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2023 Reftek Wrangler Digitizer Type Approval Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated the Reftek Wrangler digitizer. The Wrangler digitizers are intended to record sensor output for seismic and infrasound monitoring applications. The purpose of this digitizer evaluation is to measure the performance characteristics in such areas as power consumption, input impedance, sensitivity, full scale, self-noise, dynamic range, system noise, response, passband, and timing. The Wrangler digitizers are being evaluated for potential use in the International Monitoring System (IMS) and On-site Inspection (OSI) components of Comprehensive Nuclear-Test-Ban Treaty (CTBT).

ACKNOWLEDGEMENTS

This work was sponsored under Fund-In Agreement between Sandia National Laboratories and the Preparatory Commission (PrepCom) for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

We would like to thank Reftek for providing the Wrangler digitizers to evaluate and for their presence and support in conducting the evaluation.

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ACRONYMS AND TERMS

Acronym/Term	Definition
BB	Broadband
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO PrepCom	Preparatory Commission to the Comprehensive Nuclear-Test-Ban Treaty Organization
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
GNSS	Global Navigation Satellite System
HNM	High Noise Model
IMS	International Monitoring System component of the CTBT
LNM	Low Noise Model
OSI	On-site Inspection component of the CTBT
PSD	Power Spectral Density
SI	International System of Units
SNL	Sandia National Laboratories
SNR	Signal to Noise Ratio
SP	Short-period

1 INTRODUCTION

The purpose of evaluating the Wrangler digitizer is to measure its performance characteristics in such areas as power consumption, input impedance, sensitivity, full scale, self-noise, dynamic range, system noise, response, passband, and timing and compare the measured performance to the manufacturer's specifications and IMS and OSI requirements.

Figure 1 Reftek Wrangler Digitizers operating in the FACT bunker

The three Wranglers included in the evaluation are six channel units. The first, 3052C, was configured to operate with a sample rate of 250 sps for all tests. The second unit, 3052D, was configured to operate with four sample rates: 200 sps, 100 sps, 40 sps, and 20 sps. The last unit, 3052E, was configured to operate at 500 sps. All channels were configured to record at a 24-bit recording resolution.

The digitizers recorded data locally on a removable memory device and streamed data over Ethernet to a server using the Seedlink protocol. The digitizers were configured to time synchronize their internal time to the external GNSS module and maintain an active GNSS lock continuously.

SPECIFICATIONS

A/D CONVERTER	
Type	32-bit SAR A/D converters
Dynamic Range	>140 dB @100 sps
Input Channels	3 or 6
Gain Selection	x1, x4, x16 and x64
Input Full Scale	40 Vpp @ x1 gain, 0.625 Vpp @ x64 gain
Input Impendance	26 Kohms, 0.002 uFd, differential @ x1 2 Mohms, 0.002 uFd, differential @ x64
Common Mode Rejection	>90 dB
Sample Rates	4000, 1000, 500, 250, 200, 125, 100, 50, 40, 20, 10, 5, 1, 0.1 sps
Multiple Sample Rates	Supported for rates in the group 1000, 200, 100, 50, 40, 20, 10, 5, 1, 0.1
Sampling	Simultaneous on all channels
FIR Filter	140 dB down in the stopband

TIME BASE	
Type	GNSS Receiver with Internal Disciplined Oscillator
Accuracy with GNSS	±10 µsec after validated 3-D Fix and Locked
Free-Running Accuracy	0.1 ppm over the temp. range of 0°C to 70°C 0.2 ppm from −30 °C to 0 °C
Alternate Time Sources	PTP or NTP

POWER	
Input Voltage	9–30 VDC
Average Power (3 channels, no communication, GNSS duty cycle)	1.4 Watts
Average Power (3 channels, with communication, GNSS duty cycle)	1.7 Watts
Average Power (6 channels, no communication, GNSS duty cycle)	2.0 Watts
Average Power (6 channels, with communication, GNSS duty cycle)	2.3 Watts
Low Voltage Disconnect	User-programmable. Additional hardware cut-off fixed at 9.0 Volts
Reset	Resettable via WebUI, Magnet Wand, or external connector pin.

RECORDING	
Format	Miniseed, MRF
Transmission	SeedLink Server, RTP, Jopens 6.0 (Simulcasting)
Trigger Types	Continuous, STA/LTA, Time, External, Cross, Level and Vote (0.0001 to 4g)
Data Products	On-board Calculation of: PGA, PGV, PGD, MMI, PEIS, JMA (email notifications available)
Internal Capacity	8 Gb internal Flash memory data buffer
External Capacity	Removable 8, 16, or 32 GB USB drive

COMMUNICATIONS	
Ethernet	10/100 Base-T, TCP/IP, UDP/IP, FTP, RTP DHCP, Static, Link-Local
WiFi	Access-point mode for local command and control
WebUI	Accessible via WiFi or Ethernet

AUXILIARY CHANNELS	
Inputs	6 per Channel Connector (3 for Mass Position and 3 auxiliary inputs)
Resolution	16-bit A/D Converter
Full Scale	±10 V Single-ended input mode, ±10 V Differential-ended input mode
Sampling Rate	10, 1, or 0.1 sps

SENSOR CONTROL	
Cal Signal	16-bit DAC
Cal Waveforms	Pre-defined waveforms including Sine, Step, Noise, Swept Sine signals. Custom waveforms can be uploaded bythe user.
Cal Signal Recording	Additional 32-bit ADC dedicated to recording the calibration output signal
Control Signals	6 per channel connector: Including Lock, Unlock, Center, Calibration Enable, Damping, UVW
Automatic Mass Recentering	User settable thresholds, interval & retries
Sensor ID	One-wire interface to Reftek Sensors. Externally adaptable to RS232 communication for third party sensors.

