330HR 6164, Channels 4 - 6, 20 sps

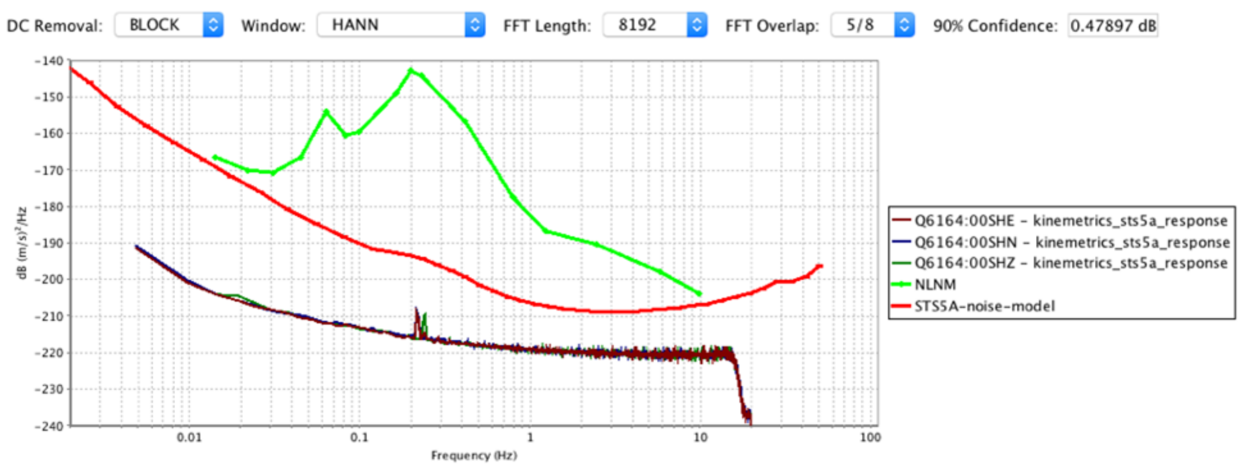

Figure 66 Seismic System Noise Q330HR 6164, Channels 1 - 3, 40 sps

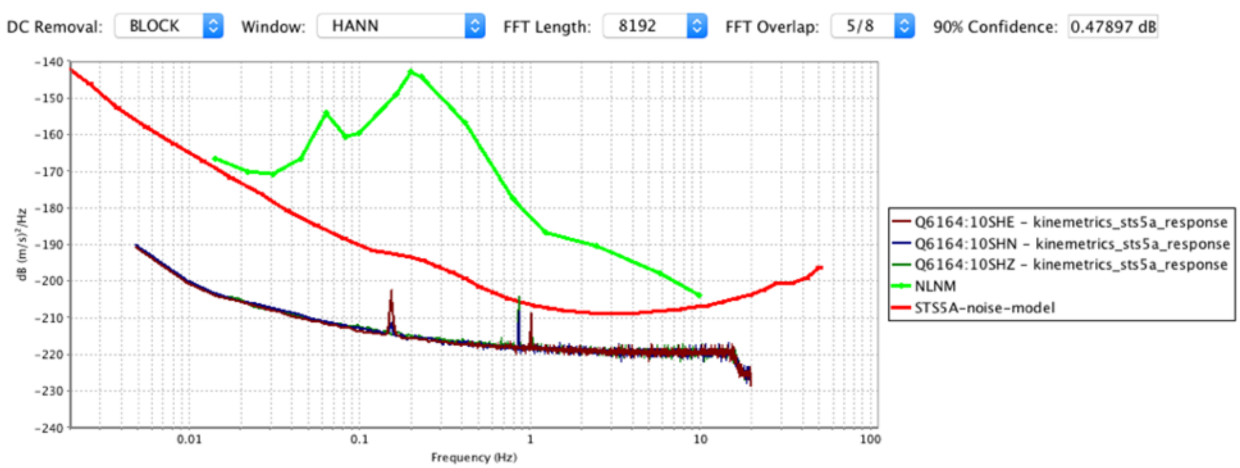

Figure 67 Seismic System Noise Q330HR 6164, Channels 4 - 6, 40 sps

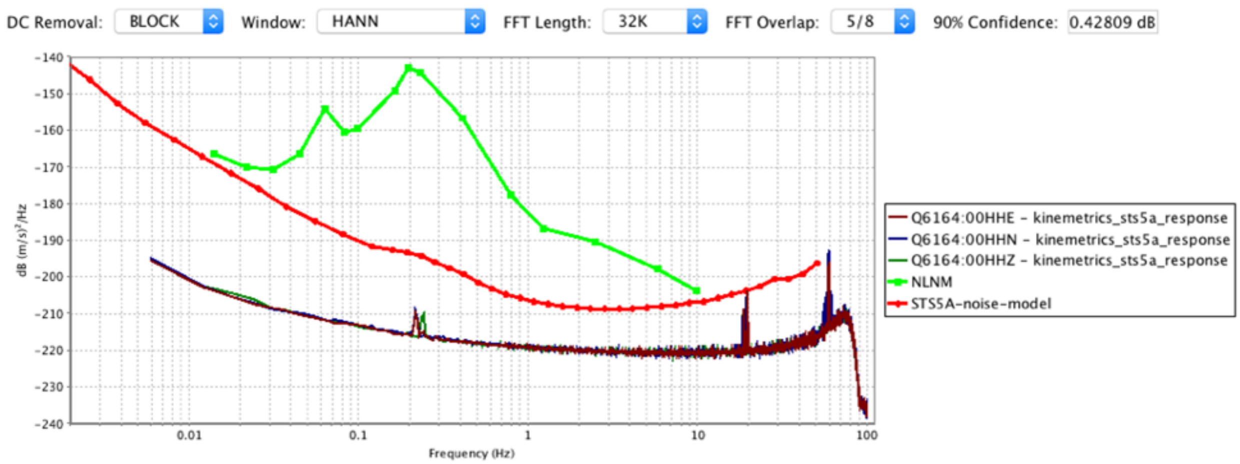

Figure 68 Seismic System Noise Q330HR 6164, Channels 1 - 3, 200 sps

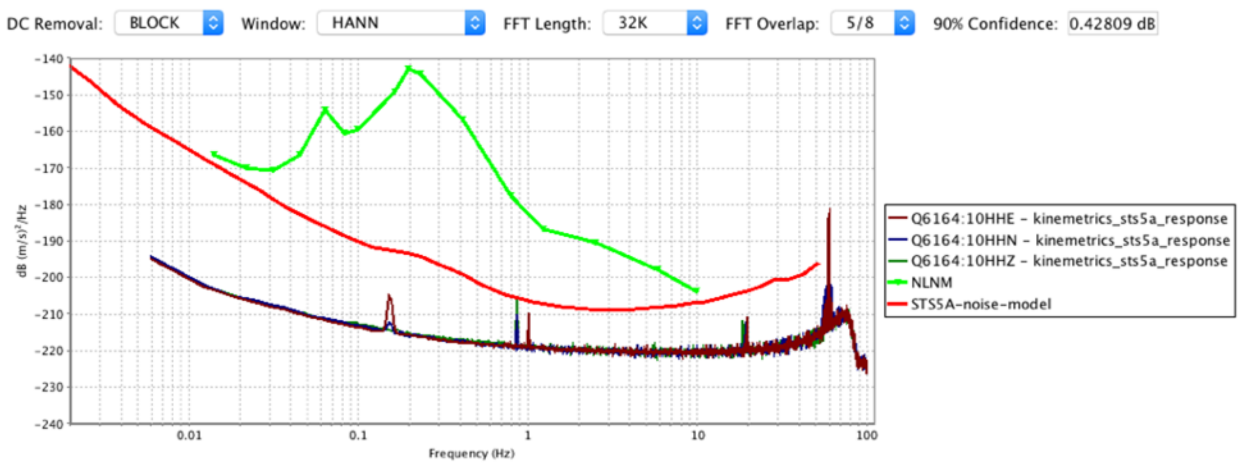

Figure 69 Seismic System Noise Q330HR 6164, Channels 4 - 6, 200 sps

In all instances, computed self noise remains well below the USGS Low Noise Model, for example, over 50.4 dB on both 26 bit and 24 bit channels at 0.1 Hz, and 18 dB (26 bit channels) and 16 Db (24 bit channels) at 10 Hz. With respect to the self noise model of the Streckheisen STS-5A sensor, computed self noise is over 18 db lower on both 26 bit and 24 bit channels at 0.1 Hz, and 13 dB (26 bit channels) and 11 dB (24 bit channels) lower 10 Hz. The average computed system noise over all channels and digitizers at 23° C are -213.12 dB and -220.83 dB at 0.1 Hz and 10 Hz, respectively; for the 26 bit channels and -212.92 dB and -220.28 dB, at 0.1 Hz and 10 Hz, respectively.

Over temperature, channel-averaged system noise of Q330HR 6164 is at a minimum of -214.38 dB at -20° C at 0.1 Hz and occurred on 24 bit channels. Over sample rates, channel averaged system noise of Q330HR 6164 improved slightly, reaching a minimum on the 26 bit channels of -220.26 dB at 40 sps. At 10 sps, channel averaged system noise reached a minimum on the 26 bit channels of -230.70 dB at 20 sps; this value is a bit of an anomaly as system noise levels remained generally around -220 dB.

3.10 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.

3.10.1 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.

3.10.2 Configuration

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

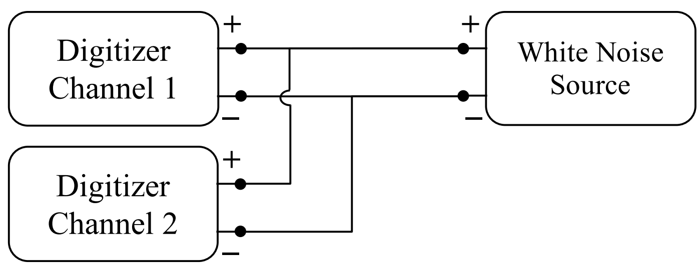

Figure 70 Response Verification Configuration Diagram

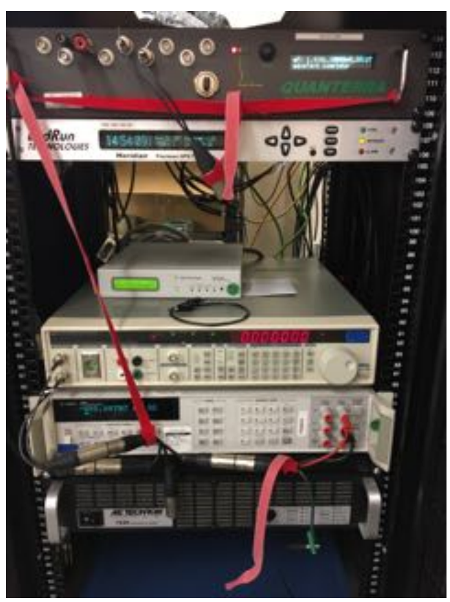

Figure 71 Relative Transfer Function Configuration Picture

Table 36 Response Verification Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
White Noise Source Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
White Noise Source SB1	Stanford Research Systems DS360	123669	+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.

3.10.3 Analysis

The measured bitweight, 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:

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

3.10.4 Result

The coherence and relative amplitude and phase response were computed between 00 HHZ (channel 1) and the five channels (6 channel datalogger) for all of the evaluated sample rate configurations utilizing a 7 hour window of data for the tests conducted at 23.

The first group of plots shows coherence between channel 1 and the remaining channels for each datalogger under test.

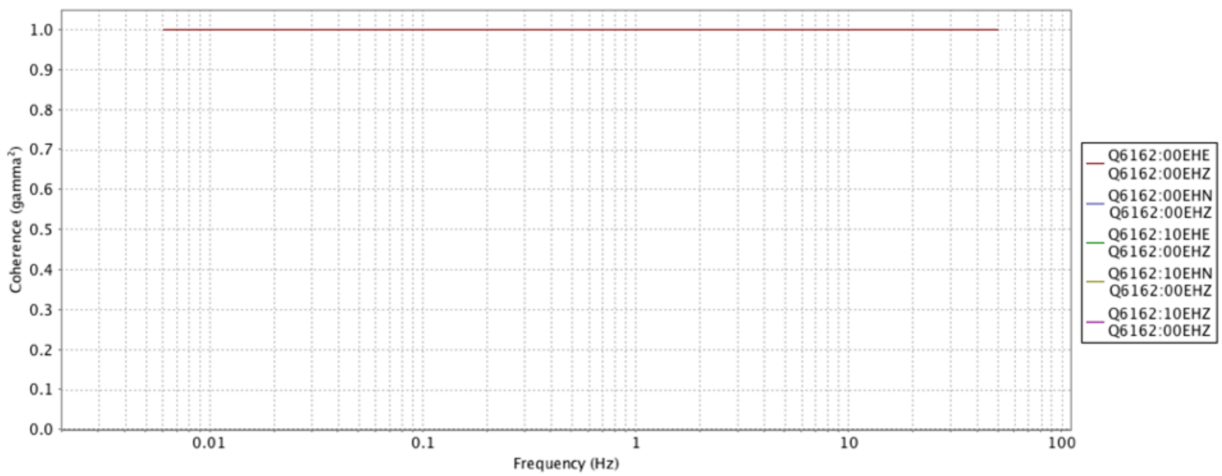

Figure 72 White Noise Coherence Q330HR 6164, 23°C

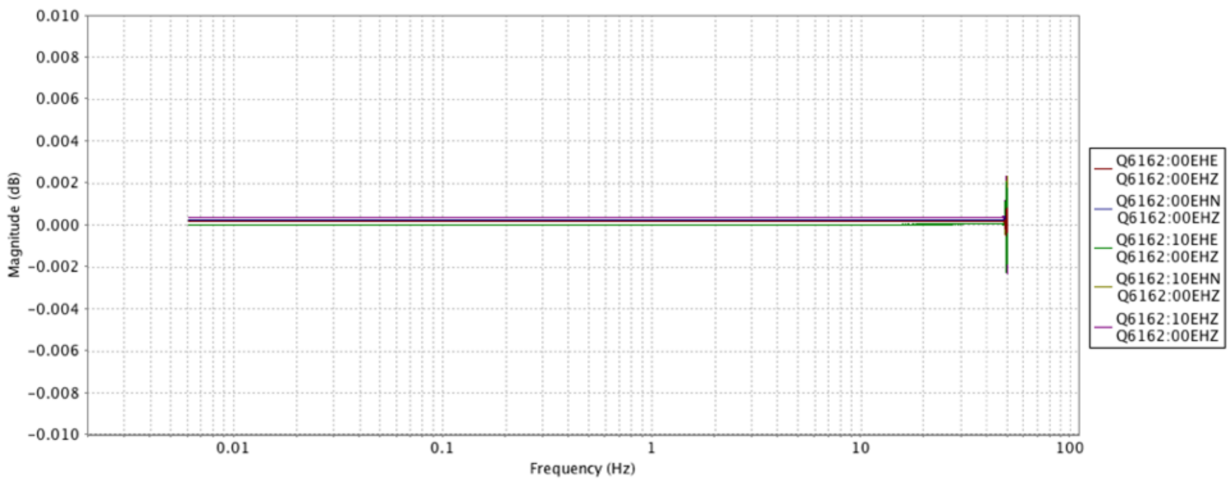

Figure 73 Relative Magnitude Q330HR 6164, 23°C

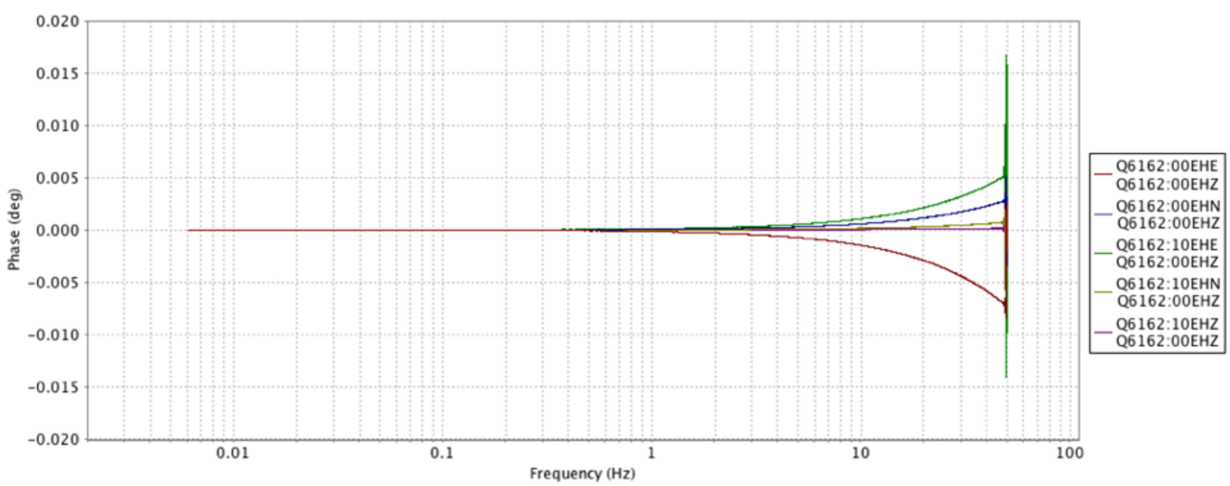

Figure 74 Relative Phase Q330HR 6162, 23°C

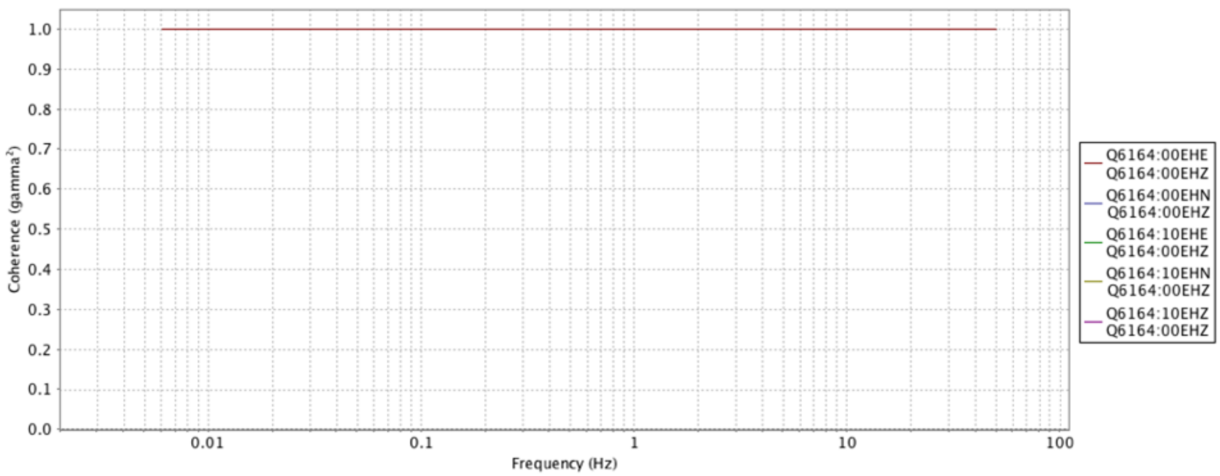

Figure 75 White Noise Coherence Q330HR 6164, 23° C

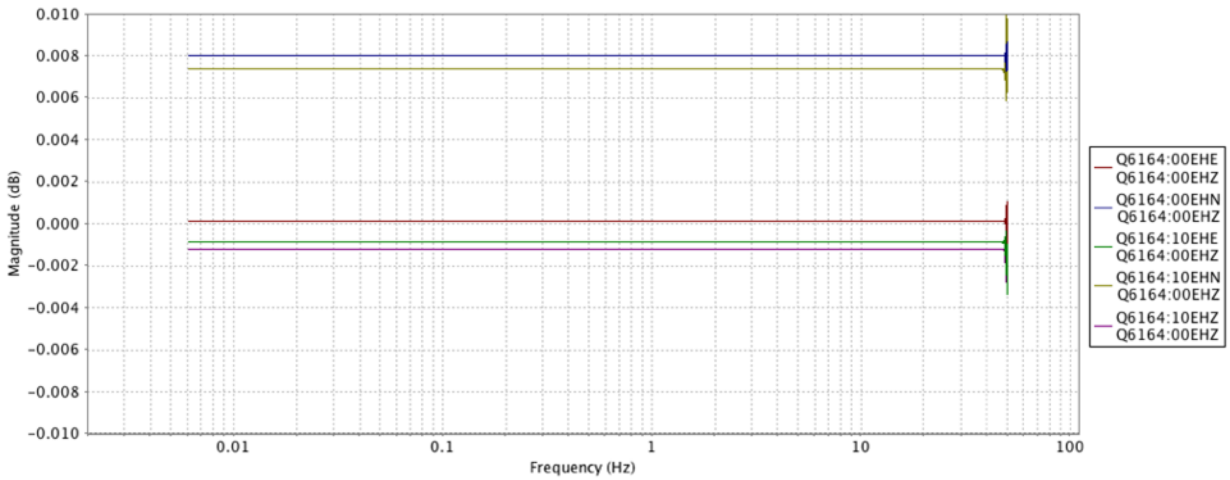

Figure 76 Relative Magnitude Q330HR 6164, 23°C

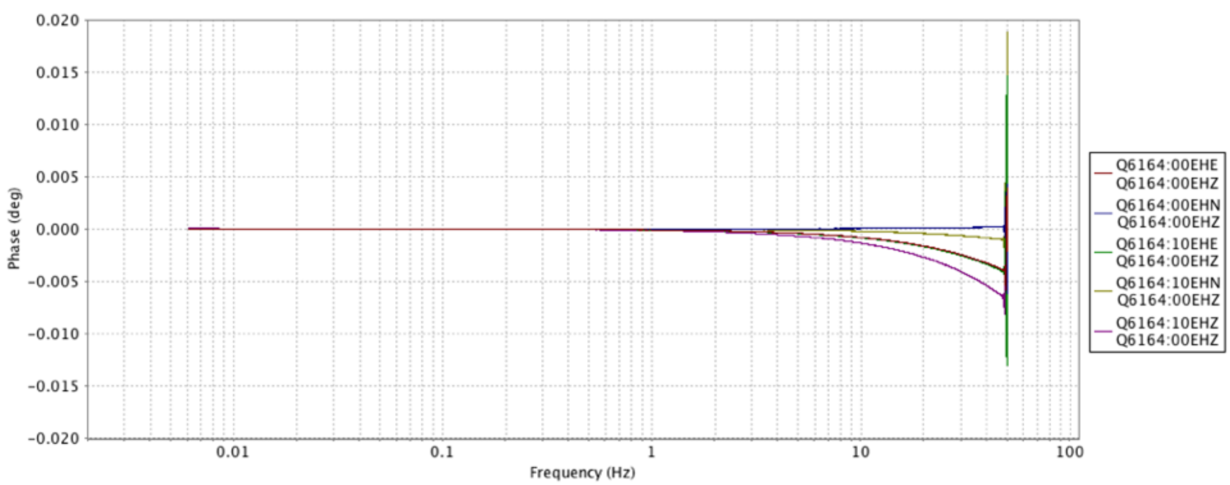

Figure 77 Relative Phase Q330HR 6164, 23°C

The coherence was identically 1.0 across the pass-band; dataloggers show near zero relative magnitude, indicating that there were no differences in response between the digitizer channels of any individual datalogger. Phase differences were very small, with some variation in the amount of the roll-off between channels. This roll-off in phase may be attributed to slight differences in timing, which will be investigated further in the Relative Transfer Function section.

The next group of plots shows relative magnitude and relative phase between channel 1 and channels 2 through 6 for datalogger 6164 at temperatures of 46° C, 20° C, -10° C and -20°C, utilizing a 1 hour window of data. Coherence, from the lowest frequencies available while utilizing a 1 hour time window to that approaching the Nyquist, is essentially 1.0 $gamma^2$; only coherence for a temperature of 46° C is shown below.

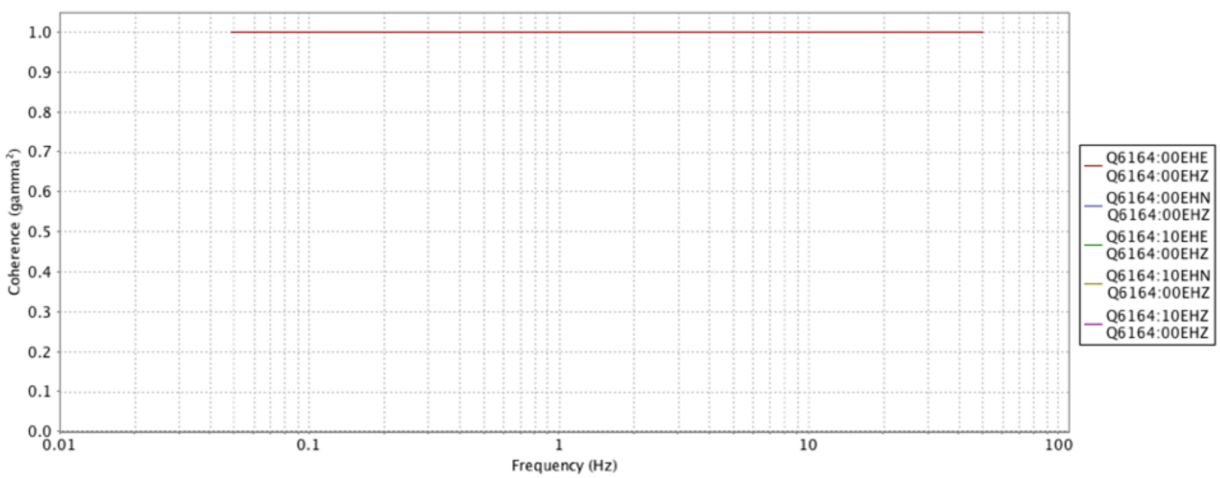

Figure 78 Coherence Q330HR 6164, 46° C

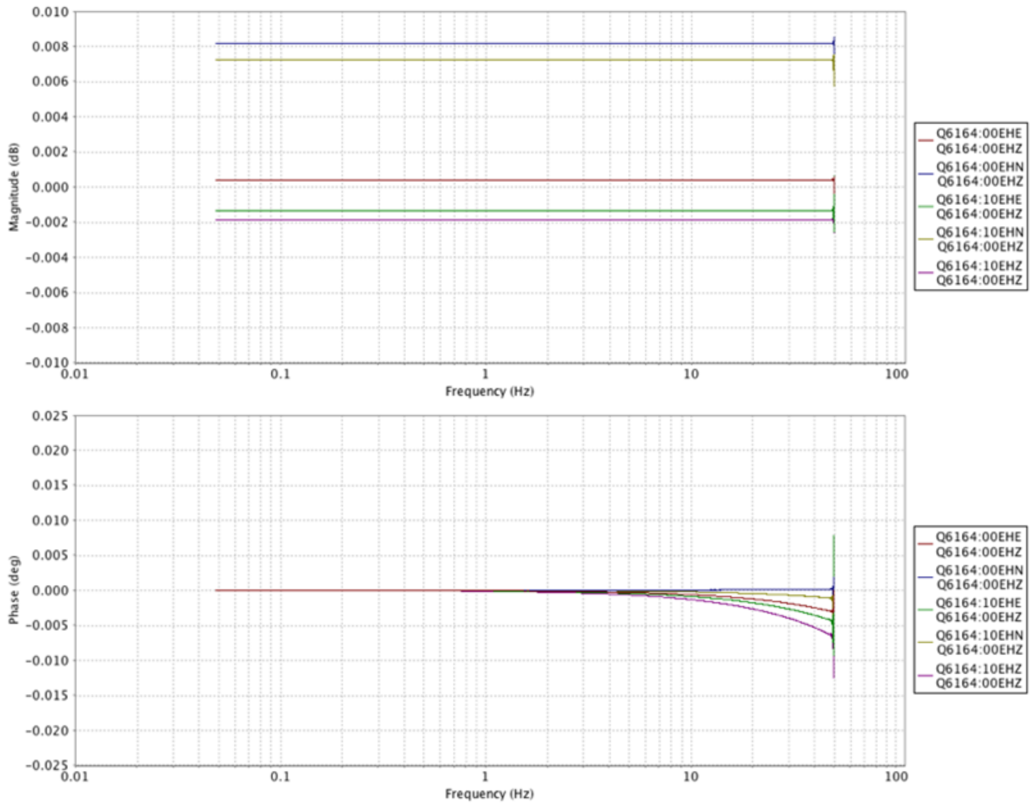

Figure 79 Relative Magnitude and Phase Q330HR 6164, 46° C

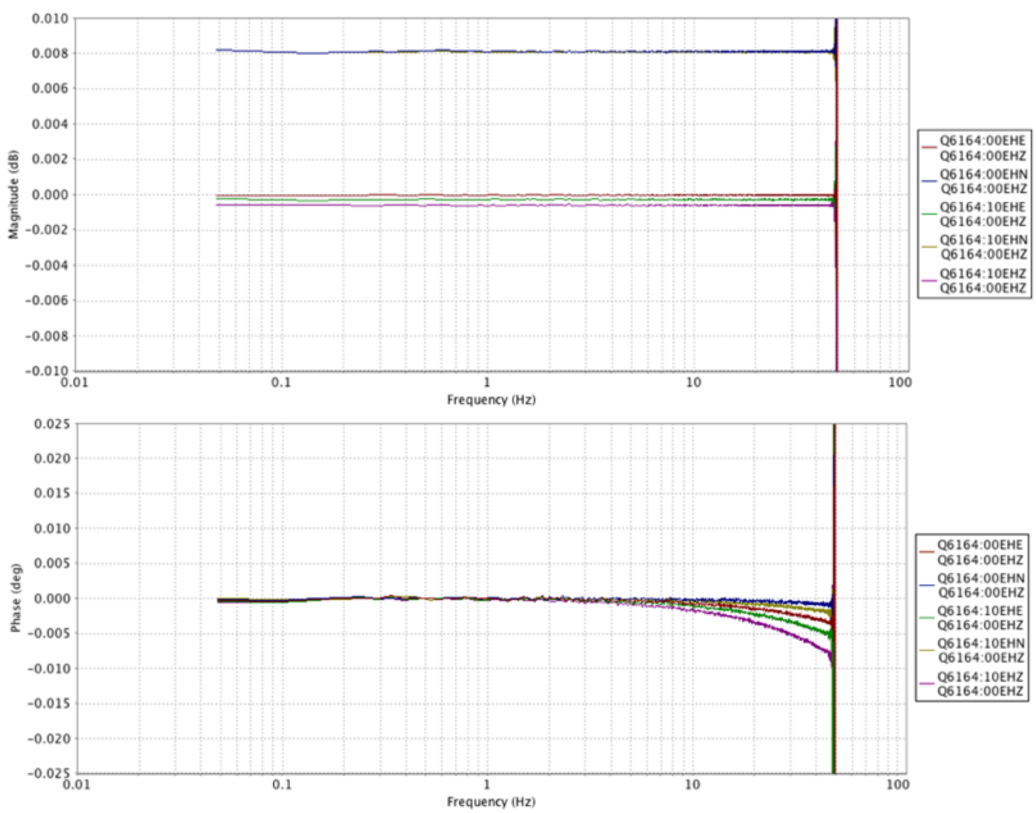

Figure 80 Relative Magnitude and Phase Q330HR 6164, 20° C

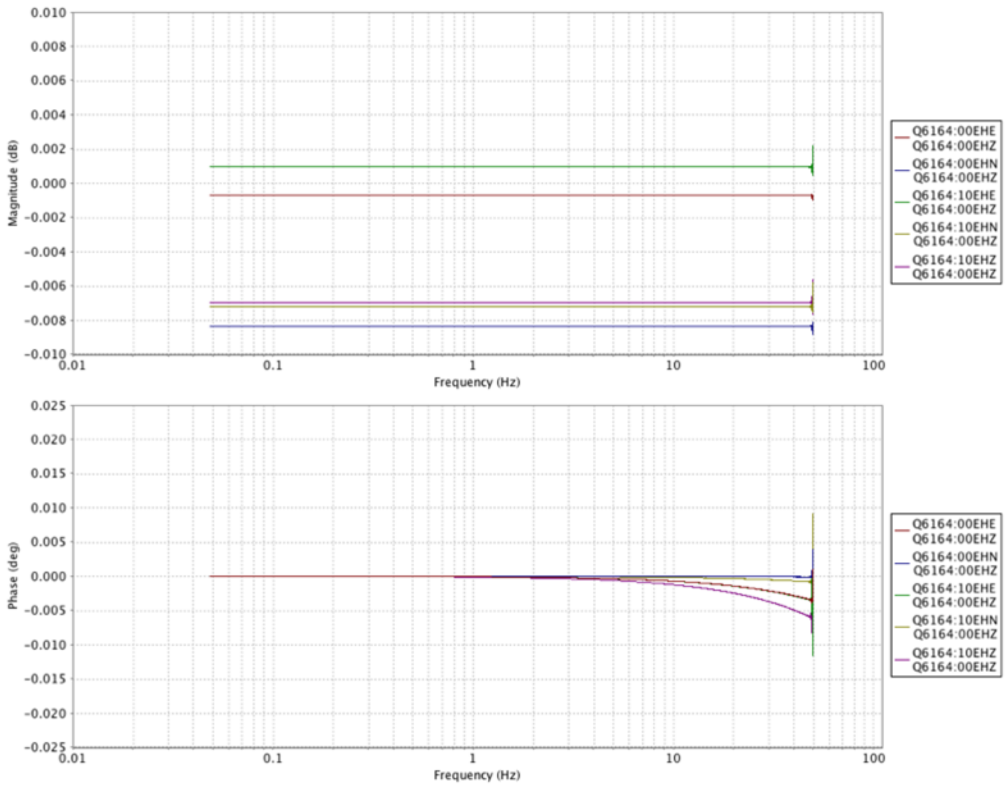

Figure 81 Relative Magnitude and Phase Q330HR 6164, -10° C

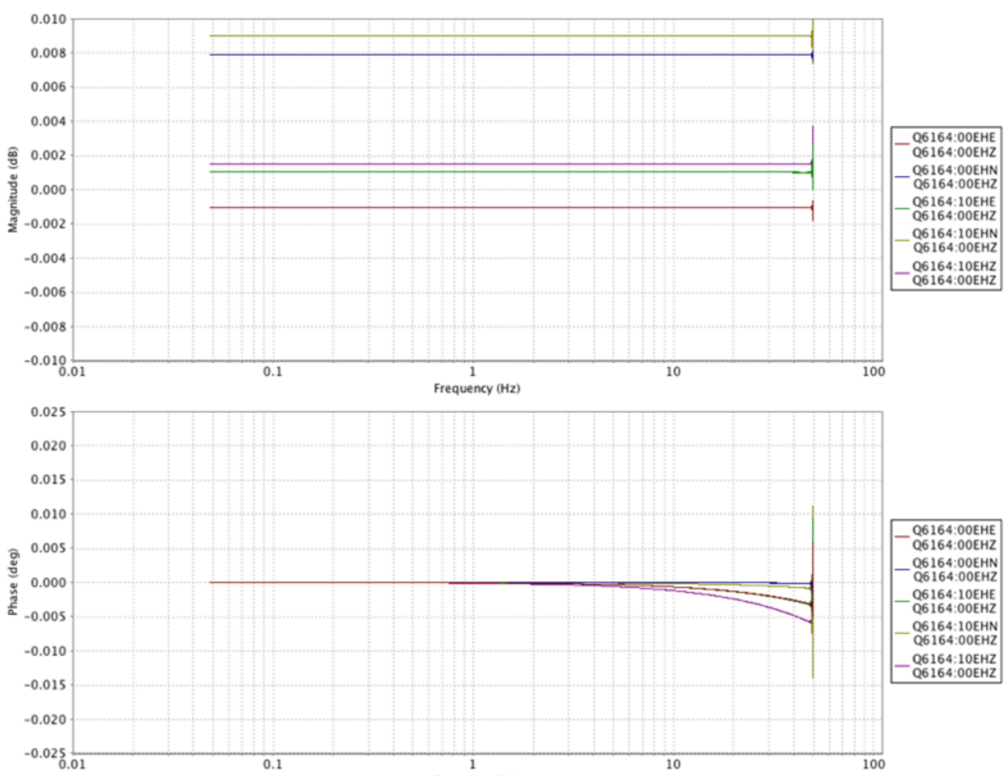

Figure 82 Relative Magnitude and Phase Q330HR 6164, -20° C

At the evaluated temperatures, the relative amplitudes were effectively zero. This indicates that there were no differences in response between the digitizer channels of any individual datalogger. Phase differences were very small, with a slight roll-off, varying little as temperature changed. This roll-off in phase may be attributed to slight differences in timing, which will be investigated further in the Relative Transfer Function section.

The following group of plots shows relative magnitude and relative phase between channel 1 and channels 2 through 6 for datalogger 6164 at sample rates of 10 sps, 20 sps, 40 sps, 100 sps and 200 sps, utilizing a 1 hour window of data. Coherence, from the lowest frequencies available while utilizing a 1 hour time window to that approaching the Nyquist, is essentially 1.0 gamma^2, given this consistency plots of coherence are omitted.

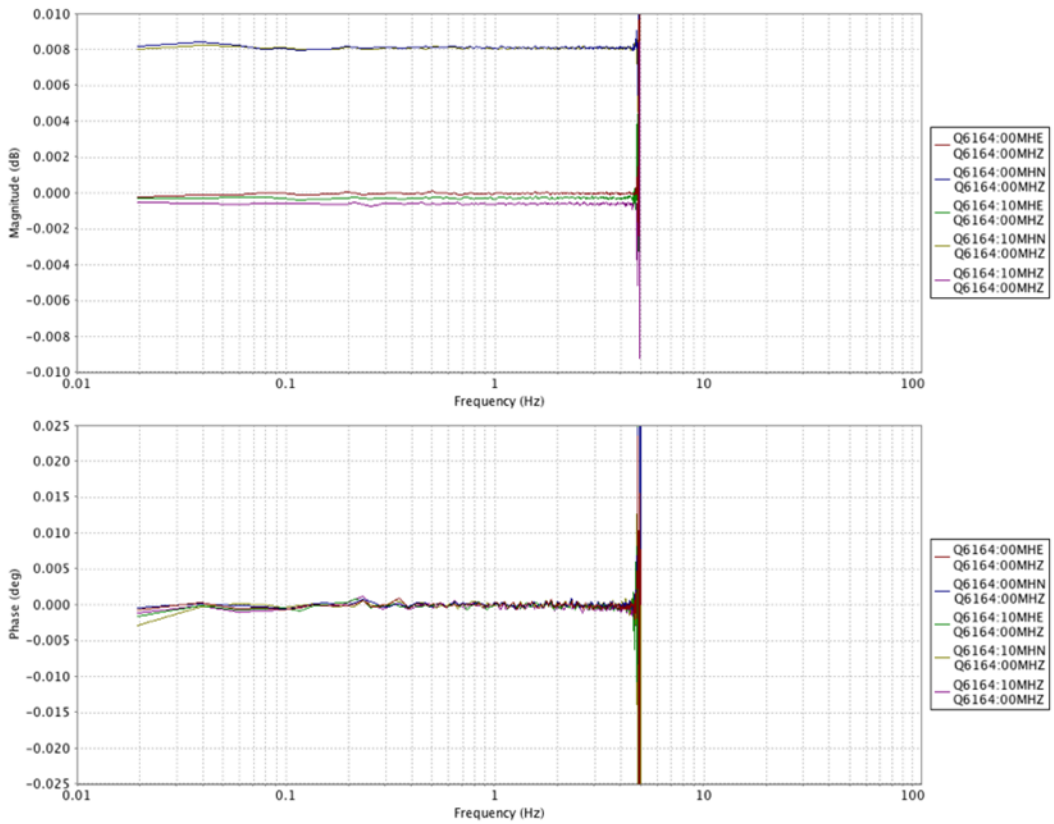

Figure 83 Relative Magnitude and Phase Q330HR 6164, 10 sps

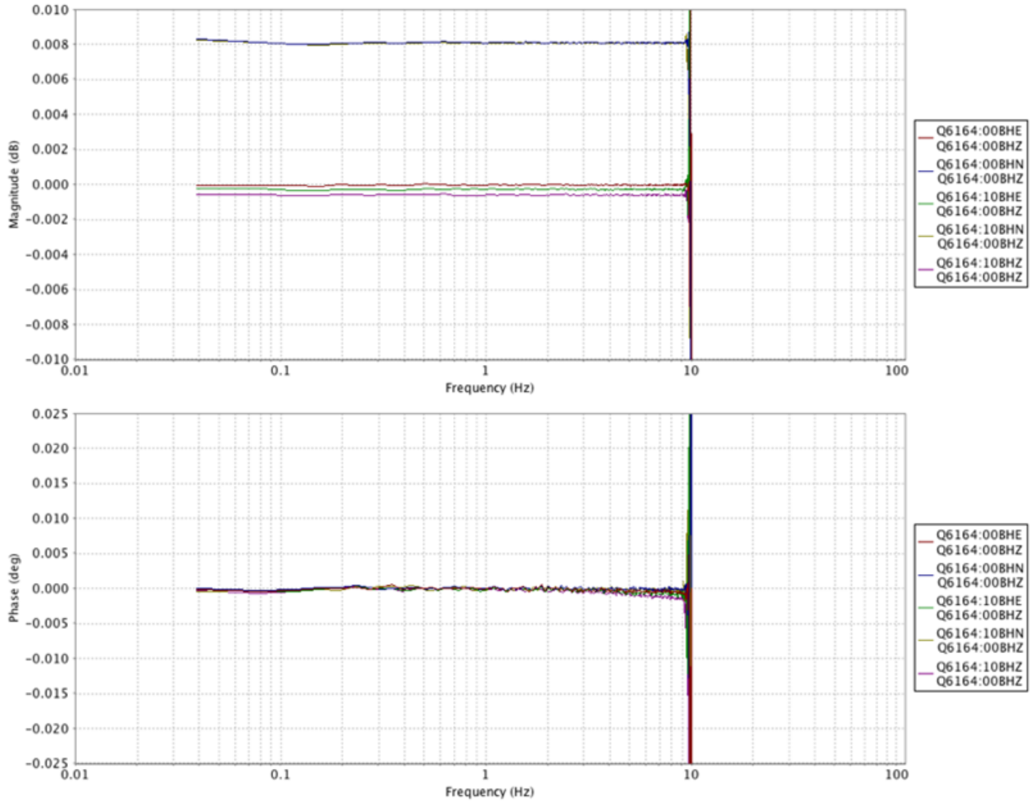

Figure 84 Relative Magnitude and Phase Q330HR 6164, 20 sps

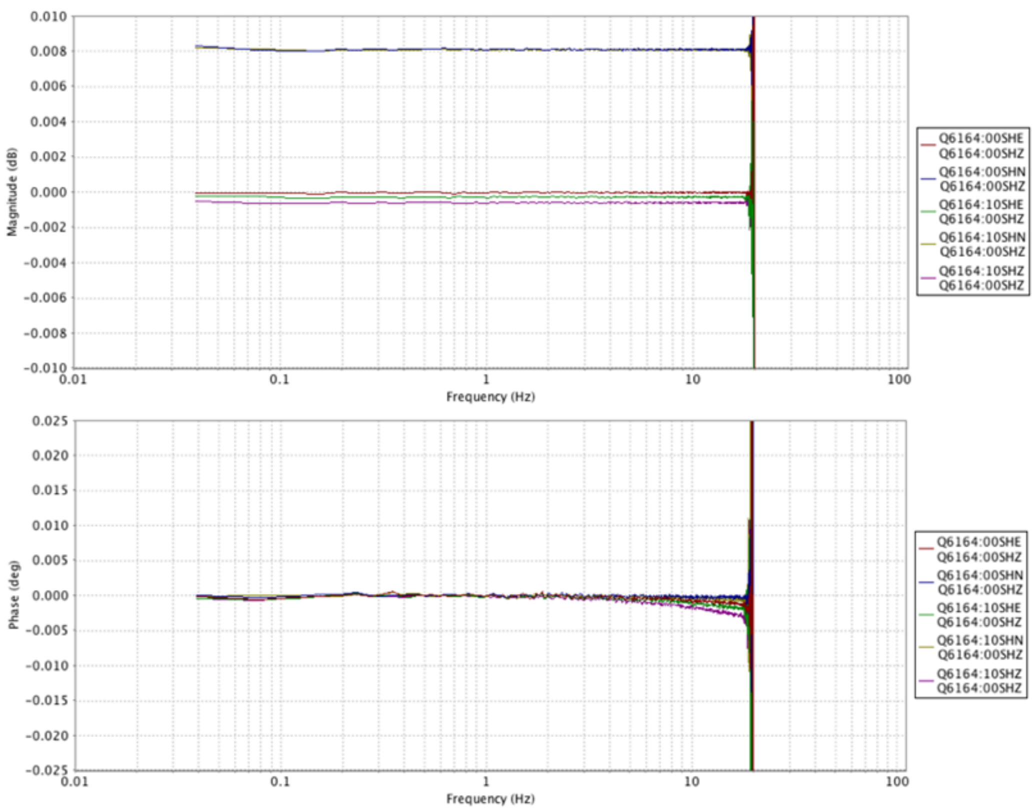

Figure 85 Relative Magnitude and Phase Q330HR 6164, 40 sps

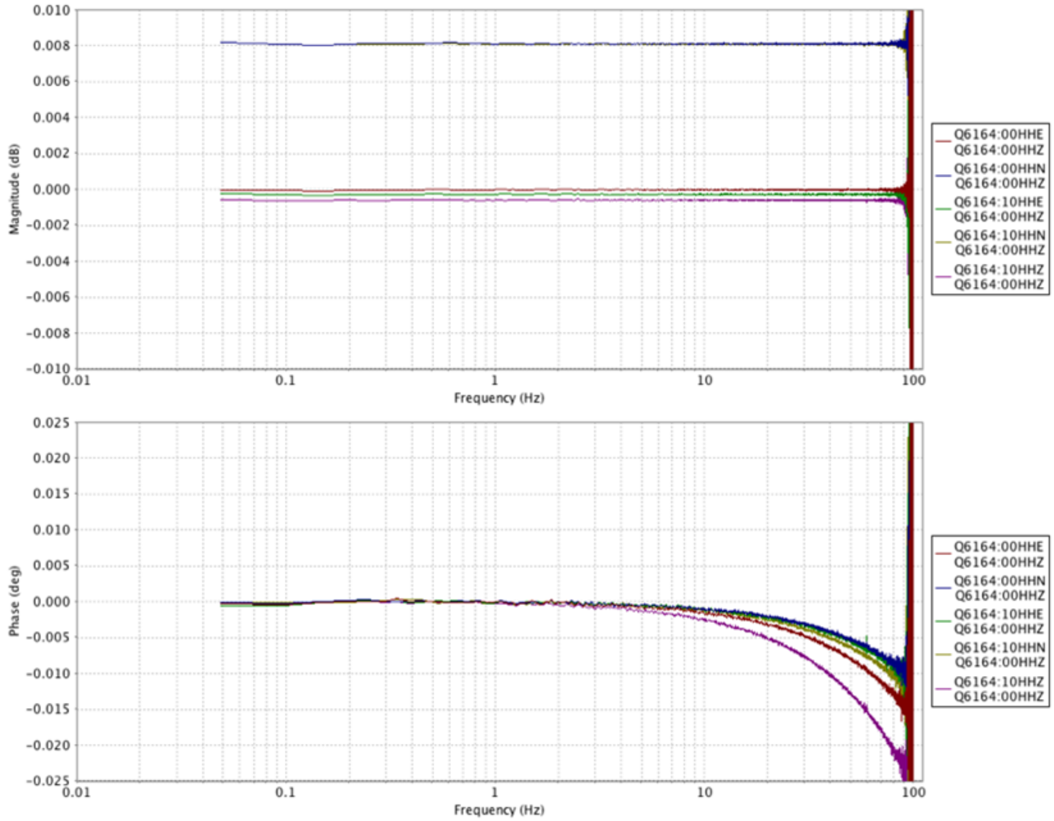

Figure 86 Relative Magnitude and Phase Q330HR 6164, 200 sps

Similar to tests at 23° C or over a variety of temperatures, magnitude and phase varied little with changes in sample rate. As sample rate increases the slightest roll-off is evident; the maximum approaching 0.025 degrees as the frequency approaches the Nyquist in the 200 sps data stream.

3.11 Relative Transfer Function

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

3.11.1 Measurand

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

3.11.2 Configuration

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

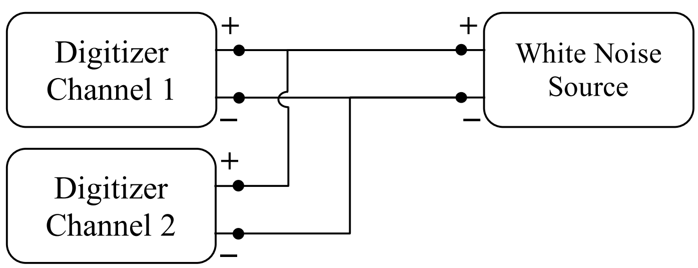

Figure 87 Relative Transfer Function Configuration Diagram

Figure 88 Relative Transfer Function Configuration Picture

Table 37 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
White Noise Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
White Noise Source - SB1	Stanford Research Systems DS360	123669	+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.

3.11.3 Analysis

The measured bitweight, 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:

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

3.11.4 Result

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

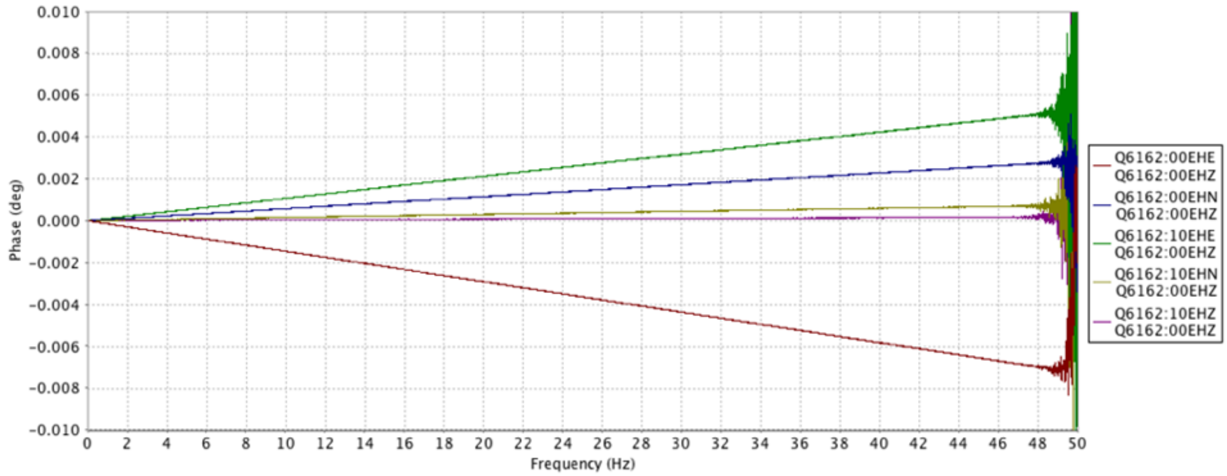

Figure 89 Relative Transfer Function, Q330HR 6162 , 23°C

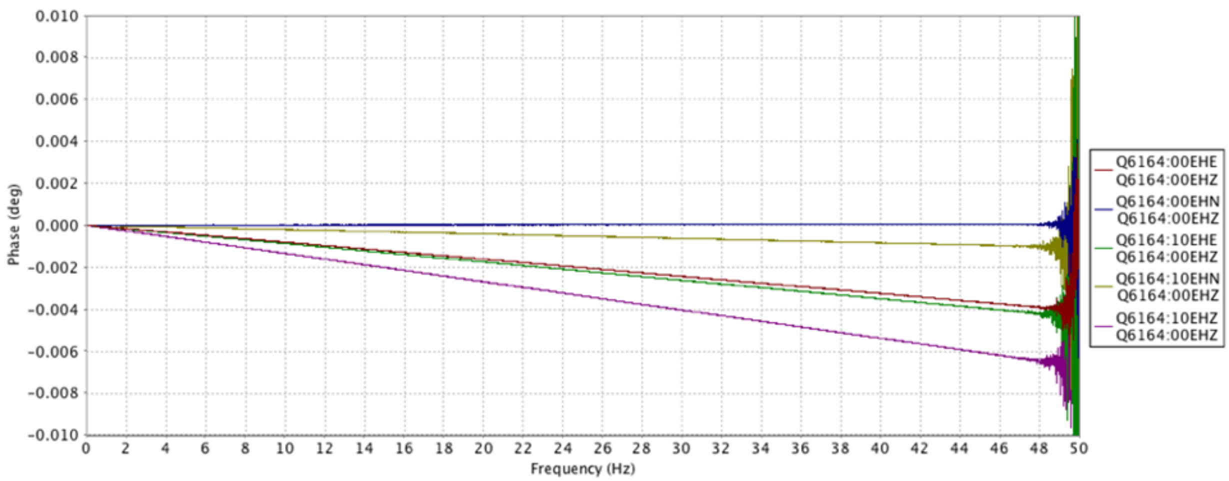

Figure 90 Relative Transfer Function, Q330HR 6164 , 23°C

Phase delays relative to channel 1 are linear with respect to frequency for both dataloggers. Both both dataloggers, the north channels (2 and 5) exhibit the least phase delay and the vertical the most. The constant channel-to-channel timing skew corresponding to these phase delays is shown in the tables below.

Table 38 Relative Transfer Function Timing Skew

DWR	00EHE (chan 3)	00EHN (chan 2)	10EHE (chan 6)	10EHN (chan 5)	10EHZ (chan 4)
6162	-0.40 us	0.16 us	0.30 us	0.04 us	0.01 us
6164	-0.22 us	0.00 us	-0.24 us	-0.06 us	-0.37 us

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

The following plots show the relative transfer function for Q330HR 6164 across variations in temperature.