MECHANICAL	
LEDs	16 status LEDs including Input Power, GNSS/Time, USB, Acquisition and Link status
Switch	Magnetic Switch for WiFi & LED wakeup
Size	5.2" W x 8.4" L x 3.5" H
Weight	3 lbs
Watertight Integrity	IP68
Humidity	0 to 100%
Shock	Survives a 1 meter drop on any axis
Transportation	Survives MIL-STD-810G transportation test
Operating Temp	−30°C to 70°C
Storage Temp	−30°C to 70°C

CERTIFICATIONS	
Compliance	CE, FCC, RoHS

REFTEK SYSTEMS INC. reftek.com HIGH RESOLUTION SEISMIC RECORDERS, SENSORS & SOFTWARE

04/26/2022

Figure 2 Reftek Wrangler Specifications (from the Wrangler Datasheet)

I.2. Minimum Requirements for Primary and Auxiliary Seismological Station Specifications

Characteristics	Minimum Requirements
Sensor type	Seismometer
Station type	Three component or array
Position (with respect to ground level)	Borehole or vault
Three component station passband[a]	Short period: 0.5 to 16 Hz plus long period: 0.02 to 1 Hz or broadband: 0.02 to 16 Hz
Sensor response	Flat to velocity or acceleration over the passband
Array station passband	(Short period: 0.5 to 16 Hz Long period: 0.02 to 1 Hz)[b]
Number of sensors for new arrays[c]	9 short period (one component) plus (1 short period (three component) plus 1 long period (three component))[d]
Seismometer noise	≤10 dB below minimum earth noise at the site over the passband
Calibration	Within 5% in amplitude and 5° in phase over the passband
Sampling rate[a]	≥40 samples per second[e] Long period: ≥4 samples per second
System noise	≤10 dB below the noise of the seismometer over the passband
Resolution	18 dB below the minimum local seismic noise
Dynamic range	≥120 dB
Absolute timing accuracy	≤10 ms
Relative timing accuracy	≤1 ms between array elements
Operation temperature	–10°C to +45°C[f]
State of health	Status to be transmitted to the International Data Centre: clock, calibration, vault and/or borehole status, telemetry
Delay in transmission to the International Data Centre	≤5 min
Data frame length	Short period: ≤10 s; long period: ≤30 s
Buffer at the station or National Data Centre[g]	≥7 days
Data availability	≥98%
Timely data availability	≥97%
Mission capable arrays	≥80% of the elements should be operational
Precision on station location	≤100 m absolute for stations (World Geodetic System 84) ≤1 m relative for arrays Elevation above sea level: ≤20 m
Seismometer orientation	≤3°
Data format	Group of Scientific Experts format
Data transmission	Primary station: continuous Auxiliary station: segmented

[a] For existing Global Telemetered Seismic Network stations, upgrading needs further consideration.
[b] For a one component element of teleseismic arrays, the upper limit is 8 Hz.
[c] In the case of noisy sites or when increased capability is required, the number of sensors could be increased.
[d] This can be achieved by a single broadband instrument.
[e] This applies to three component and regional arrays. For existing teleseismic arrays, 40 samples per second are necessary for three component sensors but 20 samples per second are suitable for other sensors.
[f] Temperature range to be adapted for some specific sites.
[g] Procedure for buffering to ensure minimum loss of data and single point failure should be addressed in the International Monitoring System Operational Manual.

Figure 3 Minimum Requirements for IMS Seismic Station Specifications

I.2. Minimum Requirements for Infrasound **Station Specifications**

Characteristics	Minimum Requirements
Sensor type	Microbarometer
Number of sensors	Four element array[a]
Geometry	Triangle with a component at the centre
Spacing	Triangle basis: 1 to 3 km[b]
Station location accuracy	≤100 m
Relative sensor location	≤1 m
Measured parameter	Absolute[c] or differential pressure
Passband	0.02 to 4 Hz
Sensor response	Flat to pressure over the passband
Sensor noise	≤18 dB below minimum acoustic noise[d]
Calibration	≤5% in absolute amplitude[e]
State of health	Status data transmitted to the International Data Centre
Sampling rate	≥10 samples per second
Resolution	≥1 count per 1 mPa
Dynamic range	≥108 dB
Timing accuracy	≤1 ms[f]
Standard temperature range	–10°C to +45°C[g]
Buffer at the station or National Data Centre	≥7 days
Data format	Group of Scientific Experts format
Data frame length	≤30 s
Data transmission	Continuous
Data availability	≥98%
Timely data availability	≥97%
Mission capable array	≥3 elements operational
Acoustic filtering	Noise reduction pipes (site dependent)
Auxiliary data	Meteorological data[h]

[a] In the case of noisy sites or when increased capability is required, the number of components could be increased.
[b] 3 km is the recommended spacing.
[c] Used for daily state of health.
[d] Minimum noise level at 1 Hz: ~5 mPa.
[e] Periodicity: once per year (minimum).
[f] Better than or equal to 1 ms.
[g] Temperature range to be adapted for some specific sites.
[h] Once per minute.