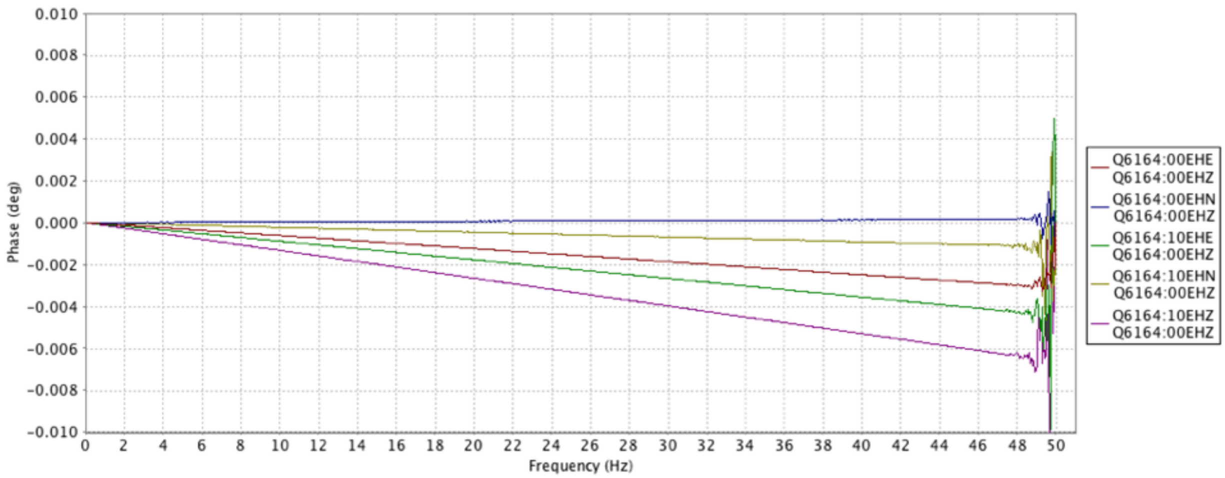

Figure 91 Relative Transfer Function, Q330HR 6164, 46° C

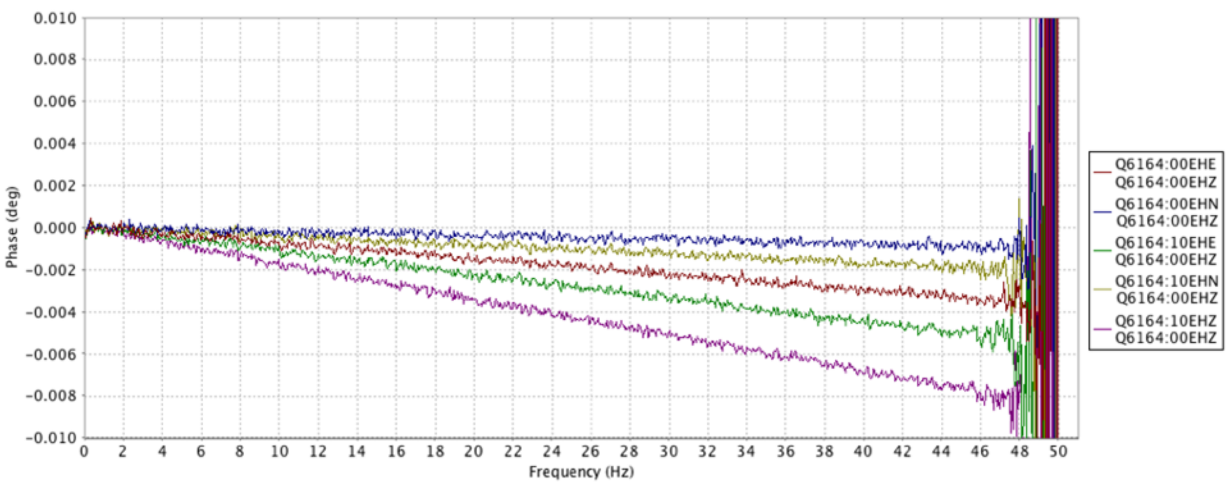

Figure 92 Relative Transfer Function, Q330HR 6164, 20° C

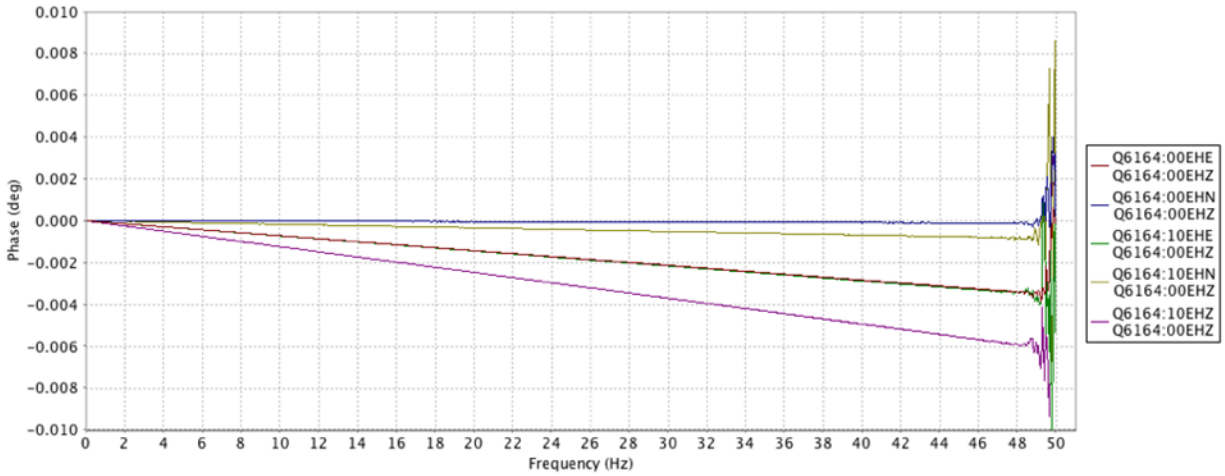

Figure 93 Relative Transfer Function, Q330HR 6164, -10° C

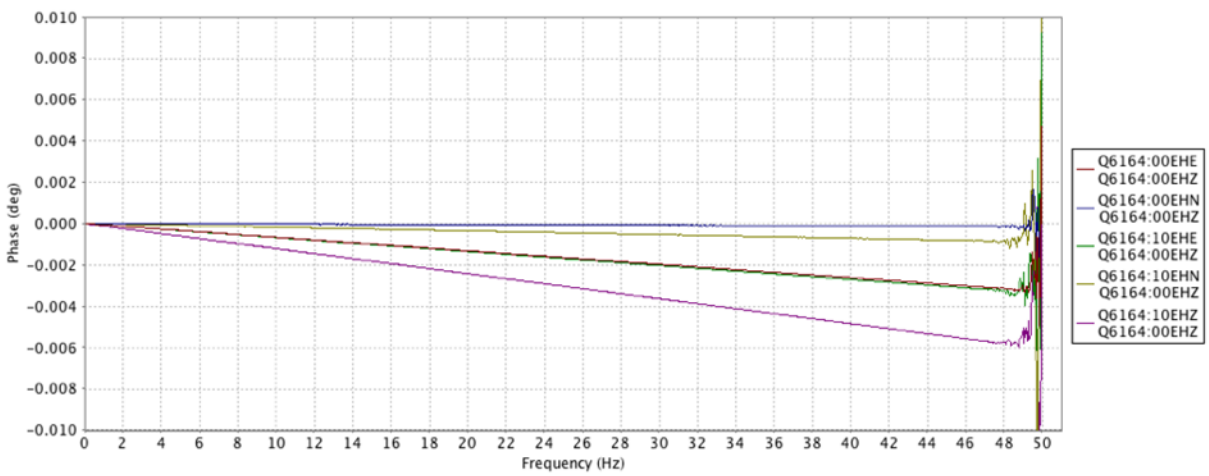

Figure 94 Relative Transfer Function, Q330HR 6164, -20° C

Table 39 Relative Transfer Function Timing Skew, Q330HR 6164 at Select Temperatures

Temperature	00HHE (chan3)	00HHN (chan 2)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
60° C	-0.17 us	0.01 us	-0.24 us	-0.06 us	-0.37 us
20° C	-0.20 us	-0.05 us	-0.30 us	-0.11 us	-0.47 us
-20° C	-0.20 us	-0.01 us	-0.20 us	-0.05 us	-0.34 us
-36° C	-0.18 us	-0.01 us	-0.19 us	-0.05 us	-0.34 us

Phase delays relative to channel 1 are linear with respect to frequency and relatively consistent across the temperature ranges at which phase delays were observed. At 20° C all channels exhibited their largest timing skew, however in all cases timing skews remained below one half microsecond. As noted in the 23° C relative transfer function tests, channels 2 and 5 (north channels) consistently exhibit the smallest timing skews and channel 6 the largest.

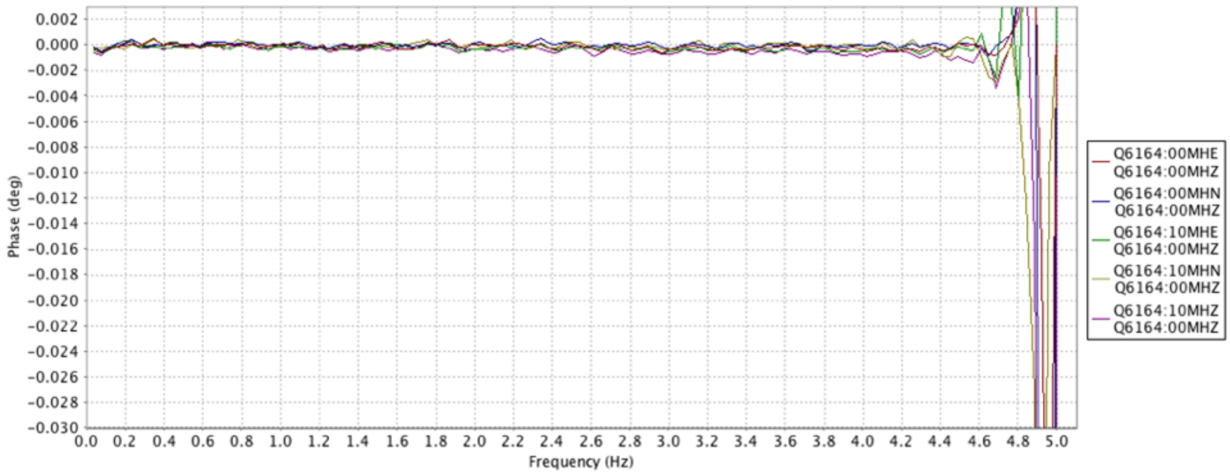

Figure 95 Relative Transfer Function, Q330HR 6164, 10 sps

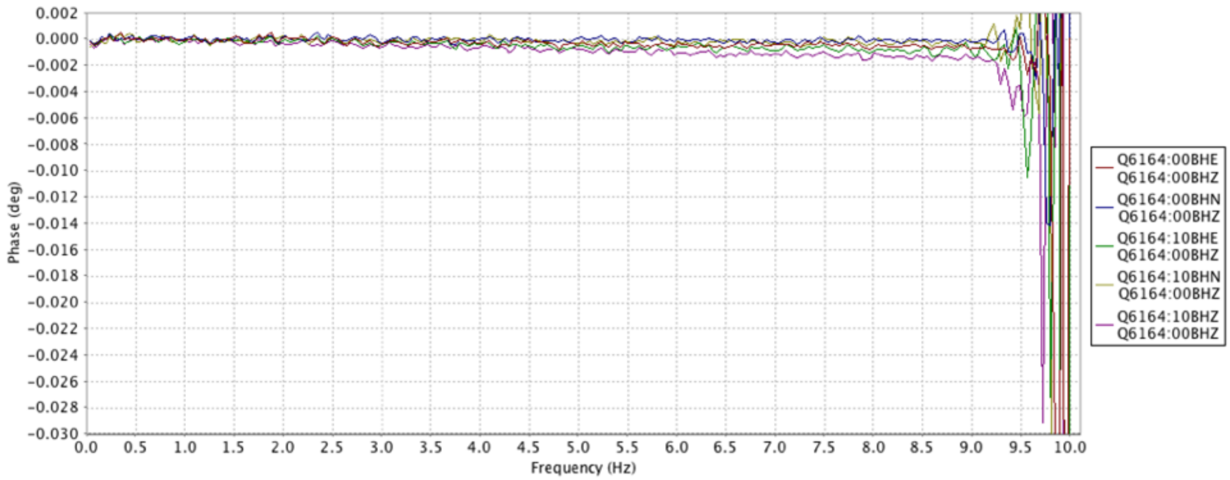

Figure 96 Relative Transfer Function, Q330HR 6164, 20 sps

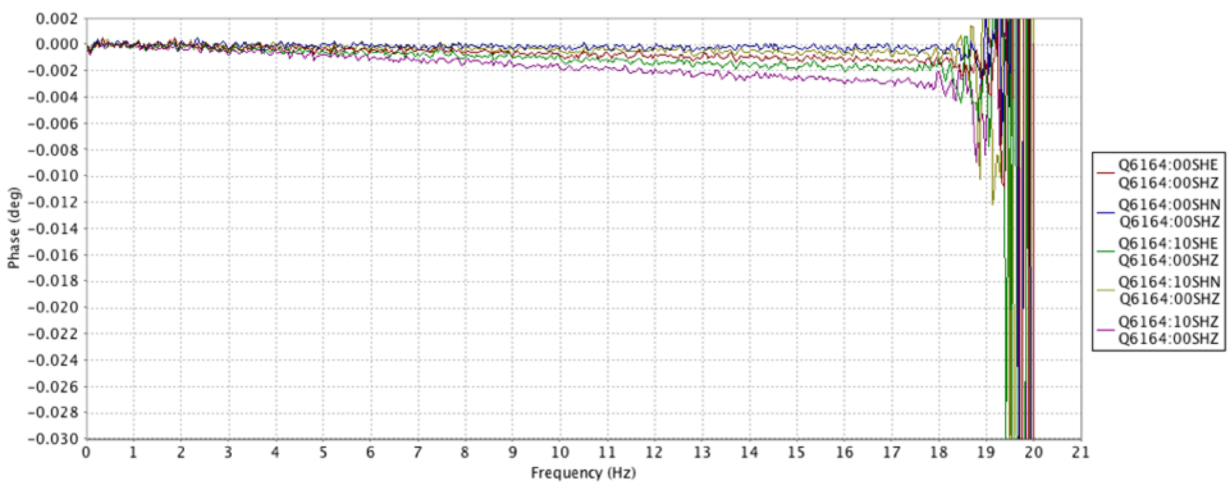

Figure 97 Relative Transfer Function, Q330HR 6164, 40 sps

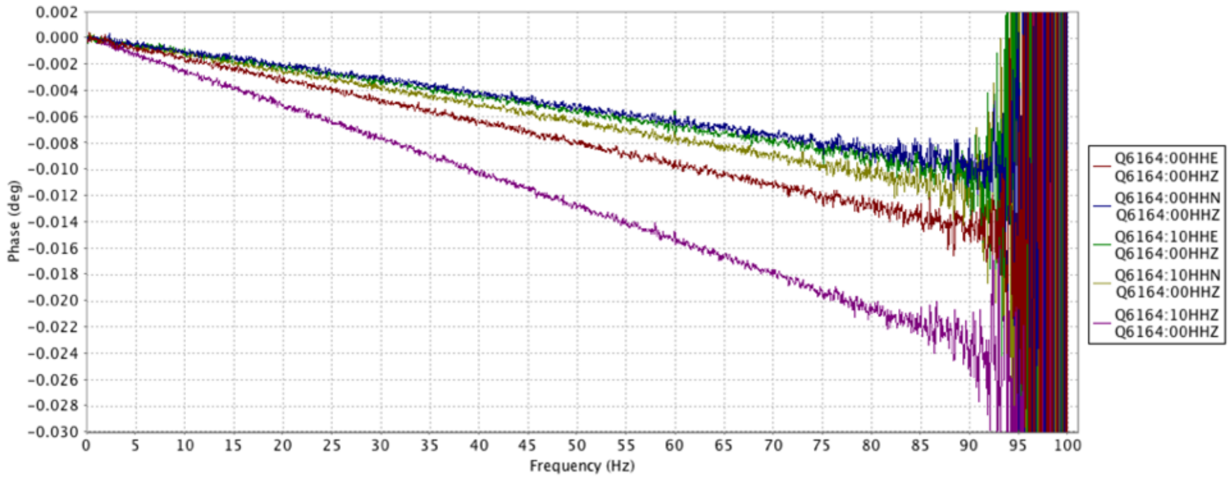

Figure 98 Relative Transfer Function, Q330HR 6164, 200 sps

Table 40 Relative Transfer Function Timing Skew, Q330HR 6164 at Select Sample Rates

Sample Rate	00HHE (chan 3)	00HHN (chan 2)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
10 sps	-0.18 us	-0.04 us	-0.31 us	-0.10 us	-0.51 us
20 sps	-0.18 us	-0.04 us	-0.29 us	-0.11 us	-0.48 us
40 sps	-0.20 us	-0.05 us	-0.30 us	-0.11 us	-0.48 us
100 sps	-0.20 us	-0.05 us	-0.30 us	-0.11 us	-0.47 us
200 sps	-0.44 us	-0.29 us	-0.31 us	-0.35 us	-0.71 us

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

3.12 Analog Bandwidth

The Analog Bandwidth test measures the bandwidth of the digitizer's analog and digital filter.

3.12.1 Measurand

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

3.12.2 Configuration

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

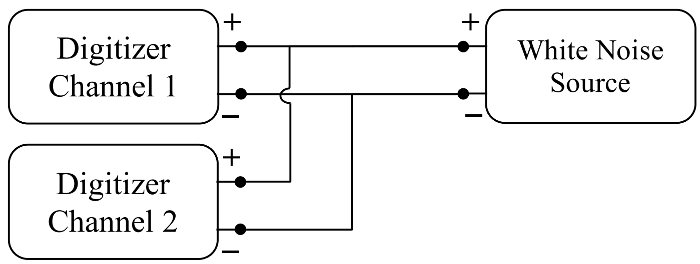

Figure 99 Analog Bandwidth Configuration Diagram

Table 41 Analog Bandwidth Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
White Noise Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
White Noise Source - SB1	Stanford Research Systems DS360	123669	+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. Seven and one hour data recordings were utilized for the evaluation across all dataloggers and for evaluations at select temperatures and sample rates, respectively.

3.12.3 Analysis

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

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

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

3.12.4 Result

The power spectra of the white noise signal recorded on the Q330HR digitizer channels are shown in the plots below.

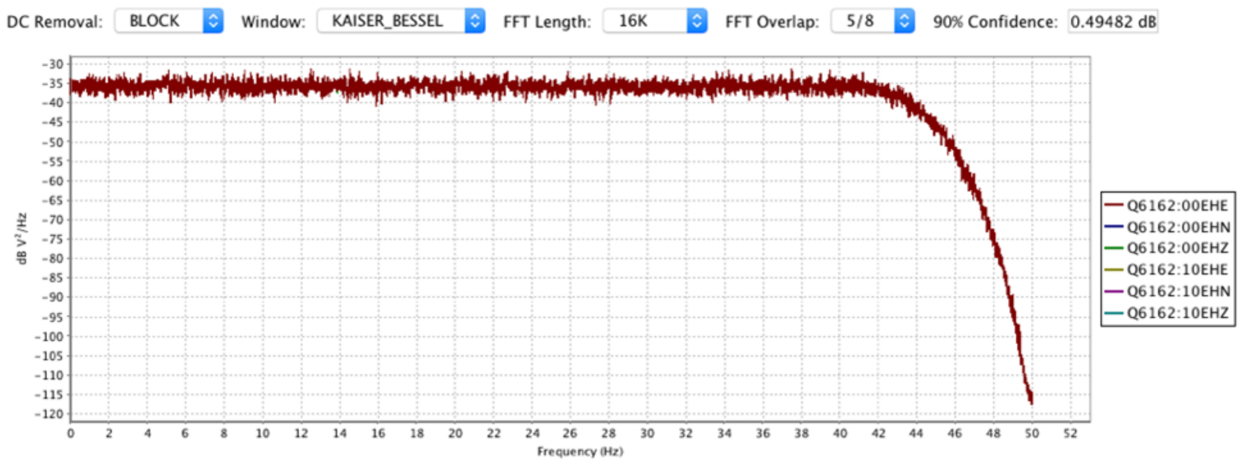

Figure 100 Analog Bandwidth Q330HR 6162, 23° C

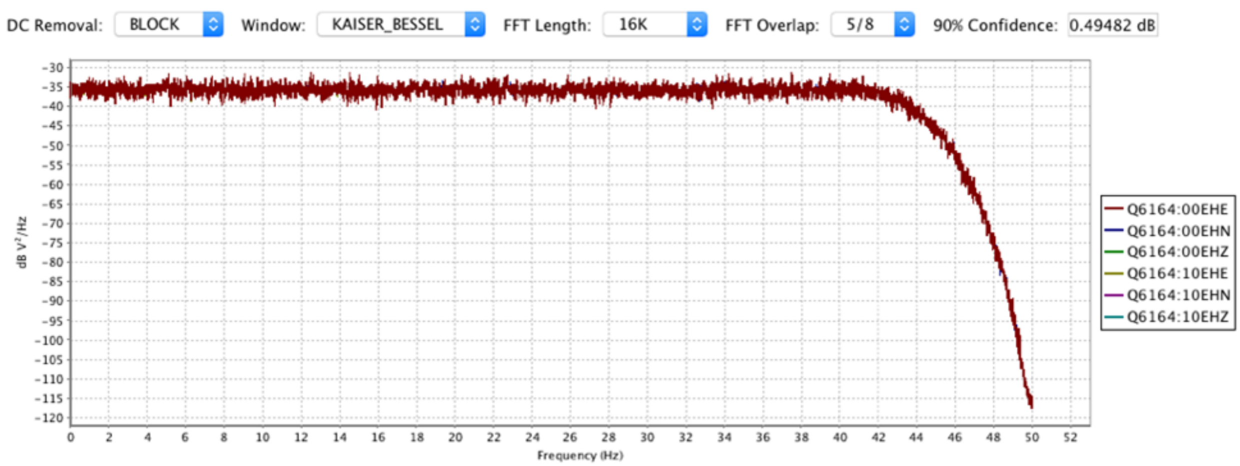

Figure 101 Analog Bandwidth Q330HR 6164, 23° C

Table 42 Analog Bandwidth, Both Q330HRs, 23° C

DWR	00HHE (chan 3)	00HHN (chan 6)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)	% Nyquist Frequency
6162	43.506 Hz	43.506 Hz	43.506 Hz	43.506 Hz	43.506 Hz	43.506 Hz	87.01 %
6164	43.506 Hz	43.506 Hz	43.506 Hz	43.506 Hz	43.506 Hz	43.506 Hz	87.01 %

The observed pass-band limit of all the dataloggers while recording 100 sps data and exposed to 23° C remained uniform at 87.01% of the 50 Hz Nyquist Frequency.

The following plots contain the bandwidth across variations in temperature and sample rate for Q330HR 6164.