Figure 4 Minimum Requirements for IMS Infrasound Station Specifications

The IMS requirements for the minimum digitizer performance are drawn from the Seismic and Infrasound Station Specifications, shown in Figure 3 and Figure 4 above.

CTBT/PTS/INF.1573/Rev.1
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EQUIPMENT CATEGORY: Passive seismological monitoring for aftershocks (Protocol to the CTBT, Part II, para. 69(e))					
Identification Code	**Item**	**Function**	**Technical Specifications**	**Specific Operational Requirements**	**Specific Certification Requirements**
PSM-2	Data acquisition system	Digitize signals from seismometers, add an authentication signature to the data, store data on media and, as required, provide data to data transmission system.	• Compatible with PSM-1 • Capable of sampling at least up to 500 Hz on six or more channels • Compatible anti-aliasing filters • Dynamic range: at least 135 dB at 100 samples per second (sps) (24 bit or better A/D) • Input full scale: at least 20 peak-to-peak voltage (Vpp) at gain ×1 and 0.6 Vpp at gain ×32 • Bit weight: at least 1.5 µV at gain ×1 and 40 nV at gain ×32 • Power consumption of 5 W or less for use of six channels at 500 sps • Digitally records the observed measurements and relevant operational parameters on an internal memory, downloadable via cable, and/or on an external memory device compatible with DIM-19 • Possibility to remotely transmit the recorded data via PSM-3 • Desirable data compression prior to data transmission or storage • Data format compatible with the acquisition and processing software • Timing with the accuracy of at least ±100 µs provided by a built-in GNSS module • Authentication capability • SOH monitoring with possibility of recording and transmitting SOH data • Possibility to configure and monitor the system in the field and remotely		
PSM-3	Data transmission field unit	Remote transfer of data from PSM-2.	• Compatible with PSM-2 • Capable of continuous data transmission of recorded data to DIM-3 • Allow bidirectional communication for SOH monitoring and remote control of the seismic mini-arrays from DIM-4		
PSM-4	Installation kit	Support installation of PSM-1 and PSM-2.	• Includes digging tools to emplace PSM-1 to a minimum depth of 0.5 m • Includes buckets to cover PSM-1 in case of installation on a hard surface • Includes distance and angular measuring devices capable of providing a relative position accuracy of 0.1 m and an orientation accuracy of 1°		

Figure 5 Minimum Requirements for OSI Data Acquisition Systems

The OSI requirements for Data Acquisition Systems are drawn from the specifications shown in Figure 5 above.

1.1 Test Configuration

For most tests, the digitizer inputs were connected to a signal source and a reference meter. This connection scheme is shown in the below figure. For the total harmonic distortion tests, a Quanterra Supertonal was used in place of the DS360 as the signal source. Other tests, such as self-noise, call for some or all the input channels of the digitizers to be terminated with low noise resistors instead of being connected to a signal source.

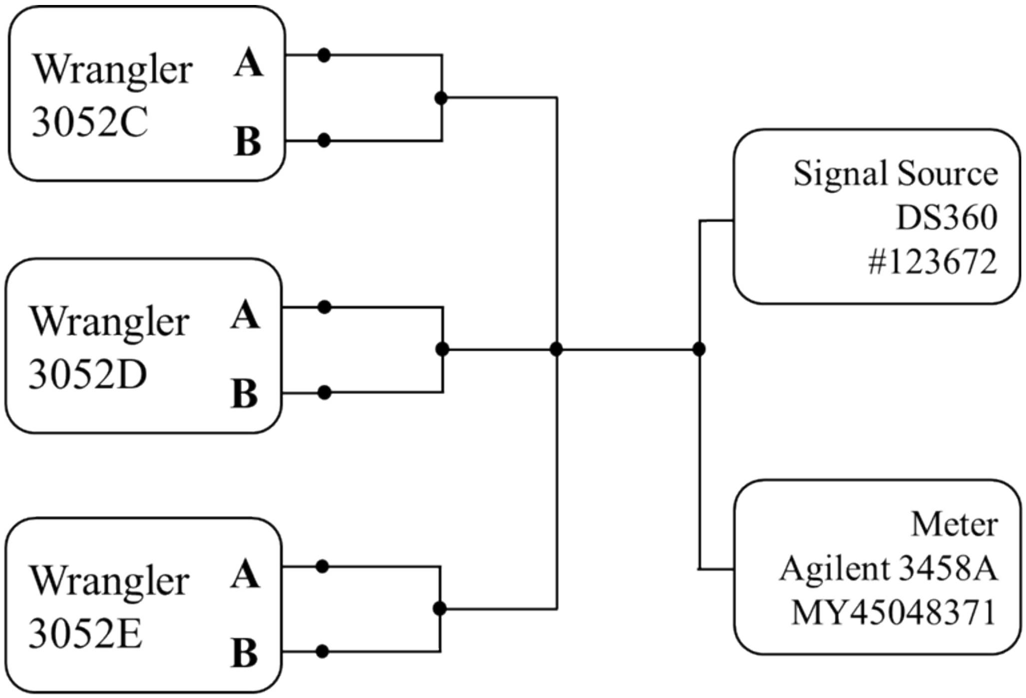

Figure 6 Digitizer Configuration Diagram

The sample rate and gain configurations that the analog performance of the digitizers were evaluated are included in Table 1, below.