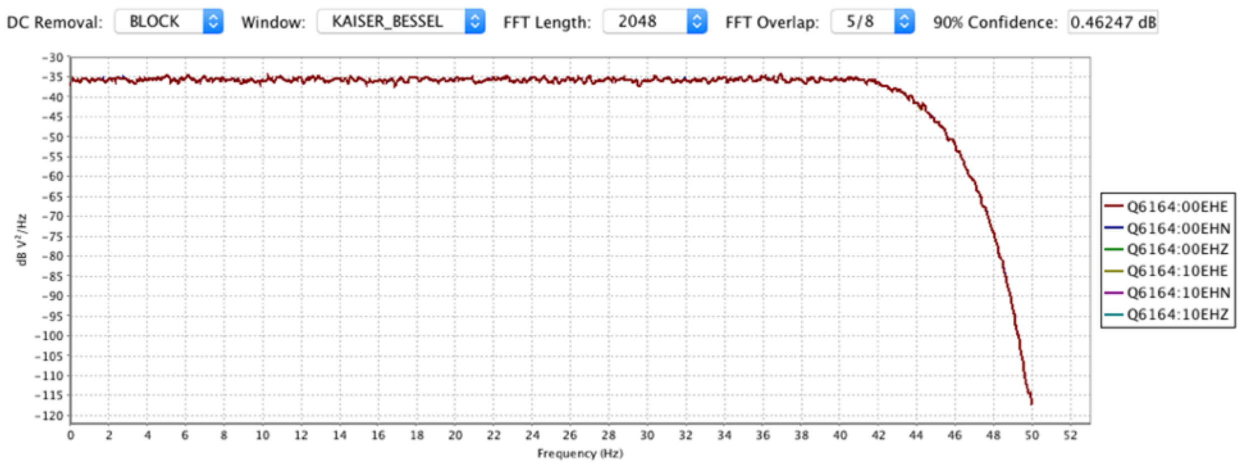

Figure 102 Analog Bandwidth Q330HR 6164, 46° C

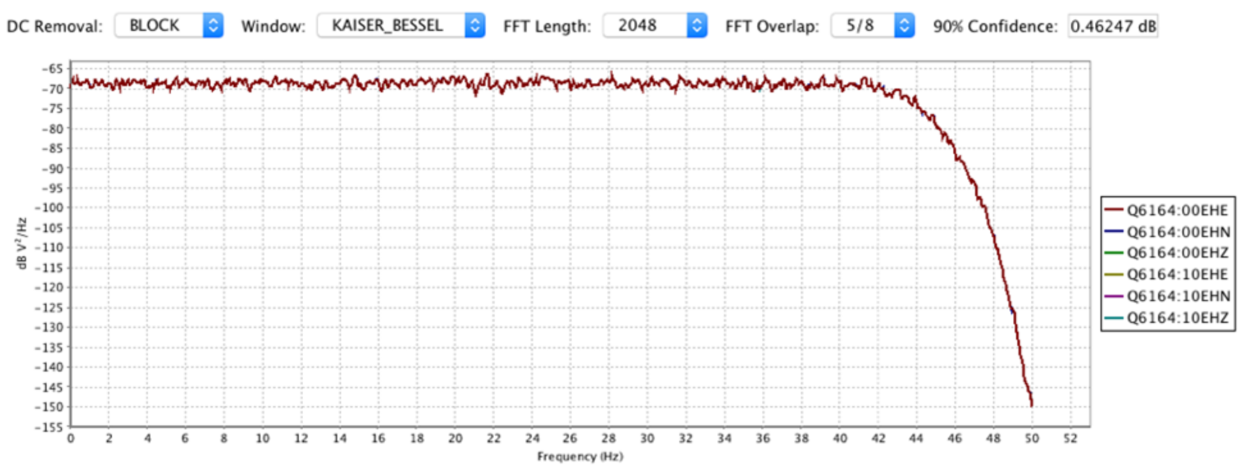

Figure 103 Analog Bandwidth Q330HR 6164, 20° C

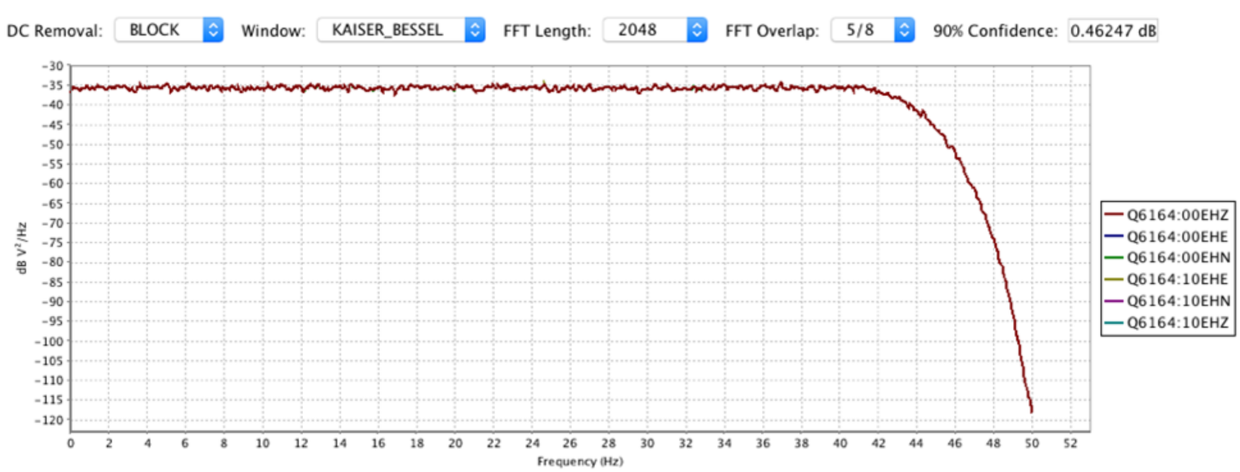

Figure 104 Analog Bandwidth Q330HR 6164, -10° C

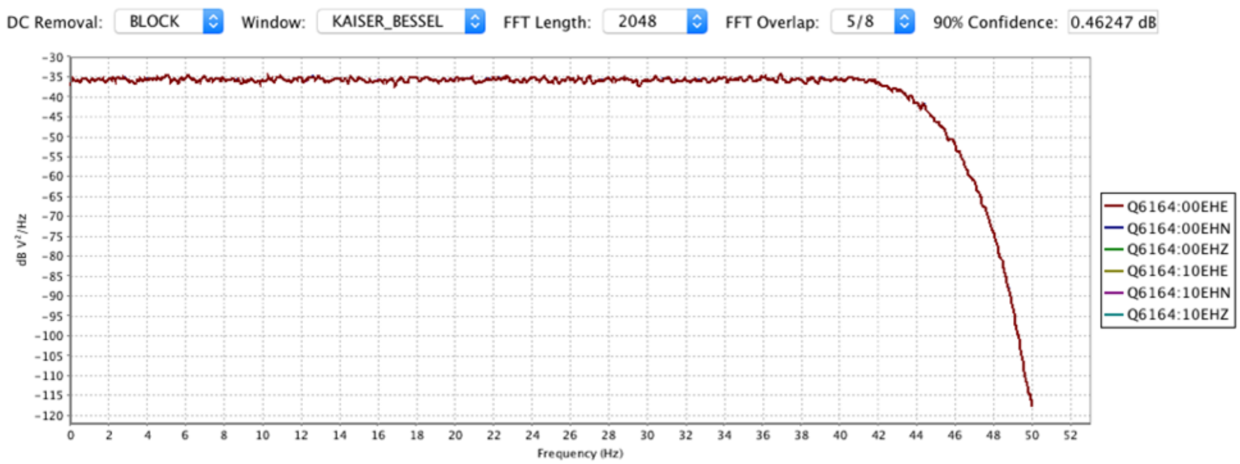

Figure 105 Analog Bandwidth Q330HR 6164, -20° C

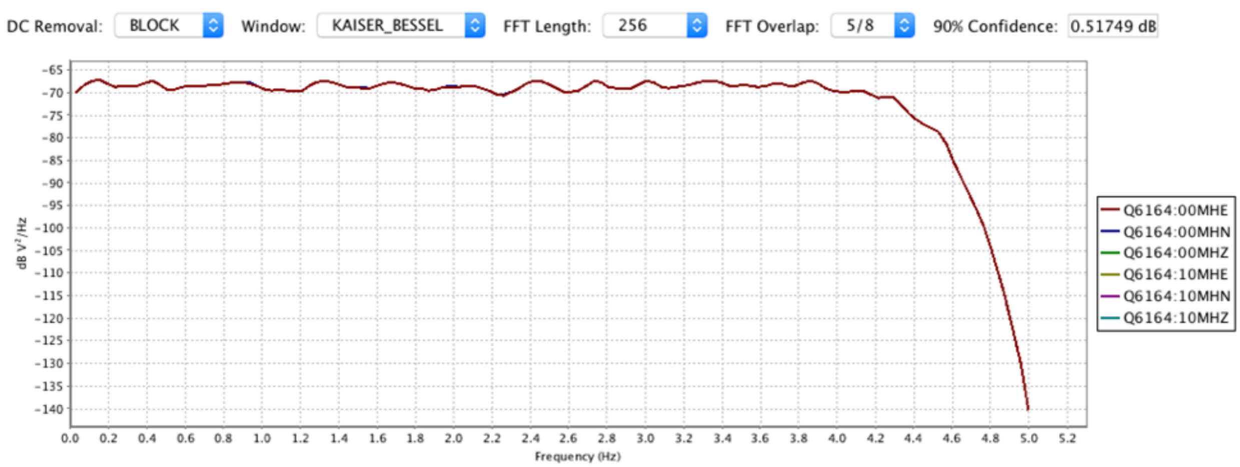

Figure 106 Analog Bandwidth Q330HR 6164, 10 sps

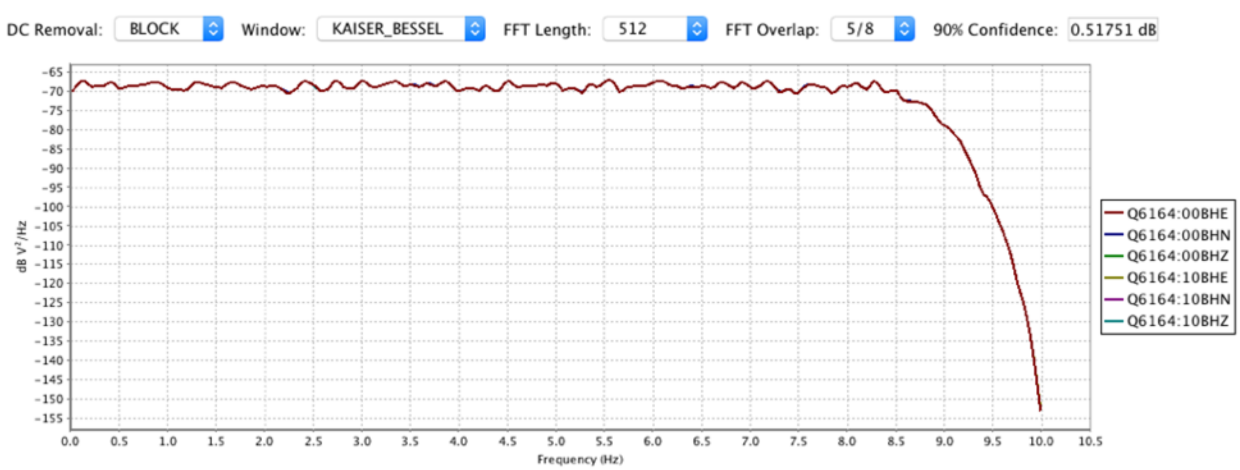

Figure 107 Analog Bandwidth Q330HR 6164, 20 sps

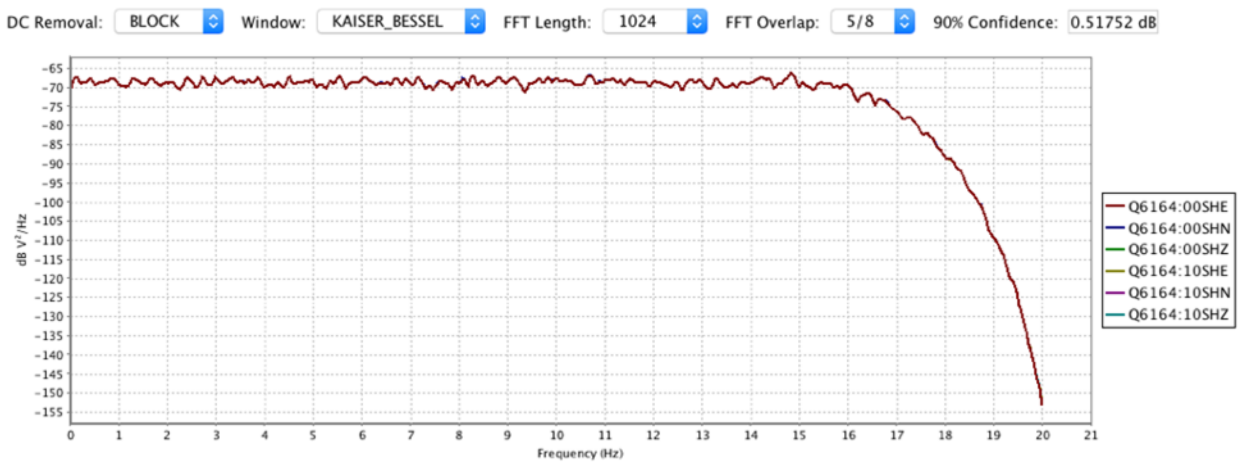

Figure 108 Analog Bandwidth Q330HR 6164, 40 sps

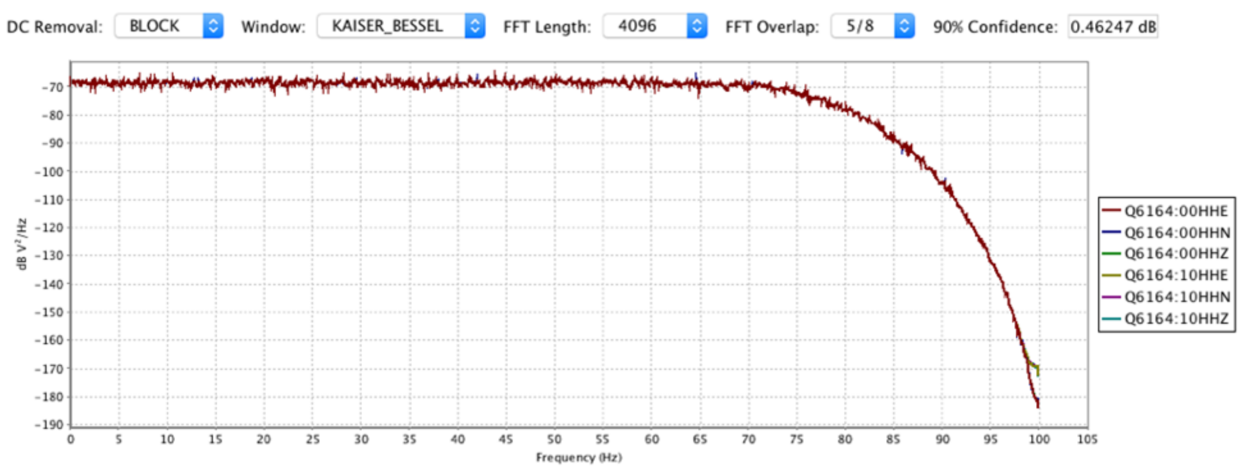

Figure 109 Analog Bandwidth Q330HR 6164, 200 sps

Table 43 Analog Bandwidth, Q330HR 6164, at Select Temperatures and Sample Rates

Temperature Sample Rate	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)	% Nyquist Freq.
60º C 100 sps	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	86.91%
20º C 100 sps	42.920 Hz	42.920 Hz	42.920 Hz	42.920 Hz	42.920 Hz	42.920 Hz	85.84%
-10º C 100 sps	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	86.01%
-20º C 100 sps	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	43.457 Hz	86.01%
20º C 10 sps	04.258 Hz	04.258 Hz	04.258 Hz	04.258 Hz	04.258 Hz	04.258 Hz	85.16%
20º C 20 sps	08.633 Hz	08.633 Hz	08.633 Hz	08.633 Hz	08.633 Hz	08.633 Hz	86.33%
20º C 40 sps	16.094 Hz	16.094 Hz	16.094 Hz	16.094 Hz	16.094 Hz	16.094 Hz	80.47%
20º C 200 sps	73.535 Hz	73.535 Hz	73.535 Hz	73.535 Hz	73.535 Hz	73.535 Hz	73.53%

The passband limits of datalogger 6164 are constant across all channels at all evaluated sample rates and temperatures at which observations were made. A relatively modest (< 1%) increase in pass-band limit, as expressed in percentage of the Nyquist, at 46º C compared to tests and the other temperratures tested. The lower corner frequency computed for the 200 sps data is also clearly evident in the nature of the roll-off at high frequencies. Across the range of sample rates and temperatures at which analog bandwidth was evaluated, the computed corner frequency varied no more than 13.48% of the respective Nyquist frequency; if one excludes the 200 sps evaluation, the remaining computer corner frequencies vary no more than 6.54% of their respective Nyquist frequency.

3.13 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.

3.13.1 Measurand

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

3.13.2 Configuration

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

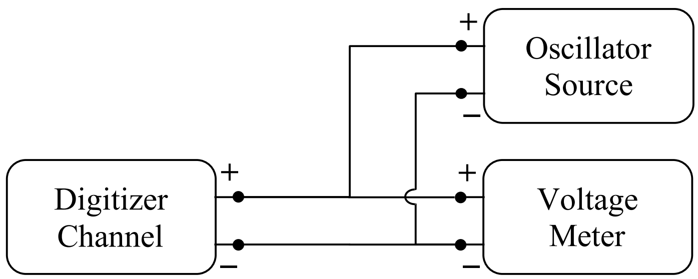

Figure 110 THD Configuration Diagram

Figure 111 Total Harmonic Distortion Configuration

Table 44 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Oscillator Source - Bunker	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	+5 V / -5 V
Voltage Meter – Bunker	Agilent 3458A	MY45048372	10 V full scale
Voltage Meter – Bunker #2	Agilent 3458A	MY45048371	10 V full scale
Oscillator Source – SB1	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010021 021204	+5 V / -5 V
Voltage Meter #1 - SB1	Agilent 3458A	2823A10915	10 V full scale
Voltage Meter – SB1 #2*	Agilent 3458A	MY45048372	10 V full scale

*Meter listed twice as it was moved after undergoing an annual calibration.

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 digital electronics containing a pulse-per-second timing.

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 sps, 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.

3.13.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a Kaiser-Bessel window varying in length from 4k to 16k window dependent upon on the sample rate of the data recorded. 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 ideally 0.5 db or below, though in practice the 90% confidence interval ranged between 0.56 dB and 0.62 dB; at the lowest sample rates the 90% confidence interval increases to has high as 1.27 dB (10 sps data).

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

Over frequencies (in Hertz):

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

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

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

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

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

3.13.4 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.

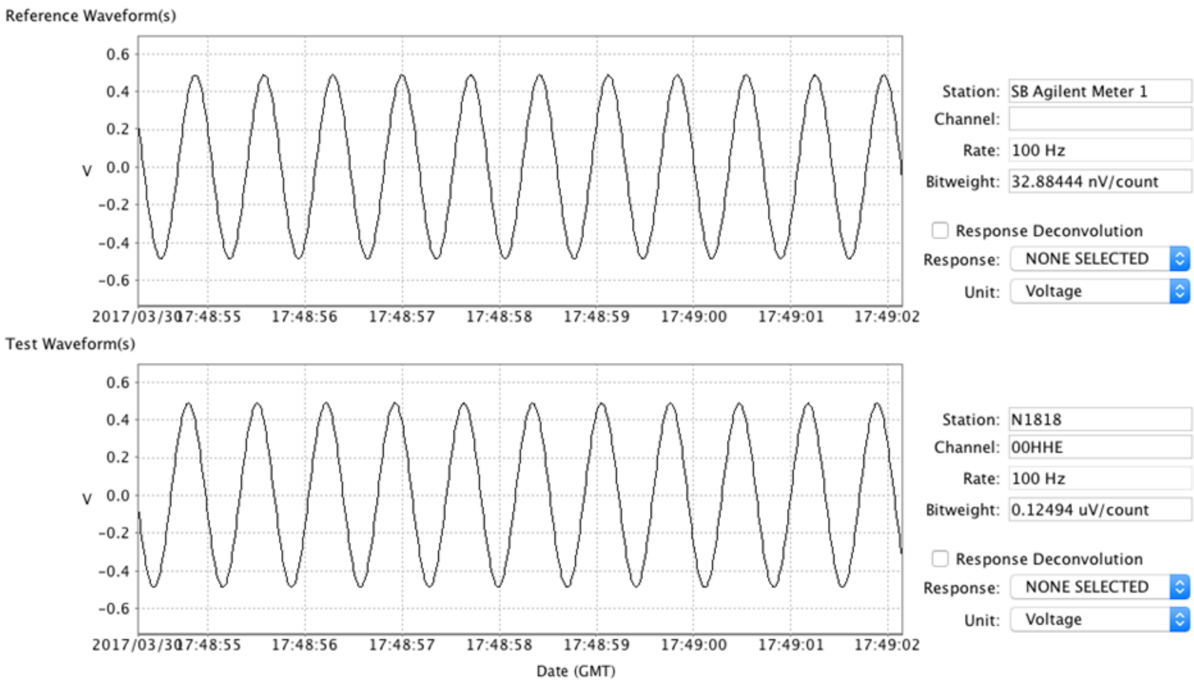

Figure 112 THD Time Series

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

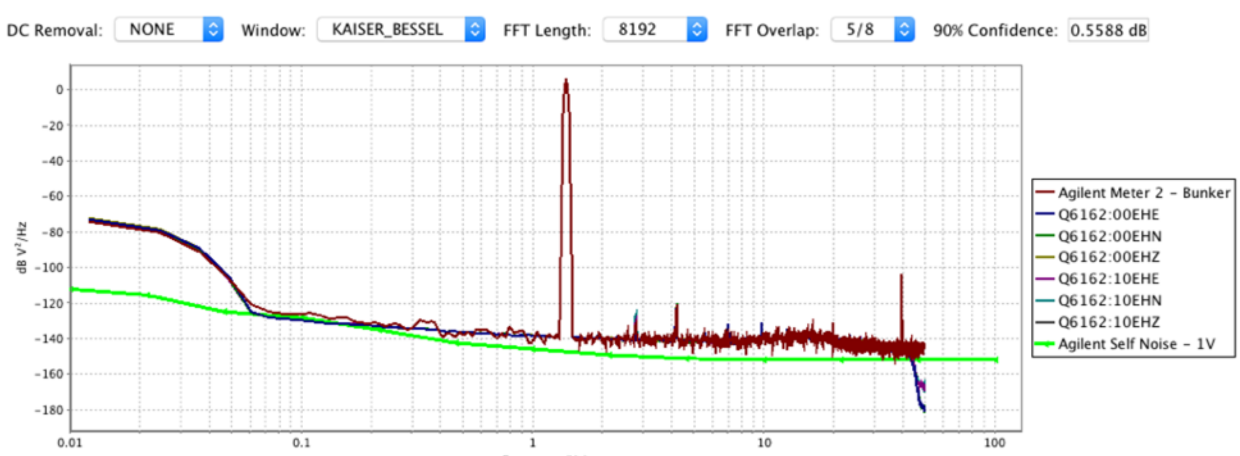

Figure 113 THD Power Spectra Q330HR 6162, 100 sps

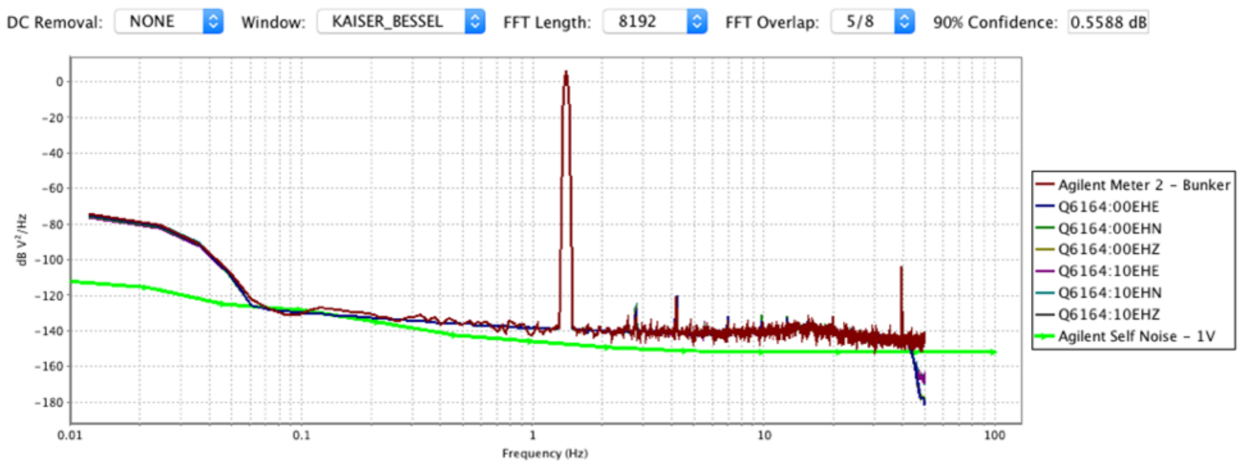

Figure 114 THD Power Spectra Q330HR 6164, 100 sps

Table 45 Total Harmonic Distortion, both Dataloggers, 23° C

DWR	Reference Meter	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
6162*	-126.17 dB	-124.29 dB	-124.37 dB	-124.32 dB	-124.21 dB	-123.76 dB	-124.40 dB
6164*	-125.94 dB	-124.18 dB	-124.22 dB	-123.99 dB	-124.29 dB	-123.85 dB	-124.28 dB

* Bunker meter #2 utilized for these measurements.

In all cases, the reference measurement of the signal generated by the low distortion oscillator exceeded the measurement made on the digitizer channel indicating that the distortion observed is due to the digitizer. The observed harmonic distortion ranged between -123.76 db (24 bit) and -124.37 dB (26 bit).

The figures below show the power spectra of the THD for Q330HR 6164 across a range of temperatures.

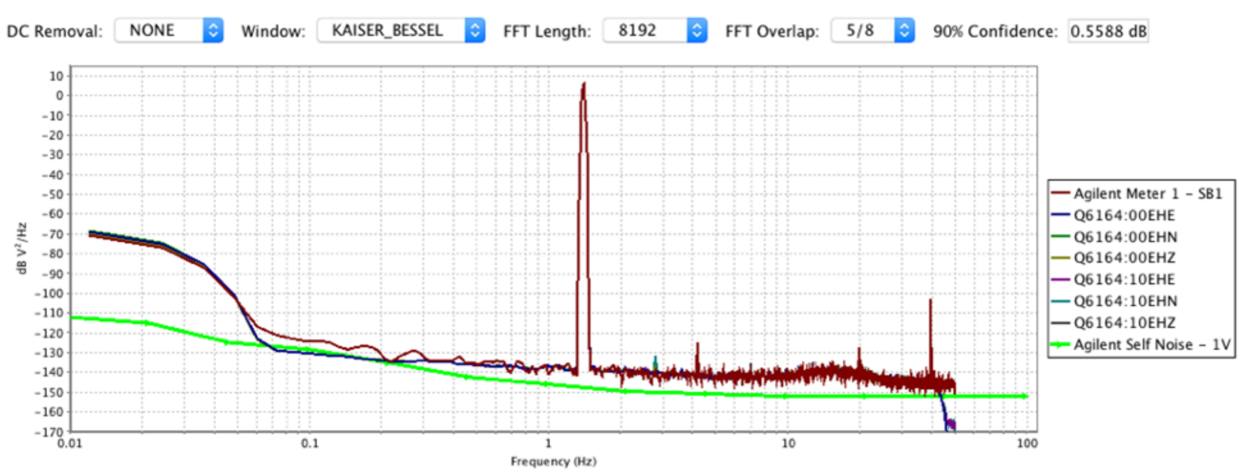

Figure 115 THD Power Spectra Q330HR 6164, 46° C

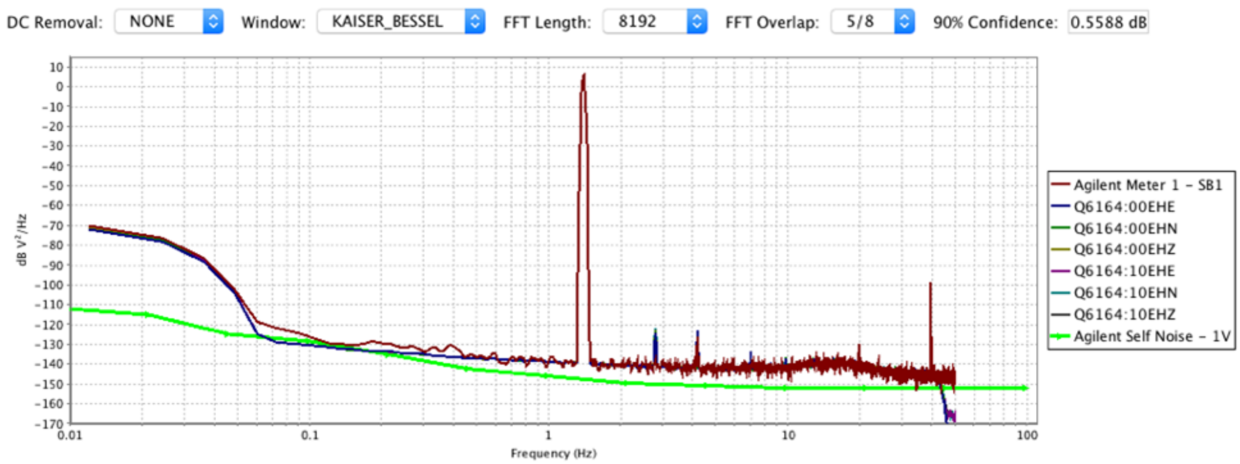

Figure 116 THD Power Spectra Q330HR 6164, 20° C

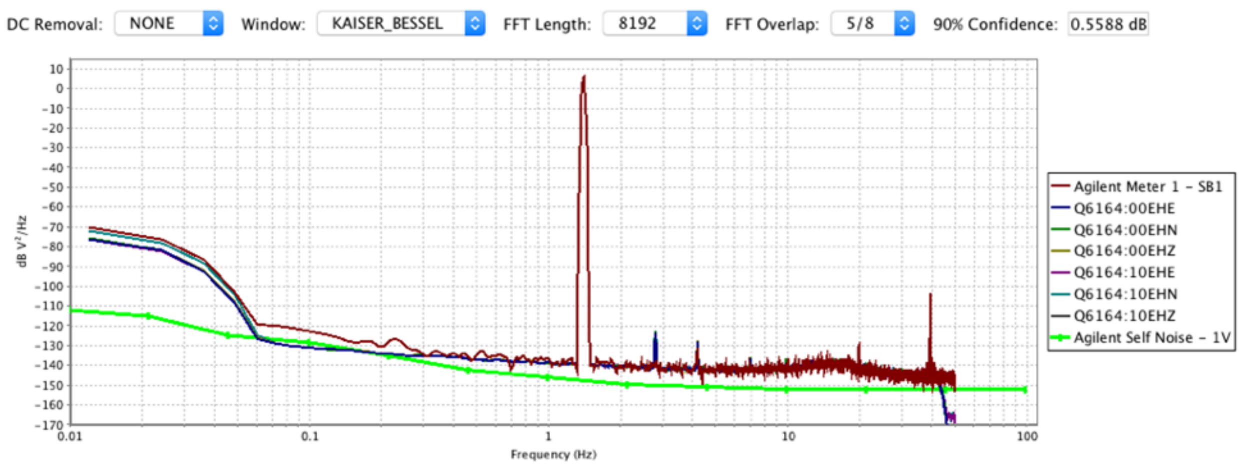

Figure 117 THD Power Spectra Q330HR 6164, -10° C

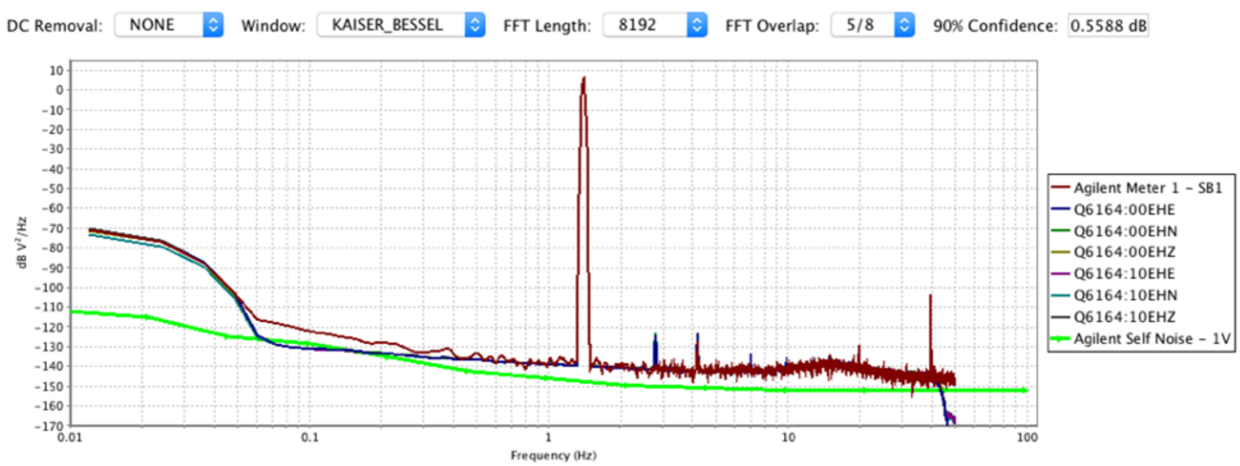

Figure 118 THD Power Spectra Q330HR 6164, -20° C

Table 46 Total Harmonic Distortion at Select Temperatures

Temp	Reference Meter	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
46° C*	-130.17 dB	-129.17 dB	-129.56 dB	-129.16 dB	-130.00 dB	-128.74 dB	-130.48 dB
20° C*	-131.20 dB	-125.04 dB	-125.11 dB	-124.78 dB	-125.49 dB	-124.28 dB	-125.18 dB
-10° C	-132.70 dB	-126.47 dB	-126.25 dB	-126.61 dB	-127.08 dB	-125.81 dB	-126.27 dB
-20° C	-132.69 dB	-125.52 dB	-125.18 dB	-125.69 dB	-125.80 dB	-125.06 dB	-125.10 dB

*SB1 meter #2 utilized for these measurements.