Table 1 Digitizer Sample Rate and Gain Configurations

Serial #	Sample Rates	Port A Gain Levels	Port B Gain Levels
3052C	250 sps	1, 4, 16, 64	1, 4, 16, 64
3052D	200/100/40/20 sps	1, 4, 16, 64	1, 4, 16, 64
3052E	500 sps	1, 4, 16, 64	1, 4, 16, 64

2 TEST PLAN

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

2.1 Test Facility

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

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

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

Most of the digitizer testing, except for tests performed in the temperature chamber, were performed within the FACT site underground bunker due to the bunker's stable temperature.

Figure 7 FACT Site Bunker

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

Figure 8 Power Supplies

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

Figure 9 Vaisala Temperature Monitor within FACT Bunker

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

Figure 10 GNSS Re-broadcaster

2.2 Scope

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

Table 2 Tests performed

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

2.3 Timeline

The digitizer testing was performed at Sandia National Laboratories between January 12 and 31, 2023, with some subsequent re-testing in November 2023. Testing was performed using three digitizers, so that different tests could be performed on each digitizer simultaneously. The following schedule of testing was followed:

Table 3 Timeline of Testing

Day	Time	Test	3052D (20, 40, 100, 200 sps) Port A (Ch 1-3)	3052D (20, 40, 100, 200 sps) Port B (Ch 4-6)	3052C (250 sps) Port A (Ch 1-3)	3052C (250 sps) Port B (Ch 4-6)	3052E (500 sps) Port A (Ch 1-3)	3052E (500 sps) Port B (Ch 4-6)
Thu, Jan 12	Morning	Equipment Setup	N/A	N/A	N/A	N/A	N/A	N/A
	Overnight	Terminated Noise Baseline	x1	x1	x1	x1	x1	x1
Mon, Jan 16	Early Morning	Bitweight, Fullscale, Response	x1	x1	x1	x1	x1	x1
	Late Morning	Bitweight, Fullscale, Response	x4	x4	x4	x4	x4	x4
	Afternoon	Input impedance, power consumption	All	All	All	All	All	All
	Overnight	MNPR	x1	x4	x1	x4	x1	x4
Tue, Jan 17	Morning	Crosstalk	All	All	All	All	All	All
	Late morning	Bitweight, Fullscale, Response	x16	x16	x16	x16	x16	x16
	Afternoon	THD	x1	x1	x1	x1	x1	x1
	Late Afternoon	Common mode	All	All	All	All	All	All
	Overnight	Bitweight, Fullscale, Response, MNPR	x64	x64	x64	x64	x64	x64
Wed, Jan 18	Early Morning	THD	x4	x4	x4	x4	x4	x4
	Morning	THD	x16	x16	x16	x16	x16	x16
	Late morning	THD	x64	x64	x64	x64	x64	x64
	Afternoon	Calibration testing	N/A	N/A	N/A	N/A	N/A	N/A
	Overnight	Timing and Drift	x1	x1	x1	x4	x1	x1
Thu, Jan 19	All day	Sensor application demonstrations	x1	x1	x1	x1	x1	x1
Fri, Jan 20 - Mon, Jan 23		Temperature Testing	x1	x1	x1	x1	x1	x1
Wed, Jan 25		Terminated Noise Test	x1	x1	x1	x1	x1	x1
Thu, Jan 26		Terminated Noise Test	x4	x4	x4	x4	x4	x4
Fri, Jan 27 - Sun, Jan 29		Terminated Noise Test	x16	x16	x16	x16	x16	x16
Mon, Jan 30		Terminated Noise Test	x64	x64	x64	x64	x64	x64
Tue, Jan 31		MNPR	x4	x4	x4	x4	x4	x4

2.4 Evaluation Frequencies

The frequency range of the measurements is from 0.01 Hz to 200 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, …, 23. The nominal center frequency values, in Hz, are:

0.01,	0.0125,	0.016,	0.020,	0.025,	0.0315,	0.040,	0.050,	0.063,	0.08,
0.10,	0.125,	0.16,	0.20,	0.25,	0.315,	0.40,	0.50,	0.63,	0.8,
1.0,	1.25,	1.6,	2.0,	2.5,	3.15,	4.0,	5.0,	6.3,	8.0,
10,	12.5,	16,	20,	25,	31.5,	40,	50,	63,	80,
100,	125,	160,	200						

3 TEST EVALUATION

3.1 Power Consumption

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

3.1.1 Measurand

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

3.1.2 Configuration

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

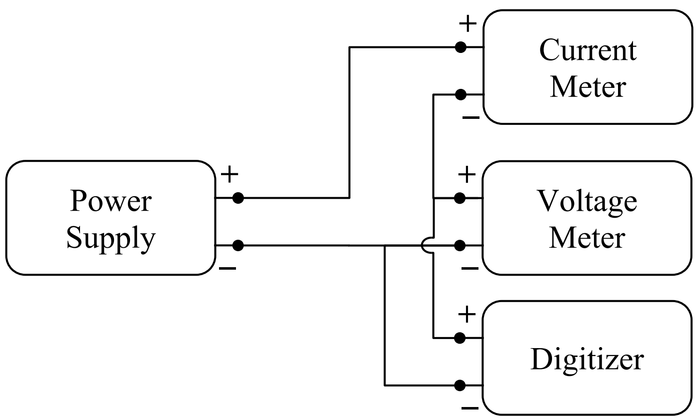

Figure 11 Power Consumption Configuration Diagram

Figure 12 Power Consumption Configuration Picture

Table 4 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
Power Supply	BK Precision 1735A DC Power Supply	N/A	15 V	
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage Mode	3052D 3052E
Current Meter	Agilent 3458A	MY45048371	DC Current Mode	
Voltage Meter	HP 3458A	2823A06443	DC Voltage Mode	3052C
Current Meter	HP 3458A	2823A10915	DC Current Mode	