Total Harmonic Distortion varies, generally rising as temperature decreased. Channel 3 (00 EHZ) had the most stable THD calculated over over varying temperatures, where THD only varied at a maximum of 3.20% at 46° C from the best THD calculated on channel 3, -129.17 dB. The least stable THD calculated occurred on channel 6 (00HHE) where at 46° C THD where it differed from best THD on channel 6 of -130.00 dB by 3.47%. The best THD calculated, -130.48 dB occurred on channel 4 (10EHZ) at a temperature of 46° C. Over all temperatures, the maximum THD variation across channels of 1.34% occurred during the 46° C test on the 24 bit channels (4-6).

The figures below show the power spectra of the THD for Q330HR 6164 across a range of sample rates.

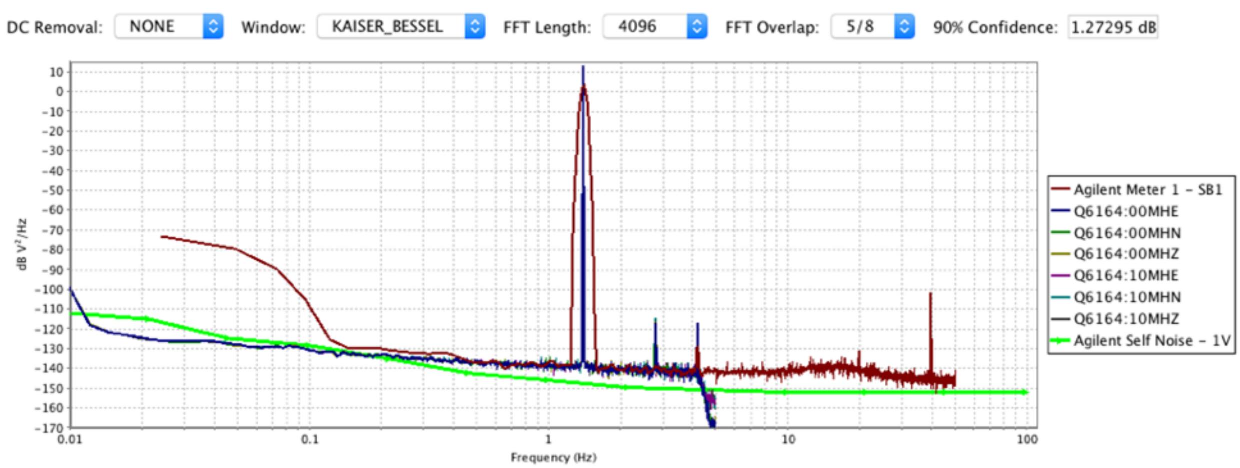

Figure 119 THD Power Spectra Q330HR 6164, 10 sps

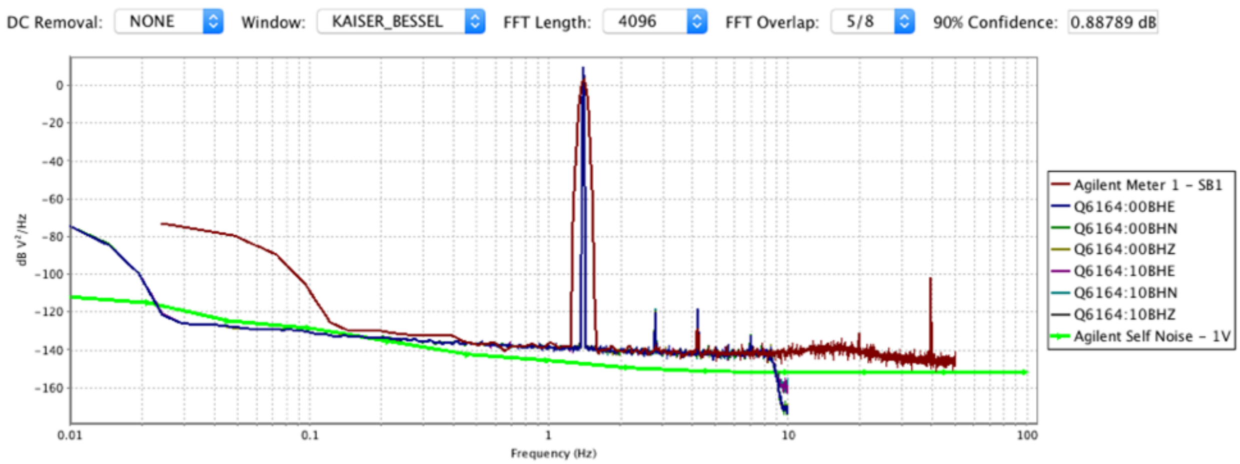

Figure 120 THD Power Spectra Q330HR 6164, 20 sps

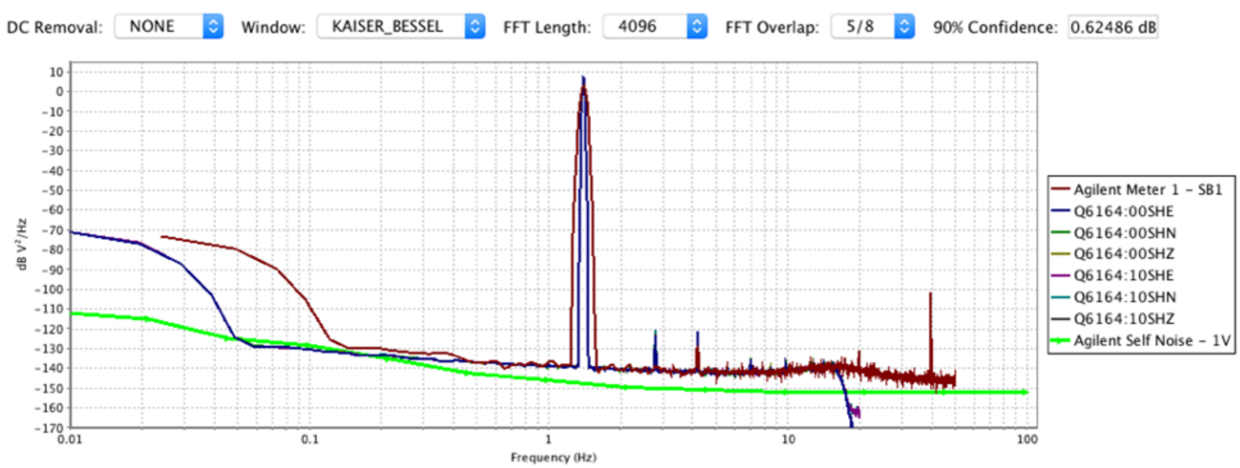

Figure 121 THD Power Spectra Q330HR 6164, 40 sps

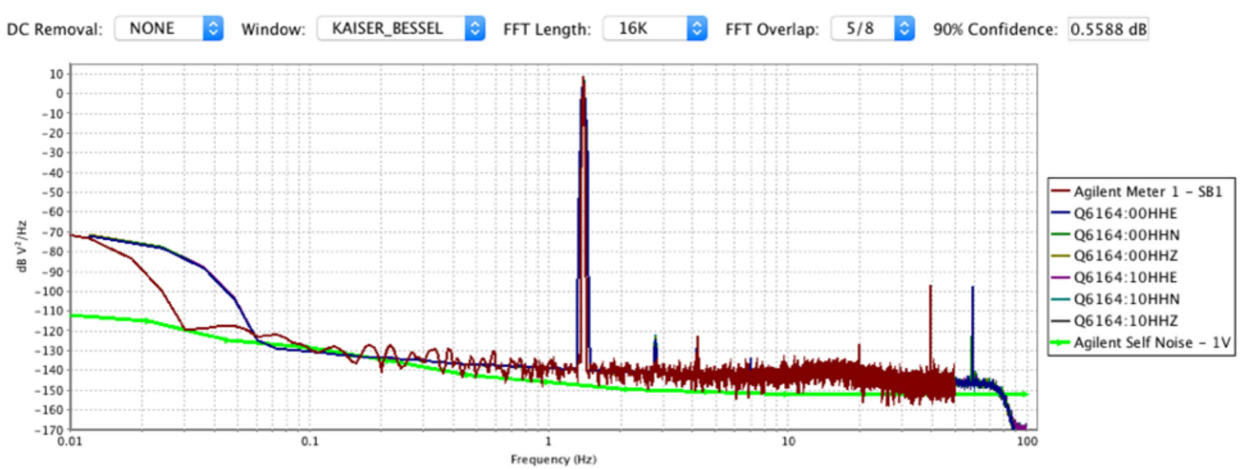

Figure 122 THD Power Spectra Q330HR 6164, 200 sps

Table 47 Total Harmonic Distortion at Select Sample Rates

Sample Rate	Reference Meter	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
10 sps*	-131.18 dB	-127.06 dB	-127.09 dB	-126.68 dB	-127.57 dB	-125.83 dB	-126.92 dB
20 sps*	-131.18 dB	-126.09 dB	-126.18 dB	-125.80 dB	-126.57 dB	-125.17 dB	-126.08 dB
40 sps*	-131.18 dB	-125.40 dB	-125.29 dB	-125.09 dB	-125.83 dB	-124.56 dB	-125.32 dB
100 sps*	-131.20 dB	-125.04 dB	-125.11 dB	-124.78 dB	-125.49 dB	-124.28 dB	-125.18 dB
200 sps*	-131.42 dB	-125.01 dB	-125.10 dB	-124.78 dB	-125.48 dB	-124.30 dB	-125.11 dB

Total Harmonic Distortion varies several dB both across channels at all sample rates and across sample rates for any channel. The lowest THD of -127.57 dB was computed on Channel 6 (10EHE) 10 sps data. Channel 5 (00EHN) varied the least from its best THD of -125.83 db by only 1.23%. The largest varying THD occurred on Channel 6 (00 EHZ), where it varied as much as 1.65% its best THD of -126.57 dB (excluding the 10 sps measurement due to the limited number of harmonics available).

THD over all test conditions ranged from -124.28 dB, at 20° C to -130.48 db, at 46° C.

3.14 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.

3.14.1 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.

3.14.2 Configuration

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

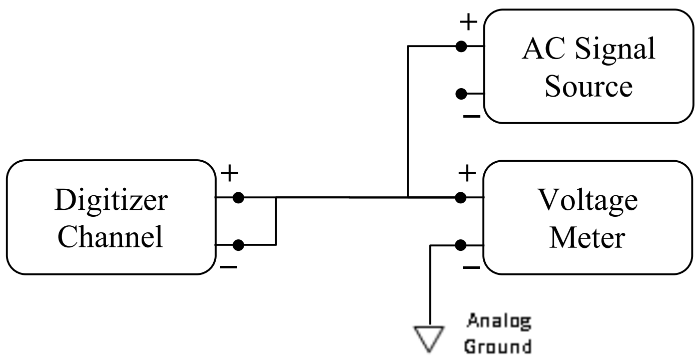

Figure 123 Common Mode Rejection Configuration Diagram

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 124 Common Mode Rejection Configuration

Table 48 Common Mode Rejection Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - Bunker	Agilent 3458A	MY45048372	1 V full scale
DC Signal Source - SB1	Stanford Research Systems DS360	123669	+1V / - 1 V
Voltage Meter - SB1	Agilent 3458A	2823A10915	1 V full scale
Voltage Meter – Bunker #2	Agilent 3458A	MY45048371	+1V / - 1 V
Voltage Meter – SB1 #2*	Agilent 3458A	MY45048372	+1V / - 1 V

*Meter listed twice as it was moved after undergoing an annual calibration.

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. 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 sps, 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.

3.14.3 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 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:

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

3.14.4 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.

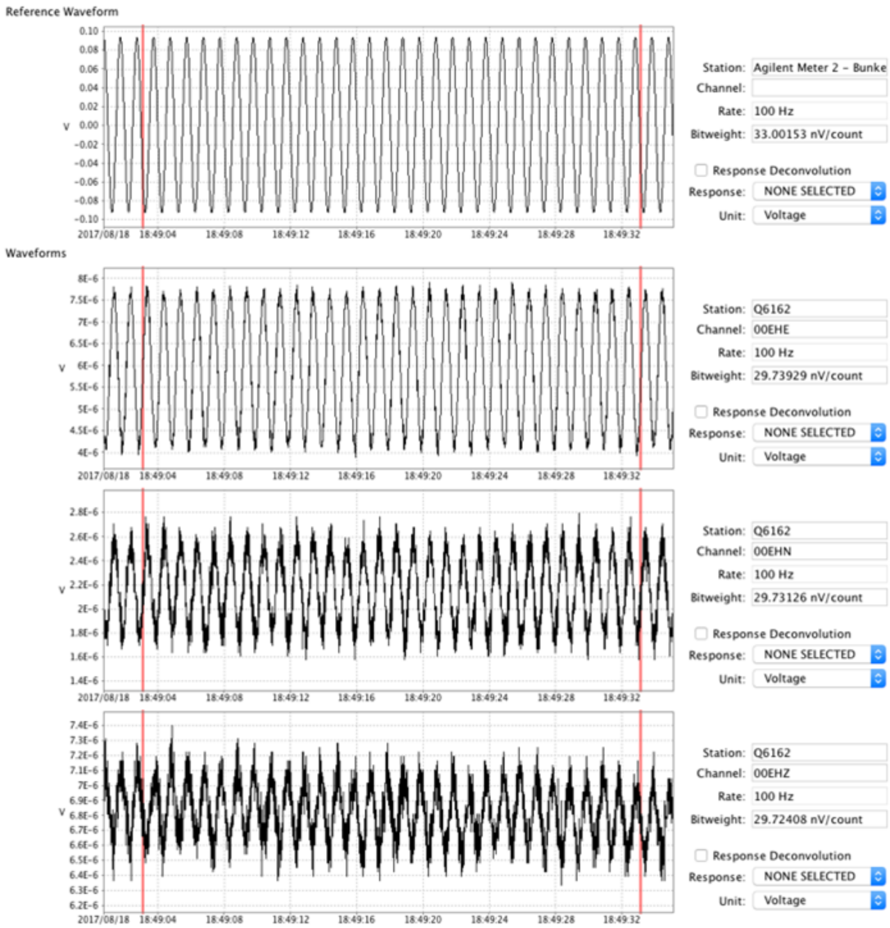

Figure 125 Common Mode Rejection Time Series

The following table contains the computed common mode rejection ratio.

Table 49 Common Mode Rejection Ratio, both Dataloggers, 23° C

DWR		00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
6162*	Amplitude	1.762 uV	0.3789 uV	0.2286 uV	0.7440 uV	1.074 uV	1.177 uV
	Rejection Gain	94.41 dB	107.76 dB	112.15 dB	101.90 dB	98.72 dB	97.92 dB
6164*	Amplitude	0.5840 uV	1.176 uV	1.502 uV	0.9563 uV	0.04606 uV	3.716 uV
	Rejection Gain	104.01 dB	97.93 dB	95.80 dB	99.72 dB	126.07 dB	87.93 dB

* Bunker meter #2 utilized for these measurements.

The observed common mode rejection of both dataloggers at 23° C ranged from 94 dB to 126 dB.

Table 50 Common Mode Rejection: 6164, at Select Temperatures and Sample Rates

Temp., Rate		00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
46° C* 100 sps	Amplitude	0.6475 uV	2.940 uV	1.505 uV	1.166 uV	0.09862 uV	3.960 uV
	Rejection Gain	103.52 dB	90.38 dB	96.19 dB	98.41 dB	119.86 dB	87.79 dB
20° C 100 sps	Amplitude	0.5947 uV	0.3349 uV	1.467 uV	0.7891 uV	0.04314 uV	4.121 uV
	Rejection Gain	104.26 dB	109.25 dB	96.42 dB	101.80 dB	127.05 dB	87.44 dB
-10° C, 100 sps	Amplitude	0.2435 uV	0.1948 uV	0.2541 uV	0.005021 uV	0.1308 uV	0.9186 uV
	Rejection Gain	100.29 dB	102.22 dB	99.92 dB	134.00 dB	105.68 dB	88.75 dB
-20° C, 100 sps	Amplitude	0.6565 uV	21.00 uV	0.7222 uV	0.04661 uV	0.3696 uV	2.2153 uV
	Rejection Gain	101.11 dB	71.01 dB	100.28 dB	124.09 dB	106.10 dB	90.55 dB
20° C, 10 sps	Amplitude	0.5989 uV	0.3369 uV	1.476 uV	0.7891 uV	0.04182 uV	4.142 uV
	Rejection Gain	104.20 dB	109.19 dB	96.36 dB	101.80 dB	127.32 dB	87.40 dB
20° C, 20 sps	Amplitude	0.5981 uV	0.3367 uV	1.476 uV	0.7916 uV	0.04324 uV	4.141 uV
	Rejection Gain	104.21 dB	109.20 dB	96.37 dB	101.77 dB	127.03 dB	87.40 dB
20° C, 40 sps	Amplitude	0.5979 uV	0.3364 uV	1.475 uV	0.7919 uV	0.04240 uV	4.141 uV
	Rejection Gain	104.21 dB	109.21 dB	96.37 dB	101.77 dB	127.20 dB	87.40 dB
20° C* 200 sps	Amplitude	0.5943 uV	0.3346 uV	1.466 uV	0.7874 uV	0.04315 uV	4.1173 uV
	Rejection Gain	104.26 dB	109.25 dB	96.42 dB	101.82 dB	127.04 dB	87.45 dB

* SB1 meter #2 utilized for these measurements

Across sample rates evaluated, the observed common mode rejection was between 71 db and 134 dB. Over variations in sample rate, channel 5 (10 HHN) consistently had the highest rejection gain. Over temperatures and sample rates channel 4 (10 EHZ) the lowest rejection gain, except at -20° C, where channel 2 (00EHN) had the lowest rejection gain.

3.15 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.

3.15.1 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.

3.15.2 Configuration

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

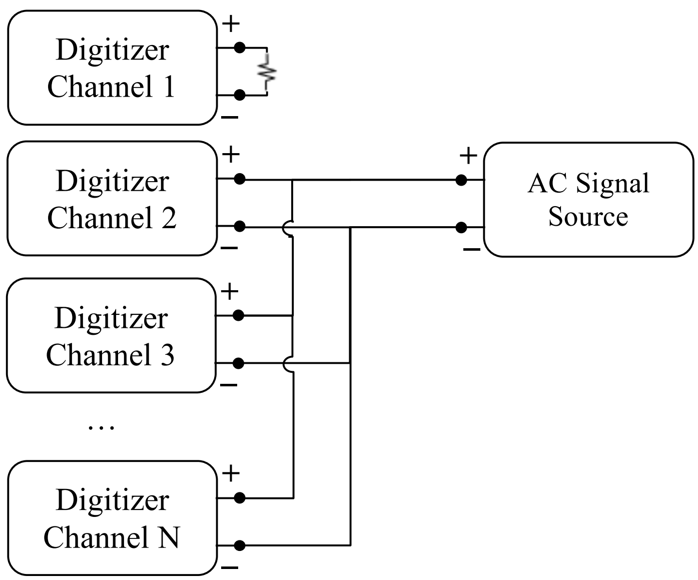

Figure 126 Crosstalk Configuration Diagram

Figure 127 Crosstalk Configuration

Table 51 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
AC Signal Source SB1	Stanford Research Systems DS360	123669	+1V / - 1 V

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 1.2 minutes of data are recorded.

3.15.3 Analysis

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

$$x[n]$$

The PSD is computed from the time series (Merchant, 2011) from the time series using a 2k-sample Hann window and 5/8 overlap of the input terminated channel and all of the tonal channels:

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

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

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

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

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

3.15.4 Result

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

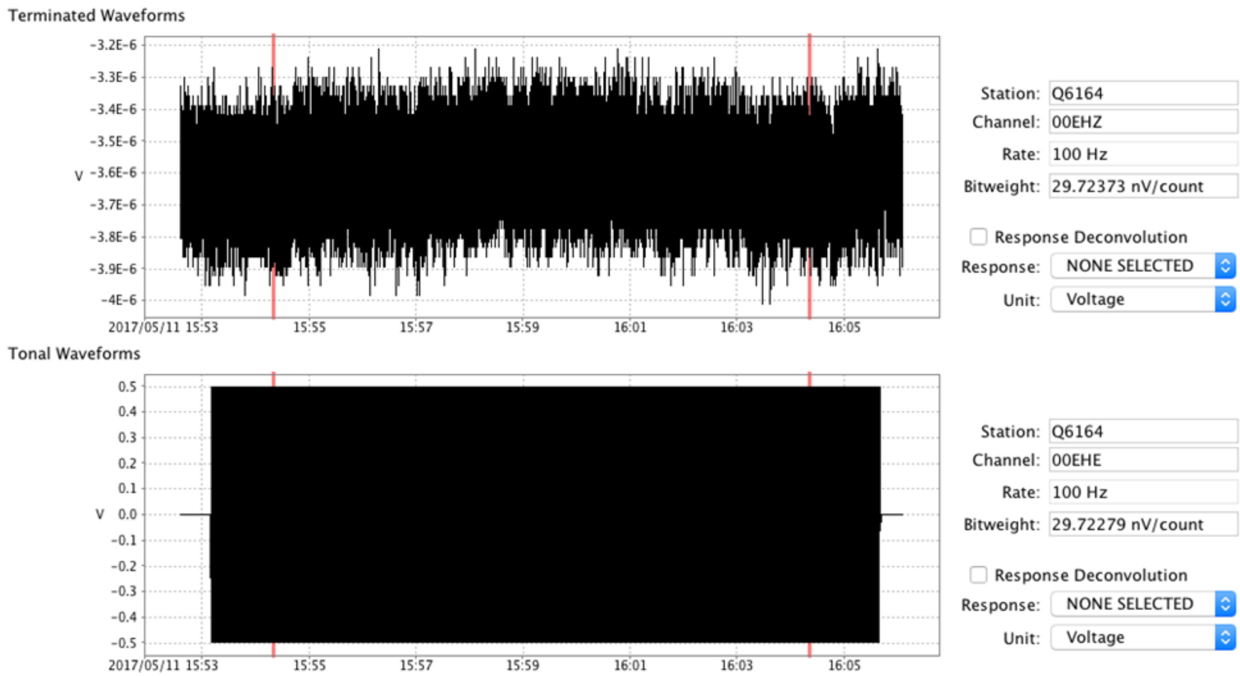

Figure 128 Crosstalk Time Series Example, Q330HR 6164

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.

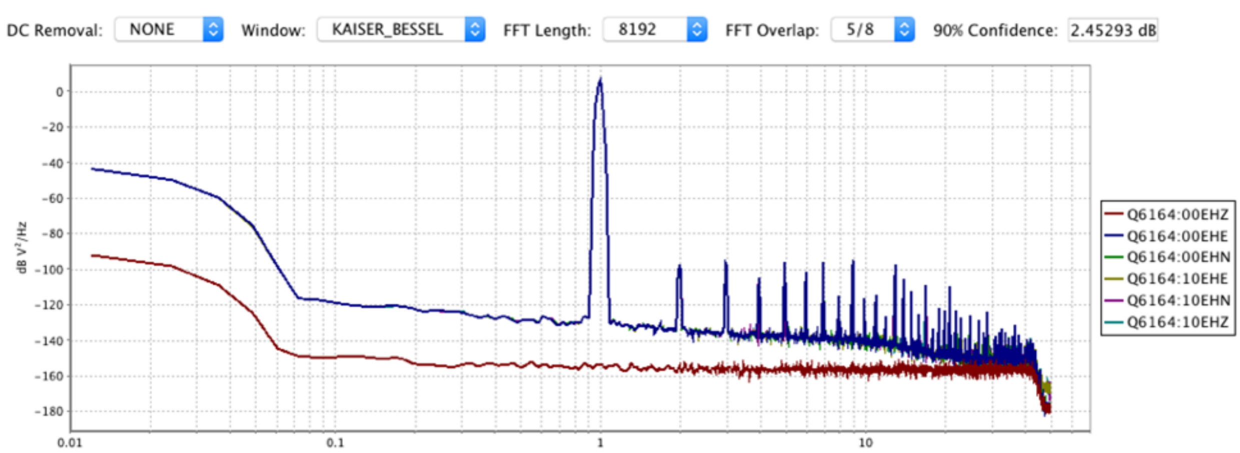

Figure 129 Crosstalk Power Spectra

The following table contains the computed crosstalk ratios for all digitizers measured in the bunker at 23 C. Notice the lack of an observable peak in the terminated channel's power spectra.