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

3.1.3 Analysis

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

$$V \text{ and } I$$

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

$$P = V * I$$

3.1.4 Result

The figure below shows a representative waveform time series for the recordings of voltage and current made on the reference meters. The window regions bounded by the red lines indicate the segments of data used to evaluate the voltage and current.

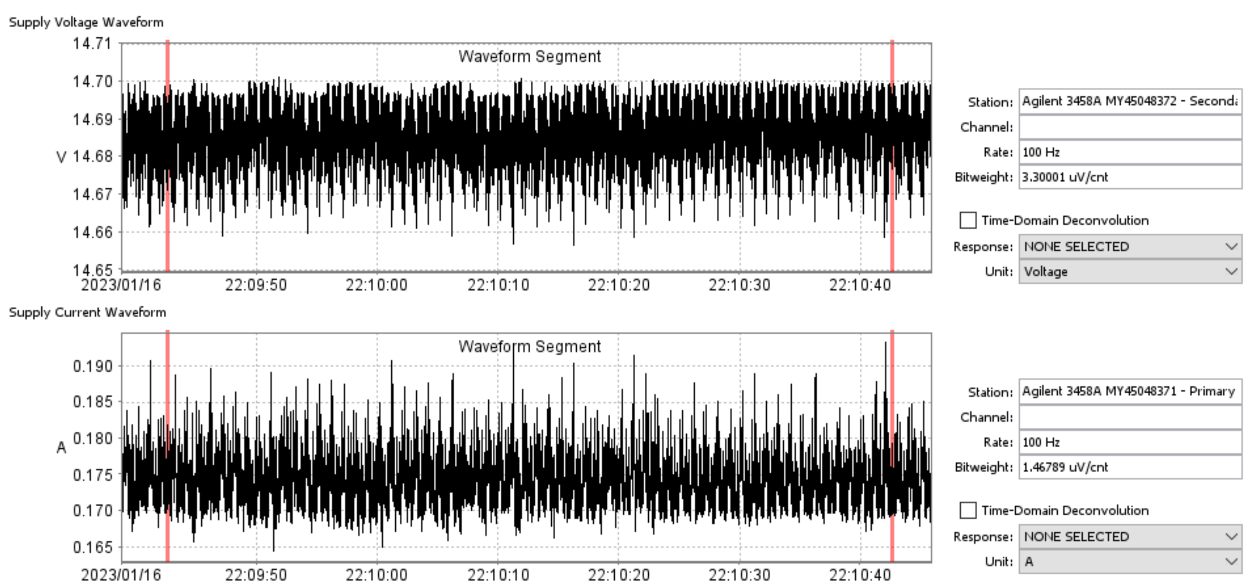

Figure 13 Power Consumption Voltage and Current Time Series

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

Table 5 Power Consumption Results: Wrangler 3052C

	Supply Voltage		Supply Current		Power Consumption	
Gain	Mean (V)	Std Dev (V)	Mean (A)	Std Dev (A)	Mean (W)	Std Dev (W)
G1	14.54	0.008	0.1960	0.005	2.85	0.07
G4	14.54	0.009	0.1960	0.004	2.85	0.05
G16	14.54	0.008	0.1959	0.004	2.85	0.06
G64	14.54	0.009	0.1957	0.003	2.85	0.05
G1 No Ethernet	14.64	0.008	0.1558	0.005	2.28	0.07

Table 6 Power Consumption Results: Wrangler 3052D

	Supply Voltage		Supply Current		Power Consumption	
Gain	Mean (V)	Std Dev (V)	Mean (A)	Std Dev (A)	Mean (W)	Std Dev (W)
G1	14.30	0.021	0.2015	0.006	2.88	0.09
G4	14.29	0.039	0.2033	0.006	2.90	0.10
G16	14.41	0.014	0.2010	0.005	2.90	0.07
G64	14.33	0.035	0.2030	0.006	2.91	0.10
G1 No Ethernet	14.45	0.016	0.1611	0.005	2.33	0.08

Table 7 Power Consumption Results: Wrangler 3052E

	Supply Voltage		Supply Current		Power Consumption	
Gain	Mean (V)	Std Dev (V)	Mean (A)	Std Dev (A)	Mean (W)	Std Dev (W)
G1	14.69	0.008	0.1733	0.003	2.55	0.05
G4	14.63	0.008	0.1753	0.005	2.56	0.08
G16	14.63	0.008	0.1765	0.005	2.58	0.08
G64	14.63	0.008	0.1780	0.006	2.60	0.10
G1 No Ethernet	14.67	0.009	0.1576	0.006	2.31	0.09

The Wrangler digitizers consumed between 2.55 W and 2.91 W of power while operating with an ethernet cable connection (actively streaming data) and with GNSS time synchronization continuously enabled. When the ethernet cable was disconnected from the digitizers they consumed between 2.28W and 2.33W. There does not appear to be any change in power consumption with gain level.

The Wrangler datasheet specifies that the expected power consumption is 2.3 W for a 6-channel configuration with communications enabled and GNSS duty cycled. The continuous use of GNSS timing in the test measurements is the likely explanation for why the measured power consumption is higher than the value specified in the datasheet.

In addition, the Wranglers were confirmed to acquire data and operate at voltages ranging from 10.5 V to 30.5 V.

The OSI requirements state a power consumption of 5 W or less, which the Wrangler demonstrates in all the tested configurations.

3.2 Input Impedance

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

3.2.1 Measurand

The quantity being measured is ohms of impedance of the digitizer input channel.

3.2.2 Configuration

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

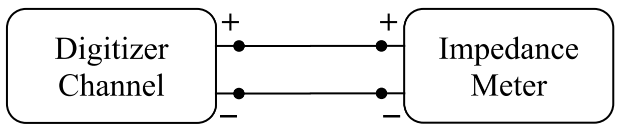

Figure 14 Input Impedance Configuration Diagram

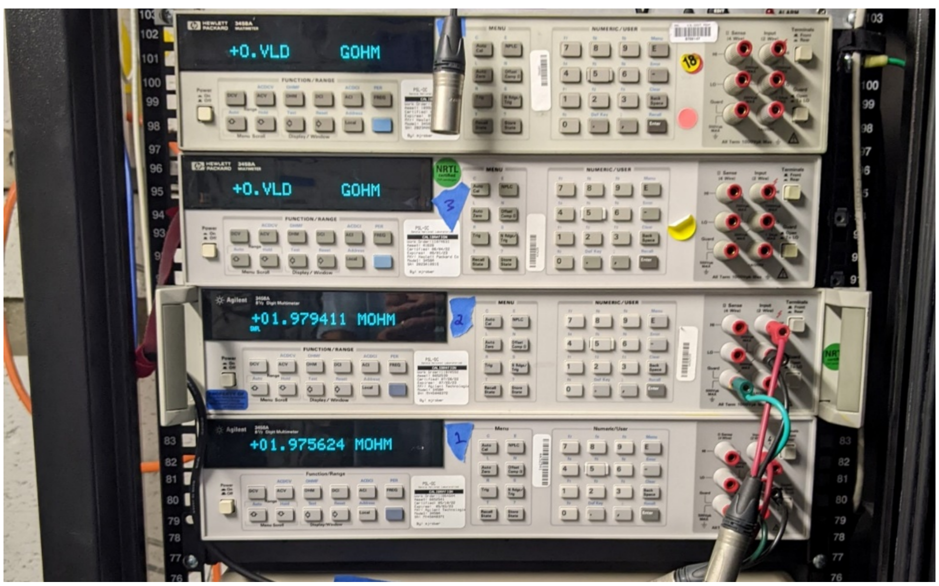

Figure 15 Input Impedance Configuration Picture

Table 8 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizer
Impedance Meter	Agilent 3458A	MY45048371	DC Impedance	3052D
Impedance Meter	Agilent 3458A	MY45048372	DC Impedance	3052E
Impedance Meter	HP 3458A	2823A06443	DC Impedance	3052C

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

3.2.3 Analysis

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

3.2.4 Result

The measured impedance for each of the digitizer channels and their percent difference from the nominal impedances are shown in the tables below. The Wranglers nominal input impedance when operating at a gain of x1 or x16 is 26 kohm and at a gain of x4 or x64 is 2 Mohm.

Table 9 Input Impedance Results: 3052C

Chn	Gain 1		Gain 4		Gain 16		Gain 64*	
1	26.35 kohm	1.33%	1.97 Mohm	-1.70%	26.35 kohm	1.33%	1.98 Mohm	-0.92%
2	26.35 kohm	1.33%	1.96 Mohm	-2.05%	26.35 kohm	1.33%	1.96 Mohm	-2.10%
3	26.35 kohm	1.33%	1.97 Mohm	-1.50%	26.35 kohm	1.34%	1.98 Mohm	-0.95%
4	26.35 kohm	1.33%	1.96 Mohm	-1.90%	26.35 kohm	1.33%	1.98 Mohm	-0.97%
5	26.34 kohm	1.32%	1.96 Mohm	-1.85%	26.34 kohm	1.32%	1.99 Mohm	-0.61%
6	26.34 kohm	1.32%	1.97 Mohm	-1.55%	26.34 kohm	1.32%	2.01 Mohm	0.60%

Table 10 Input Impedance Results: 3052D

Chn	Gain 1		Gain 4		Gain 16		Gain 64*	
1	26.35 kohm	1.33%	1.96 Mohm	-1.80%	26.35 kohm	1.33%	2.03 Mohm	1.39%
2	26.35 kohm	1.33%	1.96 Mohm	-2.05%	26.35 kohm	1.33%	1.98 Mohm	-0.77%
3	26.35 kohm	1.33%	1.97 Mohm	-1.65%	26.35 kohm	1.33%	2.01 Mohm	0.66%
4	26.34 kohm	1.32%	1.96 Mohm	-2.00%	26.34 kohm	1.32%	2.04 Mohm	2.18%
5	26.35 kohm	1.35%	1.96 Mohm	-2.00%	26.35 kohm	1.35%	2.03 Mohm	1.27%
6	26.35 kohm	1.33%	1.97 Mohm	-1.65%	26.35 kohm	1.33%	2.01 Mohm	0.27%