Table 52 Crosstalk, both Dataloggers, 100 sps, 23 C

DWR	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
6162	-157.21 dB	-157.69 dB	-156.45 dB	-152.81 dB	-155.40 dB	-156.45 dB
6164	-156.33 dB	-156.27 dB	-153.65 dB	-155.74 dB	-156.51 dB	-155.41 dB

No peak is observable in the terminated channel's power spectra (e.g. Figure 129 Crosstalk Power Spectra), therefore the values represent the maximum possible observable crosstalk. The maximum possible observable levels of crosstalk were all between -152.81 and -157.69 dB

The following table contains the computed crosstalk ratios for 6164 measured at select temperatures.

Table 53 Crosstalk, Datalogger 6164 at Select Temperatures

Temp.	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
46° C	-158.38 dB	-156.78 dB	-158.03 dB	-158.76 dB	-157.59 dB	-158.30 dB
20° C	-154.63 dB	-153.80 dB	-154.16 dB	-153.25 dB	-154.68 dB	-154.03 dB
-10° C	-160.11 dB	-154.55 dB	-158.60 dB	-159.38 dB	-159.76 dB	-158.90 dB
-20° C	-160.09 dB	-154.62 dB	-158.67 dB	-159.46 dB	-159.87 dB	-160.05 dB

No peak is observable in the terminated channel's power spectra, therefore the values represent the maximum possible observable cosstalk. The maximum possible observable levels of crosstalk calculated over the temperatures selected for evaluation varied from as little as -153.25 dB as -160.11 dB. Crosstalk generally reaches a minimum at -20° C, the lowest temperature for the datalogger was evaluated, except in the case of channel 3 (00 HHE) where the minimum crosstalk occurred at -10° C.

The following table contains the computed crosstalk ratios for 6164 measured across sample rate.

Table 54 Crosstalk, Datalogger 6164 at Select Sample Rates, 100 sps

Sample Rate	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
10 sps	-155.54 dB	-153.86 dB	-154.54 dB	-151.61 dB	-153.53 dB	-153.21 dB
20 sps	-155.83 dB	-153.57 dB	-154.05 dB	-153.05 dB	-154.77 dB	-153.43 dB
40 sps	-155.99 dB	-153.93 dB	-154.70 dB	-153.27 dB	-157.16 dB	-154.85 dB
100 sps	-154.63 dB	-153.80 dB	-154.16 dB	-153.25 dB	-154.68 dB	-154.03 dB
200 sps	-154.55 dB	-153.78 dB	-154.17 dB	-154.05 dB	-154.46 dB	-153.67 dB

No peak is observable in the terminated channel's power spectra, therefore the values represent the maximum possible observable crosstalk. No correlations are present between maximum possible observable crosstalk and changes in sample rates or temperatures; values range from -151.6 dB to as much as -160.09 dB.

3.16 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.

3.16.1 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.

3.16.2 Configuration

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

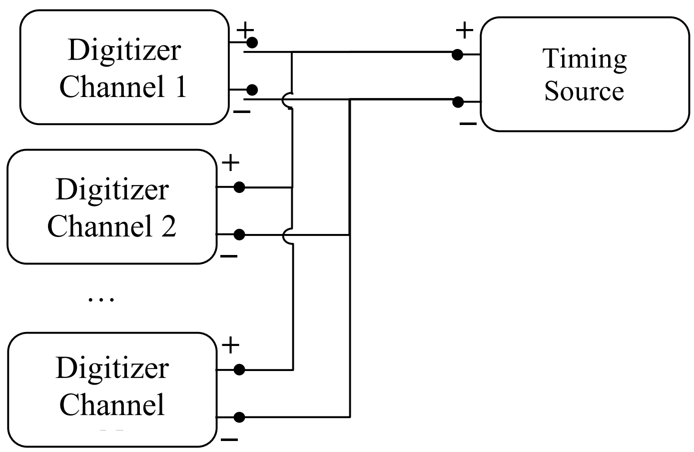

Figure 130 Time Tag Configuration Diagram

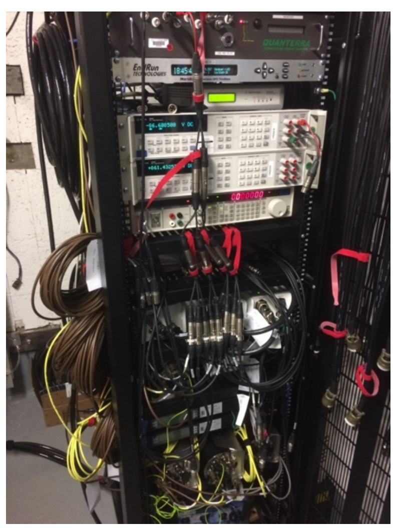

Figure 131 Time Tag Configuration Picture

Table 55 Time Tag Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
SB1	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010021 021204	GPS PPM Output
Bunker	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	GPS PPM Output

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

3.16.3 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.

3.16.4 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.

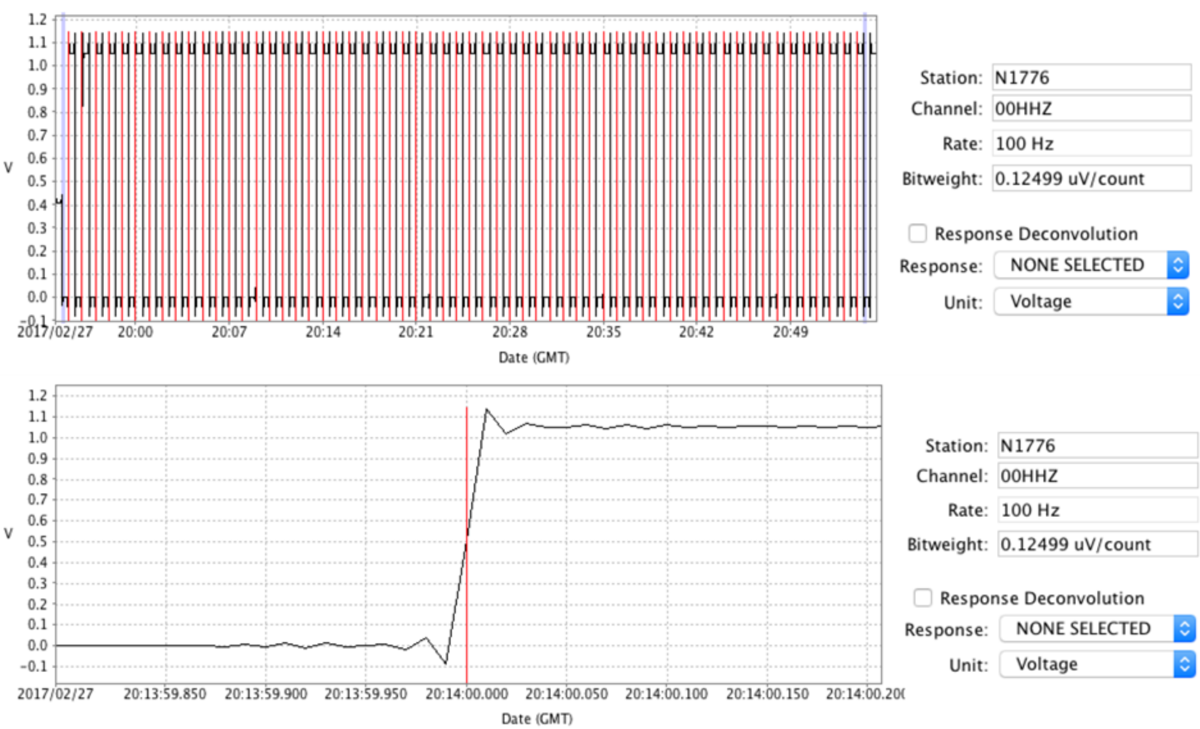

Figure 132 Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets.

Table 56 Time Tag Accuracy, Both Q330HRs, 23° C

DWR	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
6162	4449.51 us	4448.97 us	4449.14 us	4448.90 us	4449.06 us	4449.16 us
6164	4448.93 us	4448.77 us	4448.75 us	4449.03 us	4448.82 us	4449.24 us

Table 57 Time Tag Accuracy, Q330HR 6164, 100 sps, Select Temperatures

Temp.	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
46° C	4330.78 us	4330.95 us	4330.77 us	4331.35 us	4331.24 us	4331.72 us
20° C	4326.51 us	4326.59 us	4326.29 us	4326.96 us	4326.73 us	4327.15 us
-10° C	4320.29 us	4320.26 us	4320.06 us	4320.70 us	4320.47 us	4320.85 us
-20° C	4318.11 us	4318.03 us	4317.92 us	4318.52 us	4318.30 us	4318.67 us

Table 58 Time Tag Accuracy, Q330HR 6164, 100 sps, Select Sample Rates

Sample Rate	00HHE (chan 3)	00HHN (chan 2)	00HHZ (chan 1)	10HHE (chan 6)	10HHN (chan 5)	10HHZ (chan 4)
10 sps	30650.45 us	30650.55 us	30650.24 us	30650.95 us	30650.71 us	30651.16 us
20 sps	-19347.22 us	-19347.08 us	-19347.43 us	-19346.71 us	-19346.94 us	-19346.51 us
40 sps	5685.34 us	5685.45 us	5685.12 us	5686.08 us	5685.62 us	5686.27 us
100 sps	4326.51 us	4326.59 us	4326.29 us	4326.96 us	4326.73 us	4327.15 us
200 sps	1997.87 us	1997.93 us	1997.66 us	1998.28 us	1998.04 us	**3.45 s**

As is obvious in the preceding tables regarding Time Tag Accuracy, the measured errors are significantly large and are suspect.

Over the selected temperatures over which the Q330HRs were evaluated it is interesting to note in the suspect timing offsets listed in Table 57 the offsets decrease with temperature, on the order of 12 us to 13 us from over the evaluation from 46° C to -20° C

3.46 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.

3.46.1 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.

3.46.2 Configuration

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

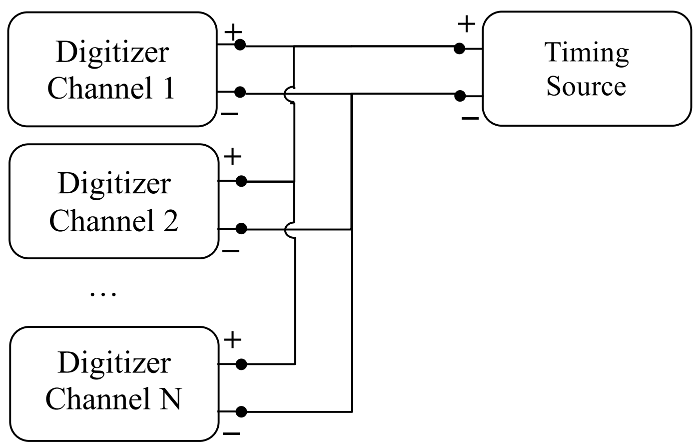

Figure 133 Timing Drift Configuration Diagram

Table 59 Timing Drift Testbed Equipment

Location	Manufacturer / Model	Serial Number	Nominal Configuration
SB1	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010021 021204	GPS PPM Output
Bunker	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	GPS PPM Output

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

The digitizer clock is allowed to stabilize before the GPS antenna is disconnected resulting in the digitizer to lose timing lock. The digitizer is allowed to drift before it is re-connected to the GPS antenna and allowed to regain its timing lock.