Table 11 Input Impedance Results: 3052E

Chn	Gain 1		Gain 4		Gain 16		Gain 64*	
1	26.35 kohm	1.33%	1.97 Mohm	-1.35%	26.35 kohm	1.33%	2.00 Mohm	0.10%
2	26.35 kohm	1.33%	1.97 Mohm	-1.65%	26.35 kohm	1.33%	1.99 Mohm	-0.39%
3	26.35 kohm	1.33%	1.97 Mohm	-1.45%	26.35 kohm	1.33%	2.06 Mohm	2.89%
4	26.35 kohm	1.33%	1.97 Mohm	-1.40%	26.35 kohm	1.33%	2.02 Mohm	1.22%
5	26.35 kohm	1.33%	1.97 Mohm	-1.60%	26.35 kohm	1.33%	2.04 Mohm	2.05%
6	26.35 kohm	1.33%	1.97 Mohm	-1.65%	26.35 kohm	1.33%	1.99 Mohm	-0.73%

**Gain 64 values were measured by applying a constant voltage across the given channel. This voltage along with the current flowing into the channel were measured. The input impedance was calculated as the ratio of the voltage over the current. This method was used because the test voltage generated by the meters when operating in their Mohm measurement range was 5V which exceeded the input range of the Wranglers when they were configured with a gain of 64.*

When the Wranglers were in the x1 and x16 gain configurations, their measured input impedance was consistently 1.33% over the nominal value of 26 kohm. This suggests their nominal input impedance is 26.35 kohm and the specification provided by the manufacturer has been rounded to an integer value. When the units were operated at the x4 and 16x gain levels, the input impedance was within +/- 2.05% and +/- 2.89% of the 2 Mohm nominal value, respectively.

3.3 DC Accuracy

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

3.3.1 Measurand

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

3.3.2 Configuration

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

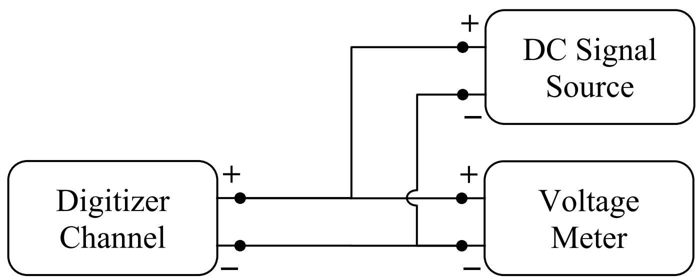

Figure 16 DC Accuracy Configuration Diagram

Table 12 DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
Signal Source	SRS DS360	123672	Square wave, 90 s period, 10% of full scale.	All
Voltage Meter	Agilent 3458A	MY45048371	10 V full scale	All

The DC Signal Source is configured to generate a DC voltage with an amplitude of 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 200 Hz.

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

3.3.3 Analysis

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

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

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

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

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

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

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

3.3.4 Result

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

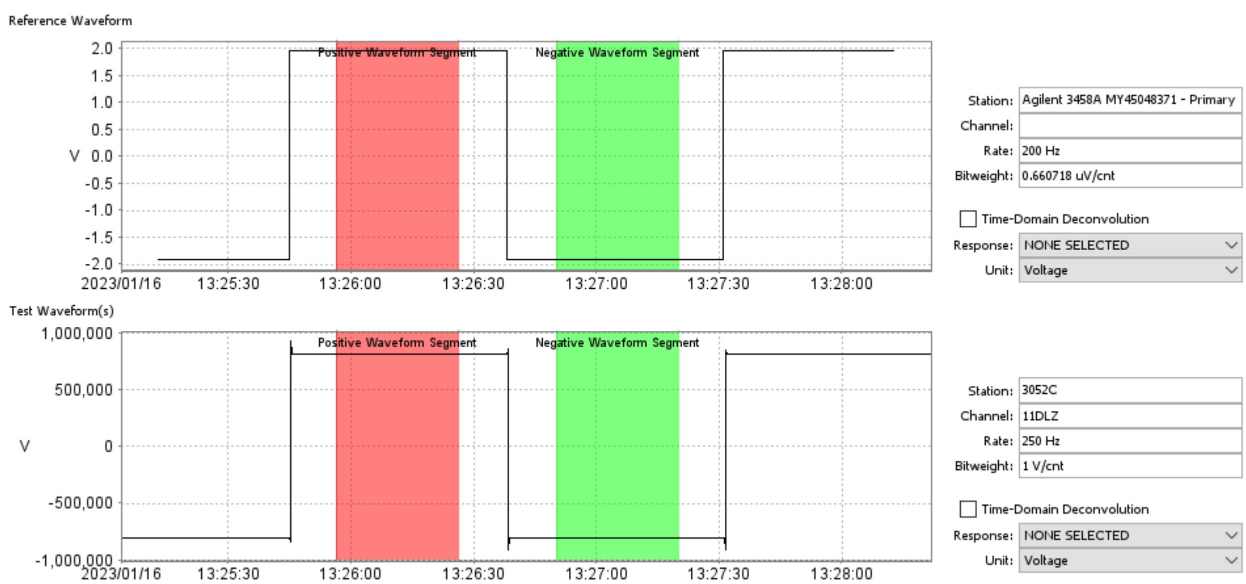

Figure 17 DC Accuracy Time Series

The following tables contain the computed bit-weights for each of the channels, sample rates, and gain levels. The measured DC bit-weights were found to be consistent with the nominal values, listed in the tables above, for all gain levels.