3.46.3 Analysis

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

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

3.46.4 Result

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

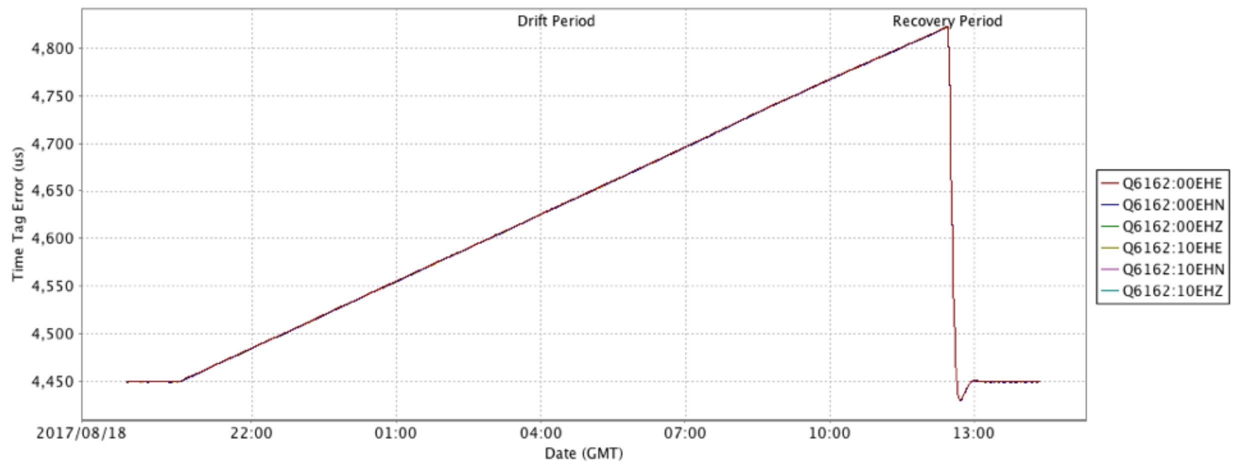

Figure 134 Time Tag Drift, Q330HR 6162, 23° C

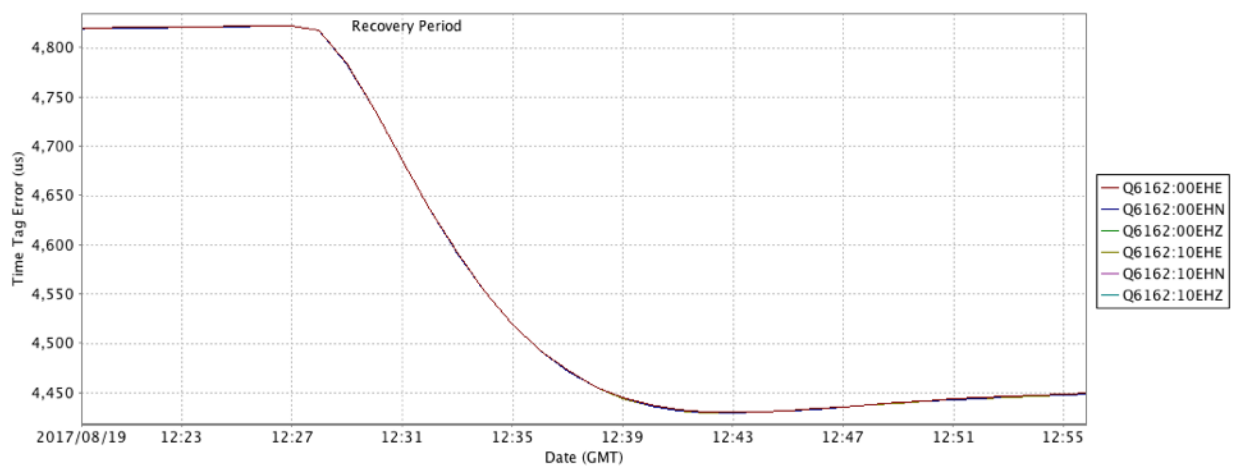

Figure 135 Time Tag Recovery Q330HR 6162, 23° C

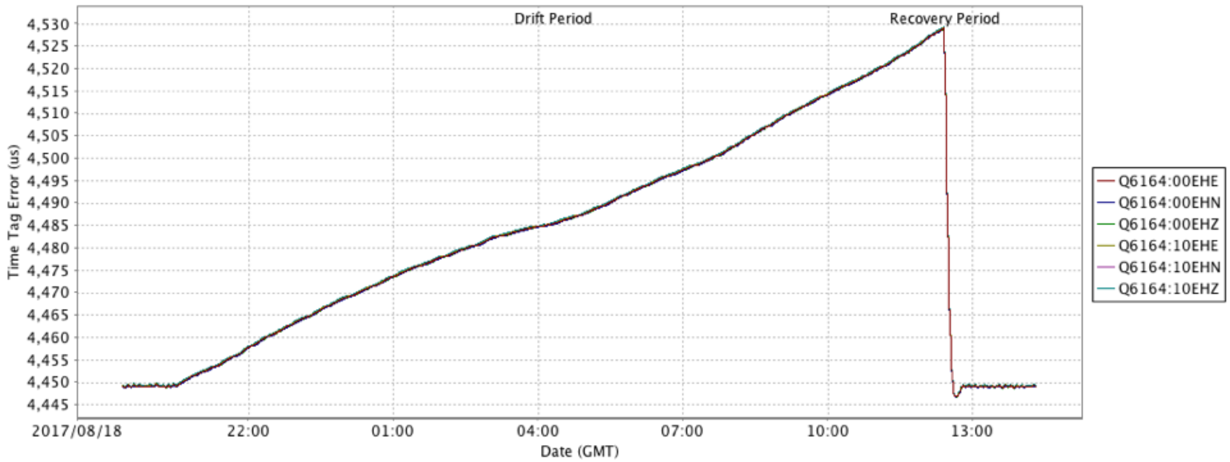

Figure 136 Time Tag Drift, Q330HR 6164, 23° C

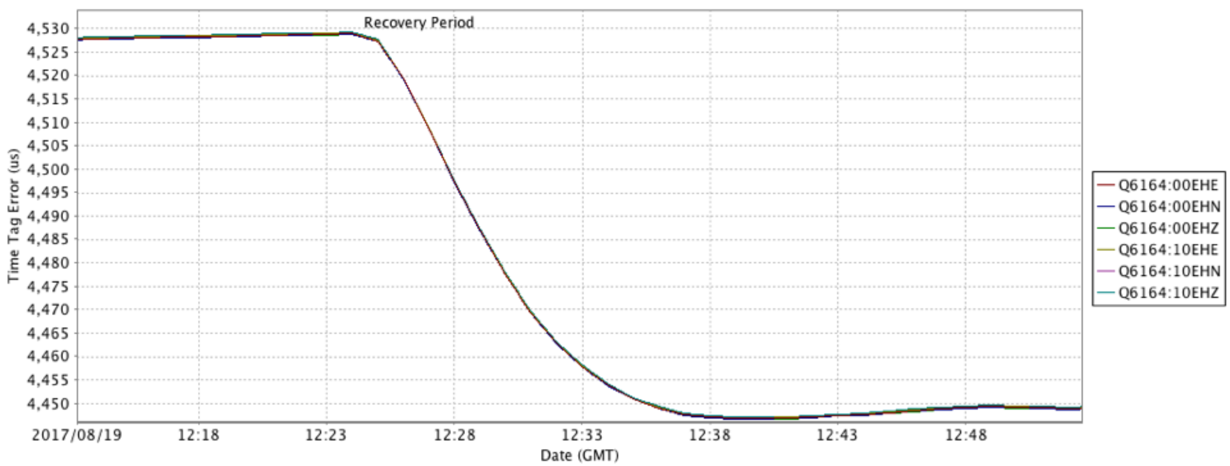

Figure 137 Time Tag Recovery, Q330HR 6164, 23° C

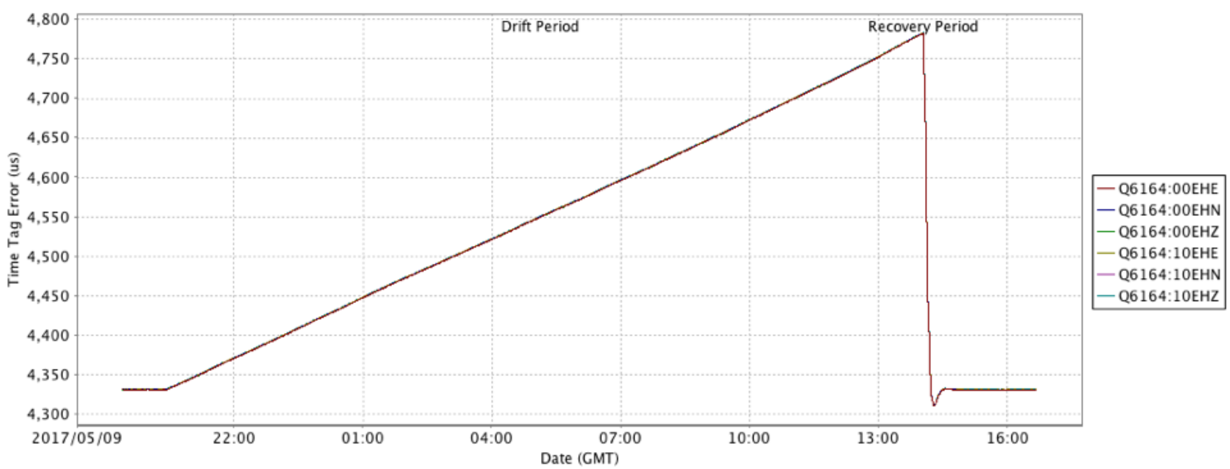

Figure 138 Time Tag Drift, Q330HR 6164, 46° C

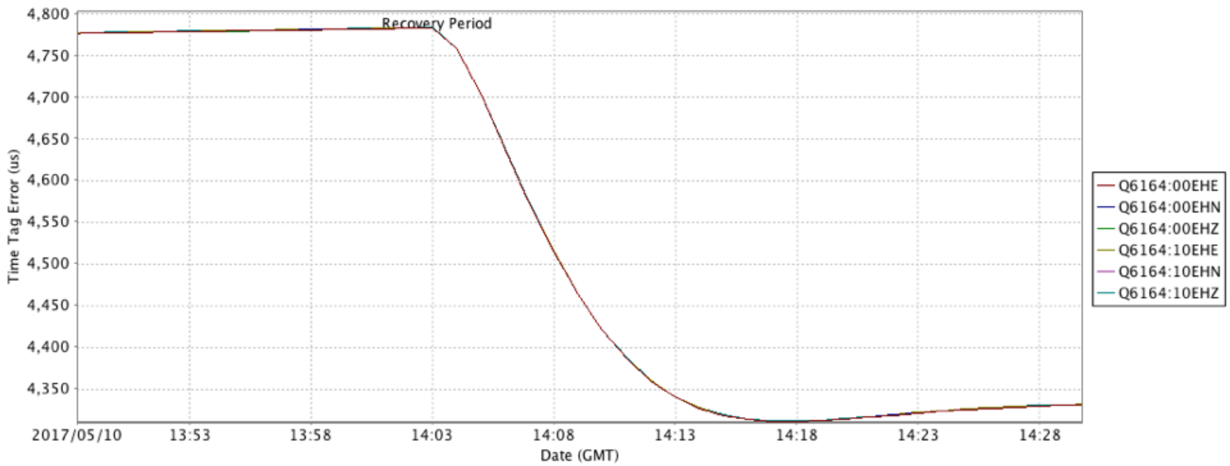

Figure 139 Time Tag Recovery, Q330HR 6164, 46° C

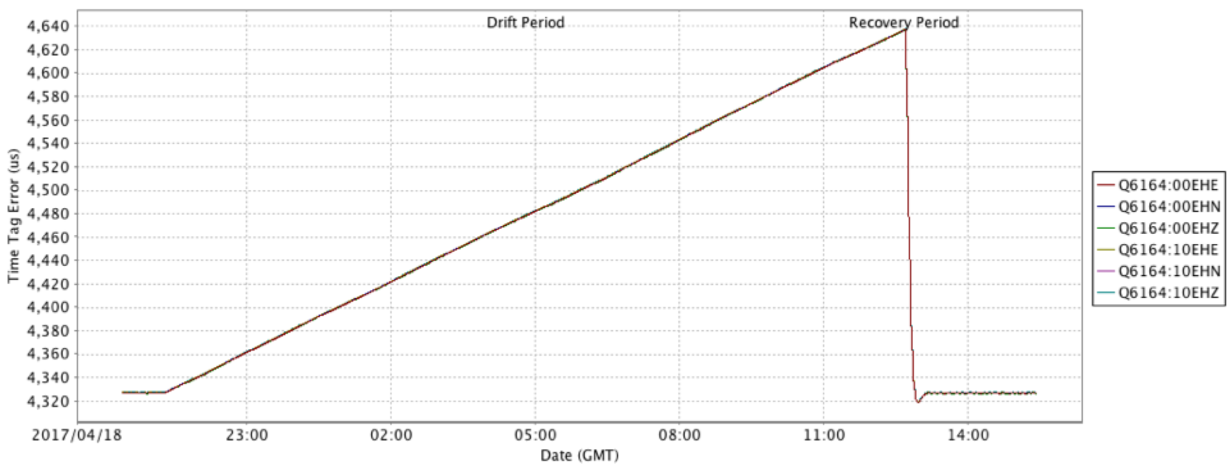

Figure 140 Time Tag Drift, Q330HR 6164, 20° C

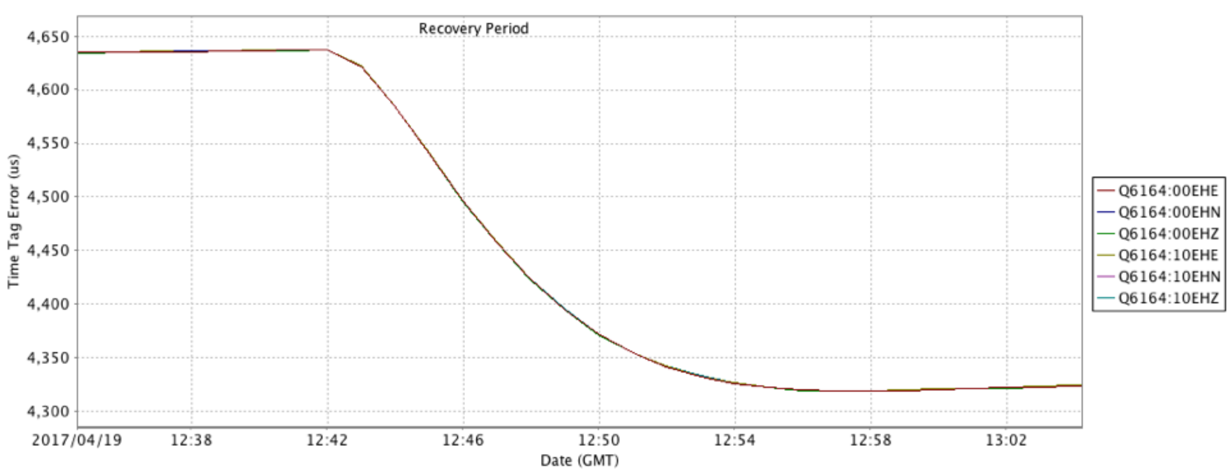

Figure 141 Time Tag Recovery, Q330HR 6164, 20° C

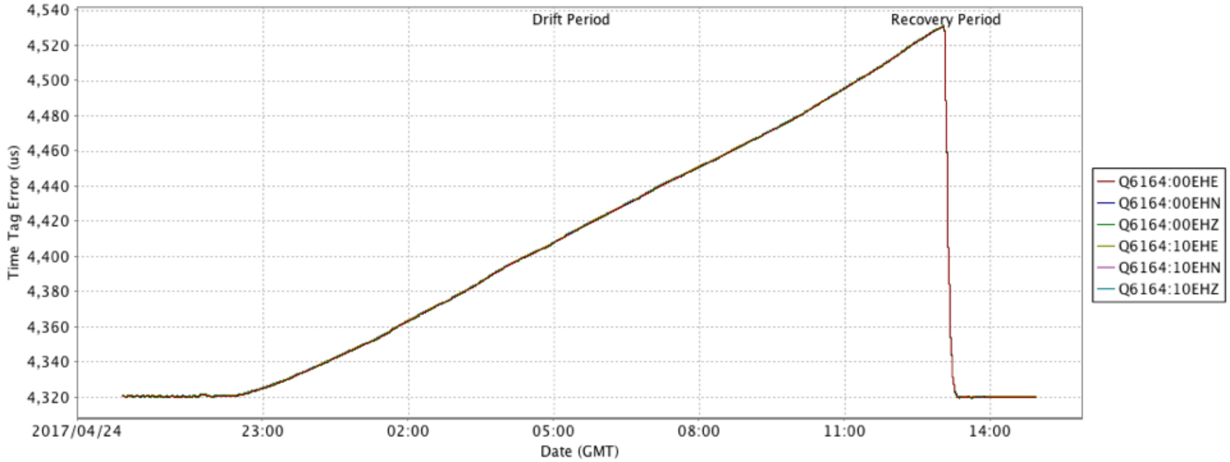

Figure 142 Time Tag Drift, Q330HR 6164, -10° C

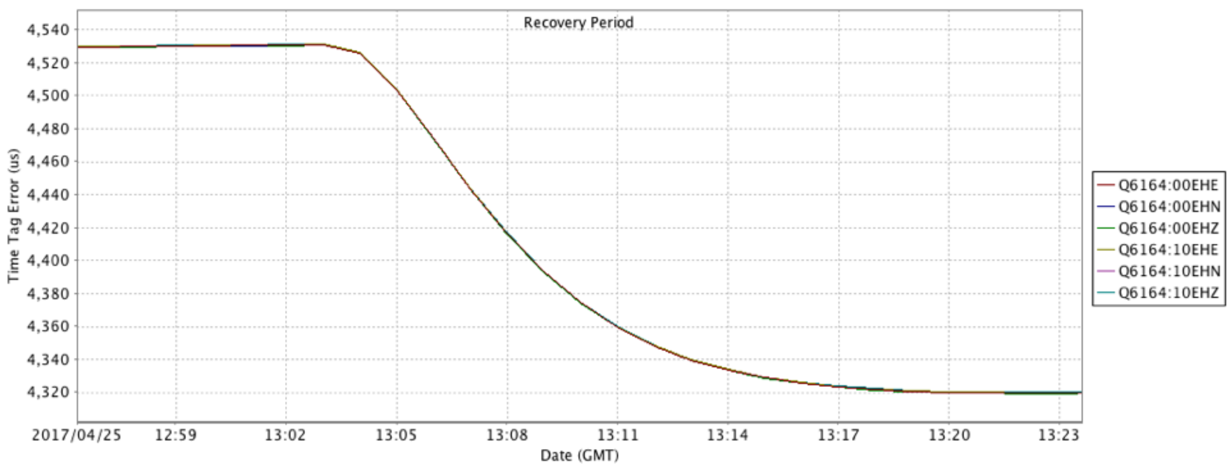

Figure 143 Time Tag Recovery, Q330HR 6164, -10° C

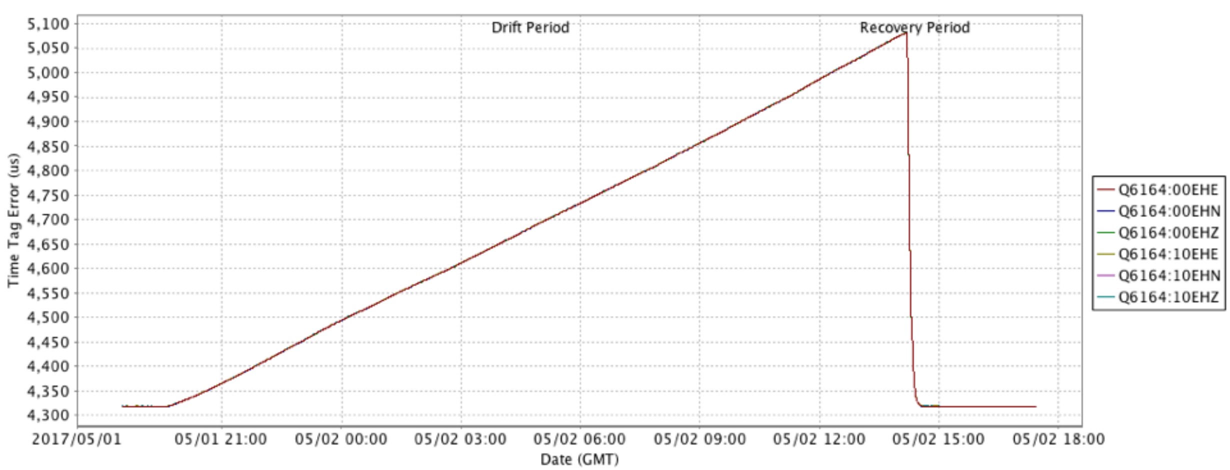

Figure 144 Time Tag Drift, Q330HR 6164, -20° C

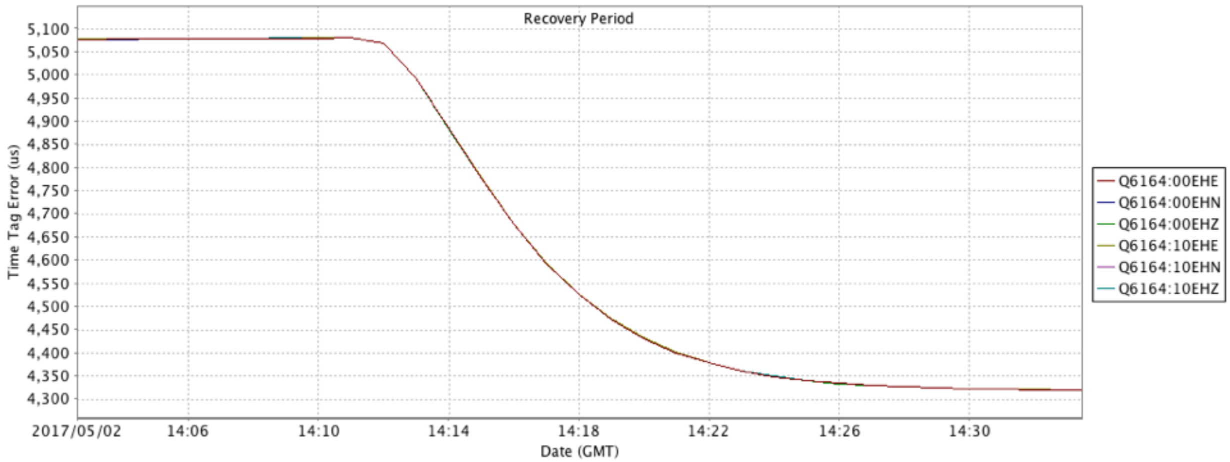

Figure 145 Time Tag Recovery, Q330HR 6164, -20° C

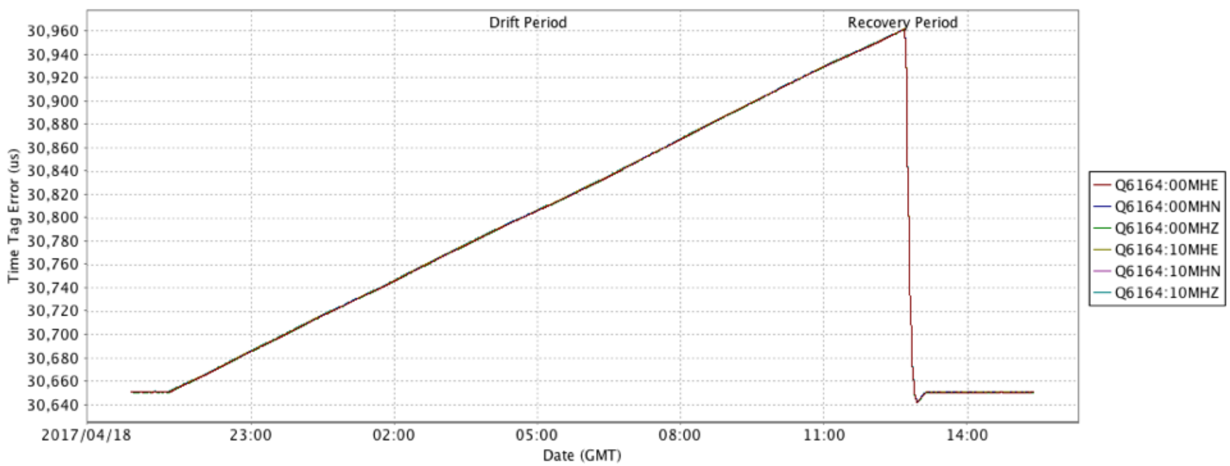

Figure 146 Time Tag Drift, Q330HR 6164, 20° C, 10 sps

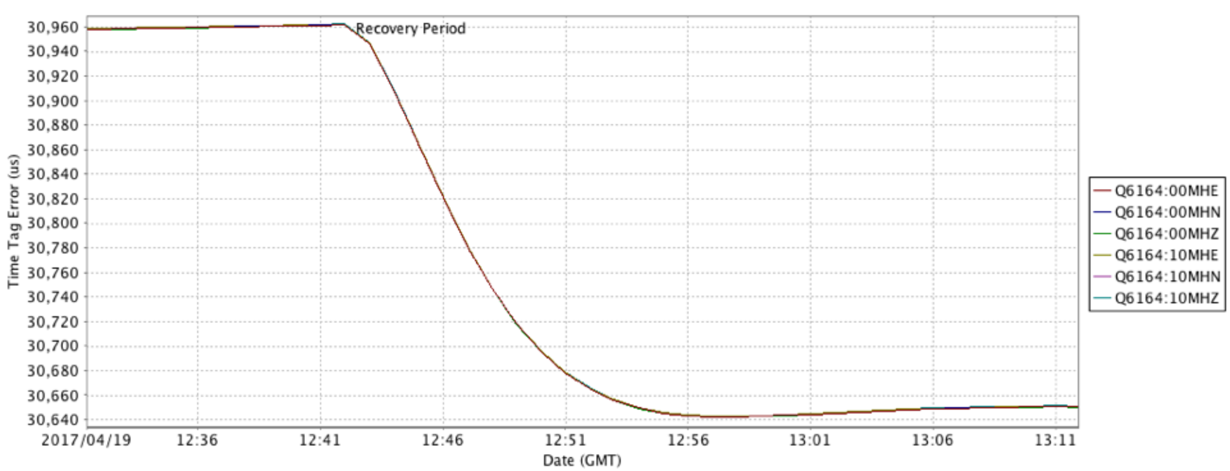

Figure 147 Time Tag Recovery, Q330HR 6164, 20° C, 10 sps

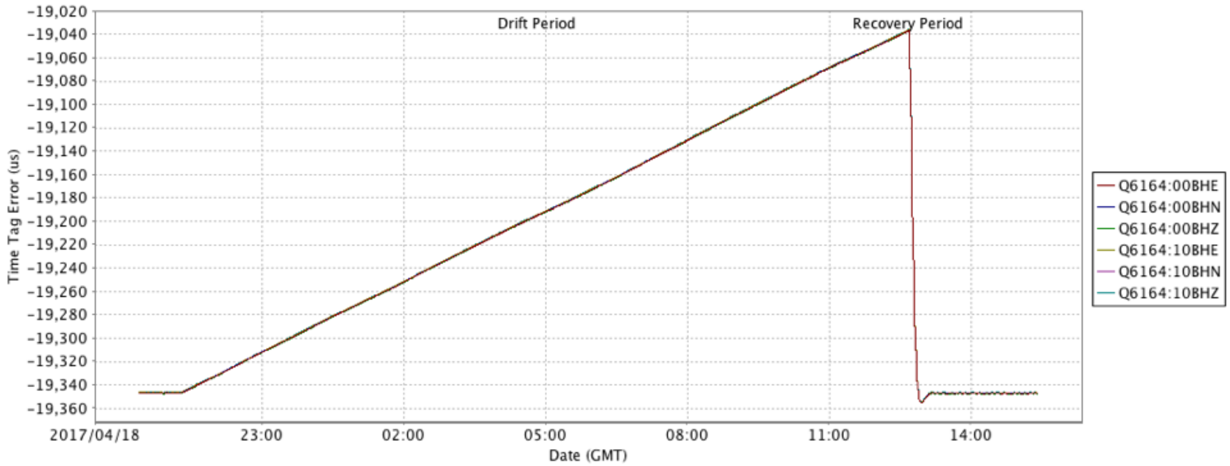

Figure 148 Time Tag Drift, Q330HR 6164, 20° C, 20 sps

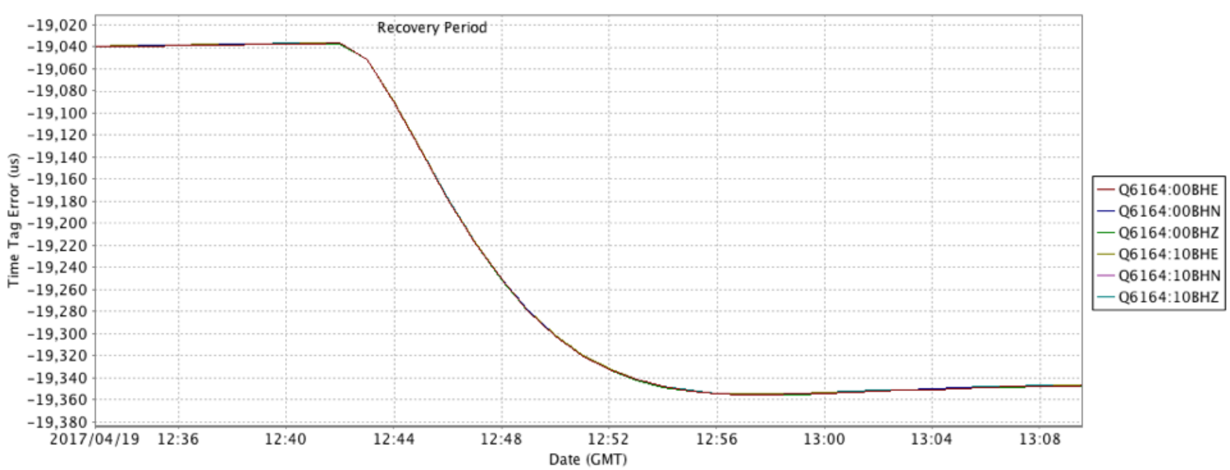

Figure 149 Time Tag Recovery, Q330HR 6164, 20° C, 20 sps

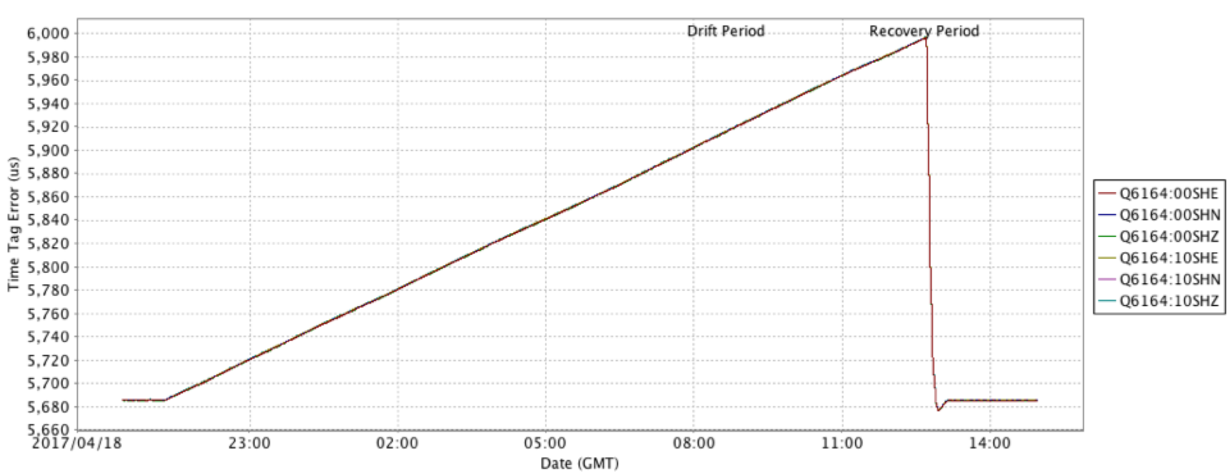

Figure 150 Time Tag Drift, Q330HR 6164, 20° C, 40 sps

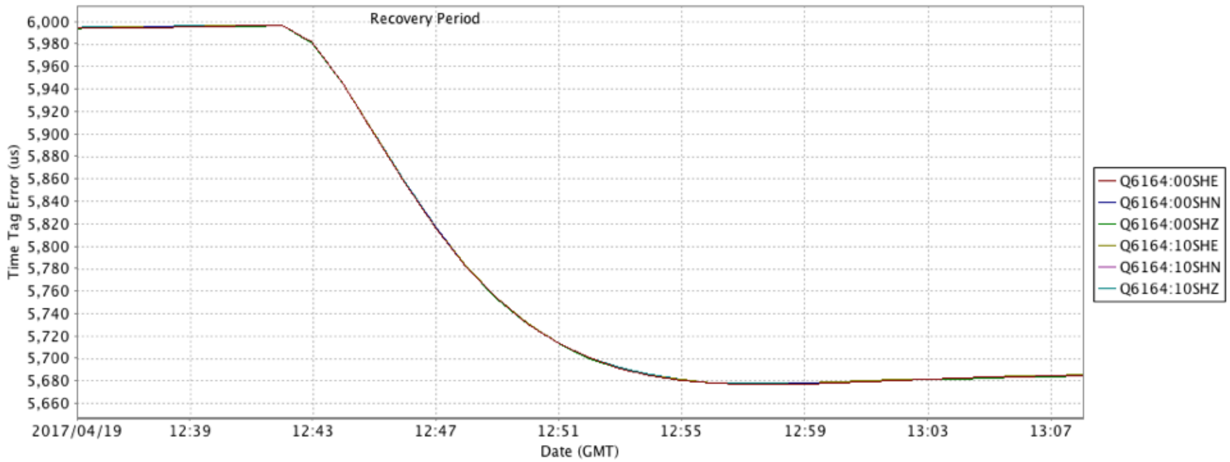

Figure 151 Time Tag Recovery, Q330HR 6164, 20° C, 40 sps

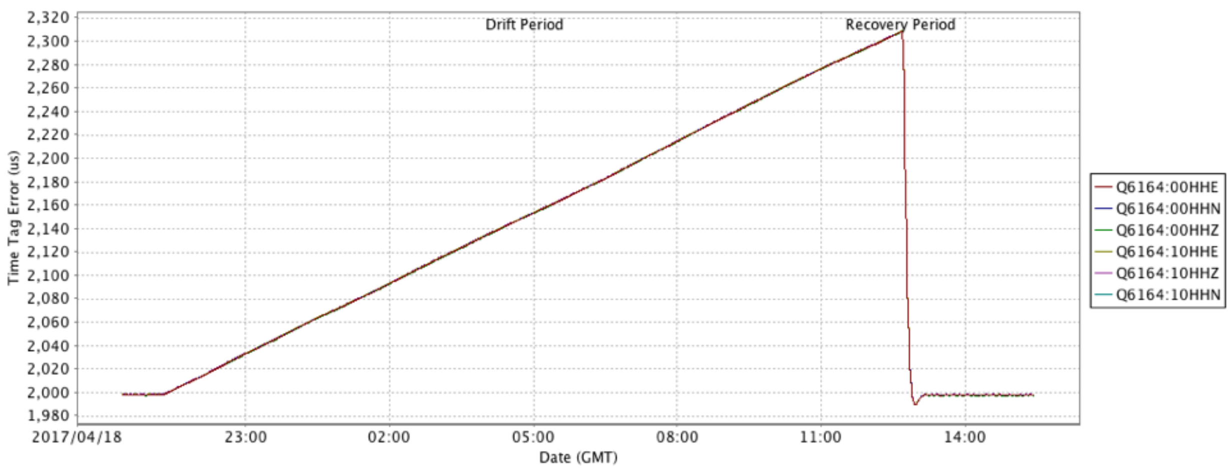

Figure 152 Time Tag Drift, Q330HR 6164, 20° C, 200 sps

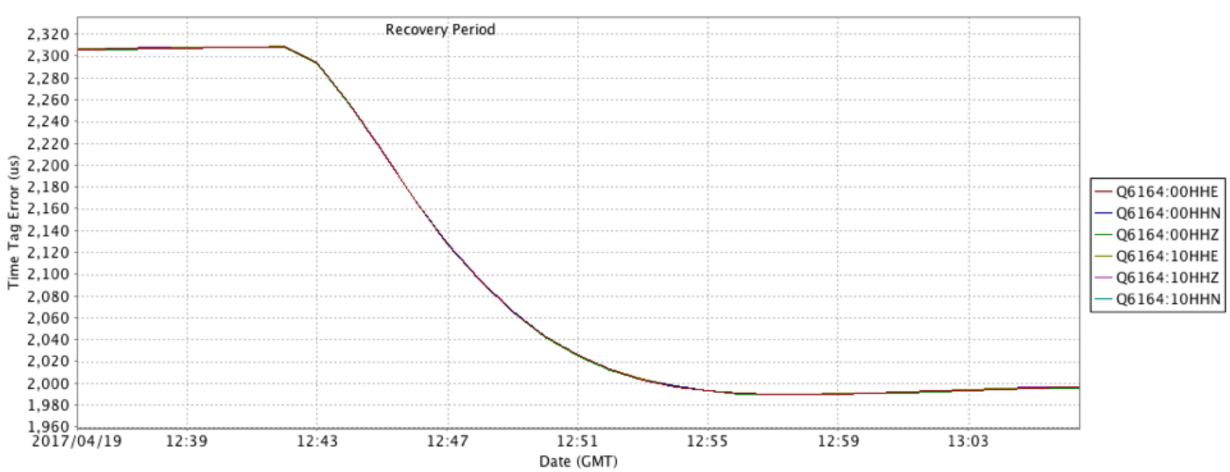

Figure 153 Time Tag Recovery, Q330HR 6164, 20° C, 200 sps

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. As suggestioned in the aforementioned section, we limit our comments regarding the evaluated timing offset to suggestion that perhaps the FIR filter delay corrections have not been applied and/or have been mis-applied to the data collected. A cursory review of the Q330 token file and parameters utilized within in the BRTT package utilized to collect the data have not yielded an explanation.

Table 60 Time Tag Drift and Recovery

Digitizer	Config/Conditions	Timing Offset	Drift Rate	Recovery Rate
6162	100 sps, 23° C	4449 us	-24 us/h	-886 us/h
6164	100 sps, 23° C	4449 us	-5 us/h	-218 us/h
6164	100 sps, 46° C	4331 us	25 us/h	-1167 us/h
6164	100 sps, 20° C	4327 us	20 us/h	-654 us/h
6164	100 sps, -10° C	4320 us	-14 us/h	-493 us/h
6164	100 sps, -20° C	4318 us	-41 us/h	-1097 us/h
6164	10 sps, 20° C	30651 us	-20 us/h	-655 us/h
6164	20 sps, 20° C	-19347 us	-20 us/h	-654 us/h
6164	40 sps, 20° C	5686 us	-20 us/h	-655 us/h
6164	200 sps, 20° C	1998 us	-20 us/h	-655 us/h

In every instance of connecting the GPS antenna to the receiver, GPS receivers locked and timing was corrected, to essentially the same measured timing offset as that prior to the drift test, within tens of minutes. Rates of recovery appear to reach a maximum at the limits of temperature, both high and low.

3.47 Operational Checks at Extreme Temperatures

General operation while the datalogger 6164 was exposed to -36° C and and 60° C, including telemetry of data to a real-time server, was demonstrated at the suite of sample rates of interest (10 sps, 20 sps, 40 sps, 100 sps and 200 Hz).

4 SUMMARY

Power Consumption
The six channel Q330HR digitizers were observed to consume between 3.44 watts to 3.61 watts during operation.

Input Impedance
The measured input impedance at 23° C of the suite of Quanterra Q330HR digitizer channels were all within 0.33% of the average impedance measured at 23° C of 47.8527 Kohm.

DC Accuracy
Across selected sample rates and temperatures, bit weights remained relatively stable, and varying no more than 0.40% from the nominal bitweights of 29.8 nV/count and 118 uV/count.

AC Accuracy
Bitweights varied as little as 0.17% of nominal for the 100 sps 46° C test to as high as 1.12% of nominal at 10 sps sampling rate test.

Input Shorted Offset
Over varying temperatures the input shorted offset appears to be at a maximum voltage at -10° C; on either side of -10° C the terminated voltage drops. The maximum differential over the temperatures at which tests were conducted is 37.625 uV, observed on channel 6.

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

Self-Noise
Over all temperatures and sample rates over which the Q330HR was evaluated, self noise did not exceed 3 counts and 1 counts, for the 26 bit and 24 bit channels, respectively.

Dynamic Range
Dynamic Ranges over all tested conditions and passband varied from as low 141 dB to as much as 151 dB.

System Noise
Over temperature, channel-averaged system noise of Q330HR 6164 is at a minimum of -214.38 dB at -20° C at 0.1 Hz and occurred on 24 bit channels. Over sample rates, channel averaged system noise of Q330HR 6164 improved slightly, reaching a minimum on the 26 bit channels of -220.26 dB at 40 sps. At 10 sps, channel averaged system noise reached a minimum on the 26 bit channels of -230.70 dB at 20 sps; this value is a bit of an anomaly as system noise levels remained generally around -220 dB.

Response Verification
Over the variety of temperatures and sample rates, magnitude and phase varied little with changes in sample rate; as sample rate increases only then is the slightest roll-off evident.

Relative Transfer Function
Phase delays relative to channel 1 appear to be linear and are more appreciable at higher sample rates (>= 40 sps). Timing skews remain below 0.71 us (channel 6 at 200 sps).

Analog Bandwidth
Across the range of sample rates and temperatures at which analog bandwidth was evaluated, the computed corner frequency varied no more than 13.48% of the respective Nyquist frequency, from 73% to 87% of Nyquist. If one excludes the 200 sps evaluation, the remaining computer corner frequencies vary no more than 6.54% of their respective Nyquist frequency.

Total Harmonic Distortion
THD over all test conditions ranged from -124.28 dB, at 20° C to -130.48 db, at 46° C.

Common Mode Rejection
Across sample rates evaluated, the observed common mode rejection was between 71 db and 134 dB.

Crosstalk
No peak is observable in the terminated channel's power spectra, therefore the values represent the maximum possible observable crosstalk*. No correlations are present between maximum possible observable crosstalk and changes in sample rates or temperatures; values range from -151.6 dB to as much as -160.09 dB.

Time Tag Accuracy
Anomolously large offsets were measured and are suspect. Over the selected temperatures over which the Q330HRs were evaluated it is interesting to note in the suspect timing offsets listed in Table 57 the offsets decrease with temperature, on the order of 12 us to 13 us from over the evaluation from 46° C to -20° C

Time Tag Drift
In every instance of connecting the GPS antenna to the receiver, GPS receivers locked and timing was corrected, to essentially the same measured timing offset as that prior to the drift test, within tens of minutes. Rates of recovery appear to reach a maximum at the limits of temperature, both high and low.

Operational Checks at Extreme Temperatures
General operation while the datalogger 6164 was exposed to -36° C and and 60° C, including telemetry of data to a real-time server, was demonstrated at the suite of sample rates of interest (10 sps, 20 sps, 40 sps, 100 sps and 200 sps).

REFERENCES

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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 SELF-NOISE

Digitizer self-noise values are reported in units of dB relative to 1 V^2/Hz at the defined octave-band frequencies. The 90% uncertainty of the provided estimates are +/- 1.347 dB .

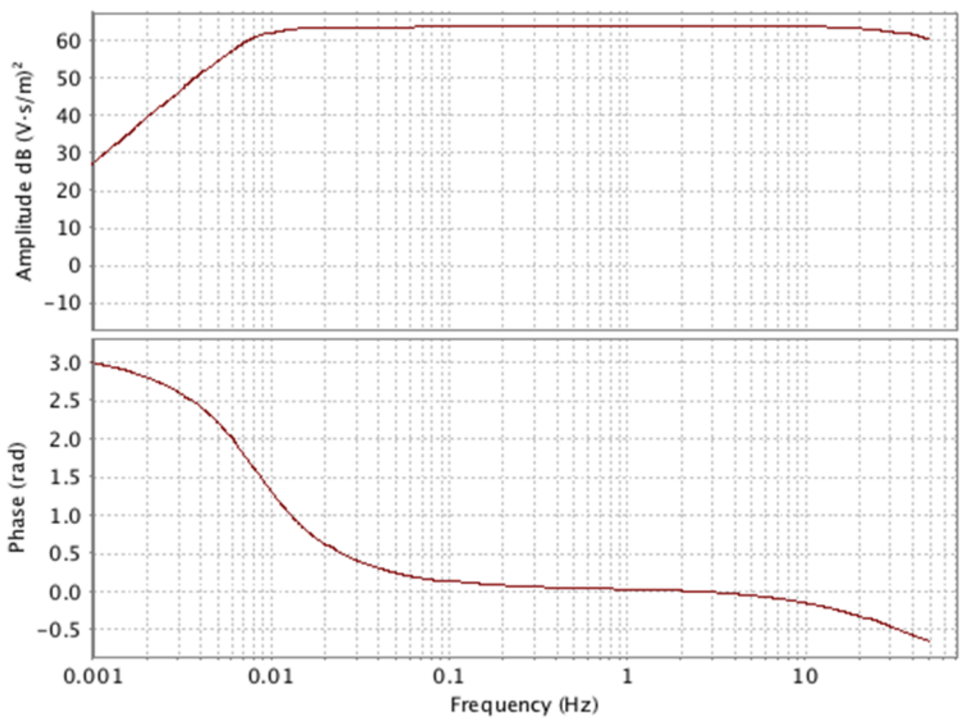
Table 61 Q330HR Digitizer Noise Model, 20x Gain

Frequency (Hz)	00EHE (chan 3)	00EHN (chan 2)	00EHZ (chan 1)	10EHE (chan 6)	10EHN (chan 5)	10EHZ (chan 4)
0.00315	-135.0 dB	-135.0 dB	-135.4 dB	-135.0 dB	-134.3 dB	-135.2 dB
0.004	-135.0 dB	-135.0 dB	-135.4 dB	-135.0 dB	-134.3 dB	-135.2 dB
0.005	-137.1 dB	-136.8 dB	-136.9 dB	-136.3 dB	-135.9 dB	-136.7 dB
0.0063	-137.1 dB	-136.8 dB	-136.9 dB	-136.3 dB	-135.9 dB	-136.7 dB
0.008	-138.8 dB	-138.9 dB	-139.0 dB	-138.3 dB	-138.1 dB	-139.1 dB
0.01	-138.8 dB	-138.9 dB	-139.0 dB	-138.3 dB	-138.1 dB	-139.1 dB
0.0125	-139.7 dB	-140.0 dB	-140.6 dB	-140.0 dB	-139.7 dB	-140.4 dB
0.016	-140.8 dB	-141.3 dB	-141.9 dB	-141.2 dB	-140.8 dB	-141.6 dB
0.02	-142.7 dB	-141.9 dB	-142.4 dB	-142.7 dB	-142.3 dB	-143.0 dB
0.025	-143.7 dB	-143.0 dB	-143.1 dB	-143.5 dB	-143.0 dB	-143.5 dB
0.0315	-144.0 dB	-144.3 dB	-144.4 dB	-144.3 dB	-143.7 dB	-144.1 dB
0.04	-145.3 dB	-146.3 dB	-145.8 dB	-145.7 dB	-145.2 dB	-145.9 dB
0.05	-146.4 dB	-146.7 dB	-146.6 dB	-146.6 dB	-146.3 dB	-146.6 dB
0.063	-147.8 dB	-148.0 dB	-147.9 dB	-147.8 dB	-147.4 dB	-147.9 dB
0.08	-148.9 dB	-148.8 dB	-149.0 dB	-149.3 dB	-148.6 dB	-148.4 dB
0.1	-149.6 dB	-149.6 dB	-149.9 dB	-150.0 dB	-149.4 dB	-149.5 dB
0.125	-150.7 dB	-150.3 dB	-150.7 dB	-150.5 dB	-150.3 dB	-150.4 dB
0.16	-151.4 dB	-151.1 dB	-151.7 dB	-151.6 dB	-151.2 dB	-150.9 dB
0.2	-152.1 dB	-152.1 dB	-152.5 dB	-152.4 dB	-152.1 dB	-151.8 dB
0.25	-152.8 dB	-152.7 dB	-153.1 dB	-153.0 dB	-152.5 dB	-152.7 dB
0.315	-153.6 dB	-153.2 dB	-153.7 dB	-153.8 dB	-153.1 dB	-153.0 dB
0.4	-154.1 dB	-154.1 dB	-154.3 dB	-154.1 dB	-153.9 dB	-153.5 dB
0.5	-154.7 dB	-154.4 dB	-154.8 dB	-154.5 dB	-154.3 dB	-154.0 dB
0.63	-155.1 dB	-155.0 dB	-155.2 dB	-154.9 dB	-154.8 dB	-154.4 dB
0.8	-155.3 dB	-155.4 dB	-155.6 dB	-155.2 dB	-155.2 dB	-154.9 dB
1	-155.8 dB	-155.8 dB	-155.9 dB	-155.5 dB	-155.5 dB	-155.3 dB
1.25	-156.1 dB	-156.0 dB	-156.3 dB	-155.8 dB	-155.7 dB	-155.5 dB
1.6	-156.3 dB	-156.3 dB	-156.4 dB	-156.0 dB	-155.9 dB	-155.8 dB
2	-156.4 dB	-156.4 dB	-156.6 dB	-156.1 dB	-156.1 dB	-156.1 dB
2.5	-156.6 dB	-156.6 dB	-156.7 dB	-156.3 dB	-156.3 dB	-156.2 dB
3.15	-156.8 dB	-156.8 dB	-156.9 dB	-156.3 dB	-156.4 dB	-156.4 dB
4	-156.9 dB	-156.9 dB	-156.9 dB	-156.4 dB	-156.6 dB	-156.4 dB
5	-157.0 dB	-156.9 dB	-157.0 dB	-156.5 dB	-156.6 dB	-156.6 dB
6.3	-157.0 dB	-157.1 dB	-157.1 dB	-156.6 dB	-156.7 dB	-156.6 dB
8	-157.1 dB	-157.1 dB	-157.1 dB	-156.6 dB	-156.7 dB	-156.7 dB
10	-157.2 dB	-157.1 dB	-157.2 dB	-156.7 dB	-156.7 dB	-156.8 dB
12.5	-157.2 dB	-157.2 dB	-157.2 dB	-156.7 dB	-156.8 dB	-156.8 dB
16	-157.2 dB	-157.2 dB	-157.2 dB	-156.7 dB	-156.8 dB	-156.8 dB
20	-157.2 dB	-157.2 dB	-157.2 dB	-156.7 dB	-156.8 dB	-156.8 dB
25	-157.1 dB	-157.2 dB	-157.1 dB	-156.7 dB	-156.7 dB	-156.8 dB
31.5	-157.0 dB	-157.1 dB	-157.0 dB	-156.6 dB	-156.6 dB	-156.7 dB
40	-157.0 dB	-157.0 dB	-157.0 dB	-156.5 dB	-156.6 dB	-156.6 dB

APPENDIX B: RESPONSE MODELS

4.1 Quanterra Trillium 120 BH Response

Streckheisen STS-5A seismometer amplitude and phase 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:
0.27503 V·s/m

APPENDIX C: TESTBED CALIBRATIONS

Agilent 3458A # 2823A10915

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Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 41628_11719482

Item Identification

Asset Number	41628
Description	Meter,Multifunction
Model	3458A
Serial #	2823A10915
Manufacturer	Hewlett Packard Co
Customer Asset Id	N/A
Purchase Order	N/A
Customer	Ground-Based Monitoring R&E 06752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1029
Date of Receipt	July 27, 2017
Dates Tested (Start – End)	August 09, 2017 - August 09, 2017
Date Approved	August 11, 2017
Calibration Expiration Date	August 11, 2018

Calibration Description

Calibration Lab	PSL-ELECTRICAL
Calibration Procedure, rev.	HP 3458A, 4.2
Temperature	23 ± 2 deg C
Humidity	40 ± 20 %RH
Barometric Pressure	NA mmHg
As Found Condition	PASS
As Left Condition	PASS
Software Used	MET/CAL 8.3.2.37
Tamper Seal	None

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Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

AC Current:

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

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

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

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Calibration Data Report

Primary Electrical Lab

Unit Under Test: HP 3458A Multimeter	Test Result: PASS
Asset Number: 41628	Test Type: FOUND-LEFT
Serial Number: 2823A10915	Calibration Date: 8/9/2017
Procedure Name: HP 3458A	Temperature: 23 °C
Revision: 4.2	Humidity: 40 %
Calibrated By: Jason Chance	

- Test Type is defined as follows:
  - AS-FOUND Data collected prior to adjustment and/or repair
  - AS-LEFT Data collected after adjustment and/or repair
  - FOUND-LEFT Data collected without adjustment and/or repair
- Test Uncertainty Ratio (TUR) is defined as:
  - TUR = Specification Limit / Uncertainty of the Measurement
- A hash (#) appended to the TUR indicates a guardbanded measurement
- An asterisk (*) appended to the TUR indicates use of a Test Accuracy Ratio (TAR) instead of a TUR
  - TAR = Specification Limit / Accuracy of the Standard

COMMENTS:

Standards Used

Asset #	Description	Due Date
11123	Keithley 5155-9 1 Gohm resistor	5/10/2018
20174	Fluke 5725A Amplifier	8/10/2017
20563	FLUKE 5790A CALIBRATOR	9/19/2017
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/15/2018
6664631	Fluke 5730A Multifunction Calibrator	9/8/2017

Test Results

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

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The internal temperature of the 3458A is 36.1 deg.C

DC Volts

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99812	99.99976	100.00188	mV	2.26#	13	
-100.00000 mV		-100.00188	-99.99974	-99.99812	mV	2.26#	14	
1.00000000 V		0.99998965	0.99999895	1.00001035	V	2.97#	10	
-1.00000000 V		-1.00001035	-0.99999926	-0.99998965	V	2.97#	7	
-10.0000000 V		-10.0000987	-9.9999912	-9.9999013	V	3.92#	9	
-5.0000000 V		-5.0000501	-4.9999960	-4.9999499	V	3.71#	8	
-2.0000000 V		-2.0000209	-1.9999976	-1.9999791	V	3.24#	12	
2.0000000 V		1.9999791	1.9999967	2.0000209	V	3.24#	16	
5.0000000 V		4.9999499	4.9999953	5.0000501	V	3.71#	9	
10.0000000 V		9.9999013	9.9999894	10.0000987	V	3.92#	11	
100.000000 V		99.998821	99.999960	100.001179	V	3.51#	3	

HP 3458A Asset # 41628
Calibration Date: 8/9/2017 05:29:47

Primary Electrical Lab TUR Report version 06/14/17

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PRIMARY STANDARDS LABORATORY

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
1000.00000 V		999.98900	999.99738	1000.01100	V	2.42#	24	
DC Current								
100.000 nA		91.597	99.976	108.403	nA	1.85#	0	
1.000000 µA		0.969900	0.999960	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999844	10.030100	µA	5.2	1	
100.00000 µA		99.95000	99.99882	100.05000	µA	5.7	2	
1.0000000 mA		0.9997500	0.9999961	1.0002500	mA	7.6	2	
10.000000 mA		9.997500	9.999991	10.002500	mA	8.1	0	
100.00000 mA		99.97500	100.00062	100.02500	mA	6.1	2	
1.0000000 A		0.9995000	1.0000213	1.0005000	A	7.6	4	
Resistance								
10.00000 Ohm	10.000270	9.99917	10.00021	10.00137	Ohm	5.8	6	
100.00000 Ohm	100.003620	99.99812	100.00318	100.00912	Ohm	6.5	8	
1.0000000 kOhm	0.99998460	0.9999336	0.9999831	1.0000356	kOhm	7.3	3	
10.000000 kOhm	9.9998320	9.999322	9.999830	10.000342	kOhm	7.3	0	
100.00000 kOhm	100.000630	99.99553	100.00075	100.00573	kOhm	6.0	2	
1.0000000 MOhm	0.99996060	0.9998586	0.9999609	1.0000626	MOhm	7.3	0	
10.000000 MOhm	9.9982380	9.996138	9.998227	10.000338	MOhm	7.2	1	
100.00000 MOhm	100.008520	99.95752	100.01760	100.05952	MOhm	6.0	18	
1.00192000 GOhm		0.9818716	1.0024808	1.0219684	GOhm	>10	3	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9346	100.1700	µA	7.4	39	
100.0000 µA @ 45 Hz		99.8300	99.9808	100.1700	µA	9.4	11	
100.0000 µA @ 1 kHz		99.8300	99.9828	100.1700	µA	9.4	10	
1.000000 mA @ 20 Hz		0.998300	0.999488	1.001700	mA	10.0	30	
1.000000 mA @ 45 Hz		0.998300	0.999938	1.001700	mA	>10	4	
1.000000 mA @ 5 kHz		0.998300	1.000172	1.001700	mA	6.3	10	
1.000000 mA @ 10 kHz		0.995013	1.000288	1.004987	mA	3.47#	6	
10.00000 mA @ 20 Hz		9.98300	9.99494	10.01700	mA	10.0	30	
10.00000 mA @ 45 Hz		9.98300	9.99944	10.01700	mA	>10	3	
10.00000 mA @ 5 kHz		9.98300	10.00133	10.01700	mA	7.7	8	
10.00000 mA @ 10 kHz		9.94970	10.00200	10.05030	mA	4.0	4	
100.0000 mA @ 20 Hz		99.8300	99.9528	100.1700	mA	10.0	28	
100.0000 mA @ 45 Hz		99.8300	99.9995	100.1700	mA	>10	0	
100.0000 mA @ 5 kHz		99.8300	100.0300	100.1700	mA	8.5	18	
100.0000 mA @ 10 kHz		99.4800	100.0495	100.5200	mA	5.5	10	
1.000000 A @ 40 Hz		0.998300	0.999896	1.001700	A	6.5	6	
1.000000 A @ 5 kHz		0.998357	1.001093	1.001643	A	3.95#	67	
AC Volts								
10.00000 mV @ 10 Hz	10.006200	9.98599	9.99880	10.02641	mV	7.2	37	
10.00000 mV @ 40 Hz	9.998000	9.99358	9.99825	10.00242	mV	2.94#	6	
10.00000 mV @ 20 kHz	9.997000	9.99258	9.99788	10.00142	mV	2.94#	20	
10.00000 mV @ 50 kHz	9.997600	9.98650	9.99413	10.00870	mV	4.1	31	
10.00000 mV @ 100 kHz		9.94890	9.98216	10.05110	mV	>10	35	
10.00000 mV @ 300 kHz	9.997300	9.59541	9.84587	10.39919	mV	>10	38	
100.0000 mV @ 10 Hz	100.07170	99.8696	99.9998	100.2738	mV	>10	36	
100.0000 mV @ 40 Hz	99.99470	99.9477	99.9957	100.0417	mV	>10	2	
100.0000 mV @ 20 kHz	99.97850	99.9315	99.9969	100.0255	mV	>10	39	
100.0000 mV @ 50 kHz	99.98210	99.8801	99.9912	100.0841	mV	>10	9	
100.0000 mV @ 100 kHz	99.98540	99.7834	99.9719	100.1874	mV	>10	7	
100.0000 mV @ 300 kHz	99.98800	98.9781	99.8645	100.9979	mV	>10	12	
1.000000 V @ 10 Hz	0.9999928	0.997973	1.000036	1.002013	V	>10	2	
1.000000 V @ 40 Hz	0.9999930	0.999523	1.000025	1.000463	V	>10	7	
1.000000 V @ 20 kHz	0.9999961	0.999526	0.999969	1.000466	V	>10	6	
1.000000 V @ 50 kHz	1.0000142	0.998994	0.999998	1.001034	V	>10	2	
1.000000 V @ 100 kHz	1.0000316	0.998012	1.000109	1.002052	V	>10	4	
1.000000 V @ 300 kHz	1.0003600	0.990256	1.001526	1.010464	V	>10	12	
10.00000 V @ 10 Hz	10.000022	9.97982	10.00055	10.02022	V	>10	3	
10.00000 V @ 40 Hz	9.999997	9.99530	10.00036	10.00470	V	>10	8	
10.00000 V @ 20 kHz	10.000074	9.99537	9.99981	10.00477	V	>10	6	
10.00000 V @ 50 kHz	10.000247	9.99005	9.99966	10.01045	V	>10	6	

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 100 kHz	10.000629	9.98043	9.99770	10.02083	V	>10	15	
10.00000 V @ 300 kHz	10.003385	9.90235	9.98995	10.10442	V	>10	13	
100.0000 V @ 10 Hz	99.99904	99.7970	100.0037	100.2010	V	>10	2	
100.0000 V @ 40 Hz	100.00010	99.9531	100.0019	100.0471	V	>10	4	
100.0000 V @ 20 kHz	100.00217	99.9552	100.0041	100.0492	V	>10	4	
100.0000 V @ 50 kHz	100.00724	99.9052	100.0091	100.1092	V	>10	2	
100.0000 V @ 100 kHz	100.01276	99.8107	100.0074	100.2148	V	>10	3	
100.0000 V @ 200 kHz	100.06317	99.0525	100.0525	101.0738	V	>10	1	
700.0000 V @ 40 Hz	700.01700	699.4370	699.9785	700.5970	V	>10	7	
700.0000 V @ 20 kHz	700.03180	699.4518	699.9037	700.6118	V	>10	22	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000040	10.005000	Hz	>10	1	
40.00000 Hz @ 1 V		39.996000	39.999966	40.004000	Hz	>10	1	
100.00000 Hz @ 1 V		99.990000	99.999887	100.010000	Hz	>10	1	
1000.0000 Hz @ 1 V		999.90000	1000.00029	1000.10000	Hz	>10	0	
10000.0000 Hz @ 1 V		9999.00000	10000.00382	10001.00000	Hz	>10	0	
20000.0000 Hz @ 1 V		19998.00000	20000.00573	20002.00000	Hz	>10	0	
50000.0000 Hz @ 1 V		49995.00000	50000.01907	50005.00000	Hz	>10	0	
100.00000 kHz @ 1 V		99.990000	100.000038	100.010000	kHz	>10	0	
500.00000 kHz @ 1 V		499.950000	500.000191	500.050000	kHz	>10	0	
1.000000 MHz @ 1 V		0.9999000	1.0000004	1.0001000	MHz	>10	0	
2.000000 MHz @ 1 V		1.9998000	2.0000006	2.0002000	MHz	>10	0	
4.000000 MHz @ 1 V		3.9996000	4.0000013	4.0004000	MHz	>10	0	
6.000000 MHz @ 1 V		5.9994000	6.0000021	6.0006000	MHz	>10	0	
8.000000 MHz @ 1 V		7.9992000	8.0000032	8.0008000	MHz	>10	0	
10.000000 MHz @ 1 V		9.9990000	10.0000038	10.0010000	MHz	>10	0	

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

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

Equipment (Standard) Used

Asset #	Description	Model	Expires
6651332	Generator,Function	33250A	February 16, 2018
20563	Standard,Measurement,AC	5790A	September 19, 2017
20174	Amplifier	5725A	August 10, 2017
6664631	Calibrator,Multifunction	5730A	April 25, 2018
11123	Resistor,Standard	5155-9	May 10, 2018

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Traceability

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

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

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

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

Note 3: The presence of names and titles under "Authorization" are properly authenticated electronic signatures conforming to the equivalent identification signatory requirements of ISO 17025:2005 5.10.2.j.

Authorization

Calibrated By:	Approved By:
Chance, Jason Metrologist	Aragon, Steven J. Metrologist

End-of-Document

Page **8** of **8**
41628_11719482

Agilent 3458A # MY45048371

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 6652541_11682157

Item Identification

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

Calibration Description

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

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

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

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

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

Test Results

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

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	10.000220	9.99552	10.00043	10.00492	V	>10	4	
10.00000 V @ 20 kHz	10.000190	9.99549	9.99959	10.00489	V	>10	13	
10.00000 V @ 50 kHz	10.000207	9.99001	10.00030	10.01041	V	>10	1	
10.00000 V @ 100 kHz	9.999795	9.97960	9.99935	10.01999	V	>10	2	
10.00000 V @ 300 kHz	10.001654	9.90064	9.99865	10.10267	V	>10	3	
100.0000 V @ 10 Hz	100.00266	99.8007	100.0055	100.2047	V	>10	1	
100.0000 V @ 40 Hz	100.00218	99.9552	100.0044	100.0492	V	>10	5	
100.0000 V @ 20 kHz	100.00295	99.9559	100.0003	100.0500	V	>10	6	
100.0000 V @ 50 kHz	100.00901	99.9070	100.0129	100.1110	V	>10	4	
100.0000 V @ 100 kHz	100.01336	99.8113	100.0096	100.2154	V	>10	2	
100.0000 V @ 200 kHz	100.06044	99.0498	100.0300	101.0710	V	>10	3	
700.0000 V @ 40 Hz	700.01590	699.4359	700.0061	700.5959	V	>10	2	
700.0000 V @ 20 kHz	700.02470	699.4447	699.7809	700.6047	V	>10	42	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000099	10.005000	Hz	>10	2	
40.00000 Hz @ 1 V		39.996000	40.000415	40.004000	Hz	>10	10	
100.00000 Hz @ 1 V		99.990000	100.000600	100.010000	Hz	>10	6	
1000.0000 Hz @ 1 V		999.90000	1000.00696	1000.10000	Hz	>10	7	
10000.0000 Hz @ 1 V		9999.00000	10000.06962	10001.00000	Hz	>10	7	
20000.0000 Hz @ 1 V		19998.00000	20000.13923	20002.00000	Hz	>10	7	
50000.0000 Hz @ 1 V		49995.00000	50000.35285	50005.00000	Hz	>10	7	
100.00000 kHz @ 1 V		99.990000	100.000696	100.010000	kHz	>10	7	
500.00000 kHz @ 1 V		499.950000	500.003481	500.050000	kHz	>10	7	
1.000000 MHz @ 1 V		0.9999000	1.0000071	1.0001000	MHz	>10	7	
2.000000 MHz @ 1 V		1.9998000	2.0000139	2.0002000	MHz	>10	7	
4.000000 MHz @ 1 V		3.9996000	4.0000278	4.0004000	MHz	>10	7	
6.000000 MHz @ 1 V		5.9994000	6.0000422	6.0006000	MHz	>10	7	
8.000000 MHz @ 1 V		7.9992000	8.0000566	8.0008000	MHz	>10	7	
10.000000 MHz @ 1 V		9.9990000	10.0000696	10.0010000	MHz	>10	7	

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

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

Equipment (Standard) Used

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

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

Traceability

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

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

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

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

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

Authorization

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

End-of-Document

Agilent 3458A # MY45048372

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 6652539_11669844

Item Identification

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

Calibration Description

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

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

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

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

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

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

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

Test Results

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

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

PRIMARY STANDARDS LABORATORY

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Test Results

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

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	9.999940	9.99524	10.00044	10.00464	V	>10	11	
10.00000 V @ 20 kHz	10.000035	9.99533	9.99981	10.00474	V	>10	5	
10.00000 V @ 50 kHz	10.000073	9.98987	10.00033	10.01027	V	>10	3	
10.00000 V @ 100 kHz	10.000197	9.98000	9.99659	10.02040	V	>10	8	
10.00000 V @ 300 kHz	10.000297	9.89929	9.99356	10.10130	V	>10	7	
100.0000 V @ 10 Hz	99.99889	99.7969	100.0082	100.2009	V	>10	5	
100.0000 V @ 40 Hz	99.99940	99.9524	100.0070	100.0464	V	>10	16	
100.0000 V @ 20 kHz	100.00103	99.9540	100.0023	100.0480	V	>10	3	
100.0000 V @ 50 kHz	100.00567	99.9037	100.0131	100.1077	V	>10	7	
100.0000 V @ 100 kHz	100.00786	99.8058	100.0083	100.2099	V	>10	0	
100.0000 V @ 200 kHz	100.04847	99.0380	100.0279	101.0590	V	>10	2	
700.0000 V @ 40 Hz	700.01380	699.4338	699.9477	700.5938	V	>10	11	
700.0000 V @ 20 kHz	700.03500	699.4550	699.6812	700.6150	V	>10	61	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000029	10.005000	Hz	>10	1	
40.00000 Hz @ 1 V		39.996000	40.000000	40.004000	Hz	>10	0	
100.00000 Hz @ 1 V		99.990000	100.000085	100.010000	Hz	>10	1	
1000.0000 Hz @ 1 V		999.90000	1000.00152	1000.10000	Hz	>10	2	
10000.0000 Hz @ 1 V		9999.00000	10000.01335	10001.00000	Hz	>10	1	
20000.0000 Hz @ 1 V		19998.00000	20000.02479	20002.00000	Hz	>10	1	
50000.0000 Hz @ 1 V		49995.00000	50000.06675	50005.00000	Hz	>10	1	
100.00000 kHz @ 1 V		99.990000	100.000133	100.010000	kHz	>10	1	
500.00000 kHz @ 1 V		499.950000	500.000668	500.050000	kHz	>10	1	
1.000000 MHz @ 1 V		0.9999000	1.0000012	1.0001000	MHz	>10	1	
2.000000 MHz @ 1 V		1.9998000	2.0000027	2.0002000	MHz	>10	1	
4.000000 MHz @ 1 V		3.9996000	4.0000053	4.0004000	MHz	>10	1	
6.000000 MHz @ 1 V		5.9994000	6.0000078	6.0006000	MHz	>10	1	
8.000000 MHz @ 1 V		7.9992000	8.0000101	8.0008000	MHz	>10	1	
10.000000 MHz @ 1 V		9.9990000	10.0000134	10.0010000	MHz	>10	1	

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

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

Equipment (Standard) Used

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

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Authorization

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

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