All measured bit-weights were within 0.33% of the nominal values of 2.384 uV/cnt, 0.596 uV/cnt, 0.149 uV/cnt, and 0.0373 uV/cnt, at gains of x1, x4, x16, and x64, respectively.

Table 13 DC Accuracy Bit-weight: Wrangler 3052C

	Port A				Port B			
	Gain 1	Gain 4	Gain 16	Gain 64	Gain 1	Gain 4	Gain 16	Gain 64
Voltage	1.9348 V	0.50007 V	0.12082 V	31.245 mV	1.9348 V	0.50007 V	0.12082 V	31.245 mV
Chan 1/4 250 sps	2.38953 uV/cnt	0.59639 uV/cnt	0.14909 uV/cnt	0.03721 uV/cnt	2.38990 uV/cnt	0.59643 uV/cnt	0.14906 uV/cnt	0.03720 uV/cnt
Chan 2/5 250 sps	2.38956 uV/cnt	0.59637 uV/cnt	0.14905 uV/cnt	0.03720 uV/cnt	2.38908 uV/cnt	0.59634 uV/cnt	0.14904 uV/cnt	0.03720 uV/cnt
Chan 3/6 250 sps	2.39003 uV/cnt	0.59652 uV/cnt	0.14912 uV/cnt	0.03722 uV/cnt	2.38982 uV/cnt	0.59645 uV/cnt	0.14910 uV/cnt	0.03721 uV/cnt
Nominal	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt
Maximum Difference	0.2529%	0.0871%	0.0812%	0.1420%	0.2475%	0.0752%	0.0664%	0.1358%

Table 14 DC Accuracy Bit-weight: Wrangler 3052D

	Port A				Port B			
	Gain 1	Gain 4	Gain 16	Gain 64	Gain 1	Gain 4	Gain 16	Gain 64
Voltage	1.93483 V	0.50007 V	0.12082 V	31.245 mV	1.9348 V	0.50007 V	0.12082 V	31.245 mV
Chan 1/4 20 sps	2.38949 uV/cnt	0.59631 uV/cnt	0.14909 uV/cnt	0.03720 uV/cnt	2.38867 uV/cnt	0.59628 uV/cnt	0.14902 uV/cnt	0.03720 uV/cnt
Chan 2/5 20 sps	2.38964 uV/cnt	0.59640 uV/cnt	0.14908 uV/cnt	0.03721 uV/cnt	2.38971 uV/cnt	0.59627 uV/cnt	0.14903 uV/cnt	0.03718 uV/cnt
Chan 3/6 20 sps	2.38910 uV/cnt	0.59636 uV/cnt	0.14907 uV/cnt	0.03721 uV/cnt	2.38884 uV/cnt	0.59625 uV/cnt	0.14898 uV/cnt	0.03718 uV/cnt
Chan 1/4 40 sps	2.38750 uV/cnt	0.59582 uV/cnt	0.14896 uV/cnt	0.03717 uV/cnt	2.38668 uV/cnt	0.59579 uV/cnt	0.14890 uV/cnt	0.03717 uV/cnt
Chan 2/5 40 sps	2.38765 uV/cnt	0.59591 uV/cnt	0.14896 uV/cnt	0.03718 uV/cnt	2.38773 uV/cnt	0.59577 uV/cnt	0.14891 uV/cnt	0.03715 uV/cnt
Chan 3/6 40 sps	2.38711 uV/cnt	0.59586 uV/cnt	0.14895 uV/cnt	0.03718 uV/cnt	2.38685 uV/cnt	0.59575 uV/cnt	0.14886 uV/cnt	0.03715 uV/cnt
Chan 1/4 100 sps	2.39170 uV/cnt	0.59686 uV/cnt	0.14922 uV/cnt	0.03724 uV/cnt	2.39087 uV/cnt	0.59683 uV/cnt	0.14916 uV/cnt	0.03723 uV/cnt
Chan 2/5 100 sps	2.39184 uV/cnt	0.59695 uV/cnt	0.14922 uV/cnt	0.03724 uV/cnt	2.39192 uV/cnt	0.59682 uV/cnt	0.14917 uV/cnt	0.03722 uV/cnt
Chan 3/6 100 sps	2.39131 uV/cnt	0.59691 uV/cnt	0.14921 uV/cnt	0.03724 uV/cnt	2.39104 uV/cnt	0.59680 uV/cnt	0.14912 uV/cnt	0.03722 uV/cnt
Chan 1/4 200 sps	2.38971 uV/cnt	0.59637 uV/cnt	0.14910 uV/cnt	0.03721 uV/cnt	2.38888 uV/cnt	0.59634 uV/cnt	0.14903 uV/cnt	0.03720 uV/cnt
Chan 2/5 200 sps	2.38985 uV/cnt	0.59646 uV/cnt	0.14910 uV/cnt	0.03721 uV/cnt	2.38993 uV/cnt	0.59632 uV/cnt	0.14904 uV/cnt	0.03719 uV/cnt
Chan 3/6 200 sps	2.38932 uV/cnt	0.59641 uV/cnt	0.14909 uV/cnt	0.03721 uV/cnt	2.38905 uV/cnt	0.59630 uV/cnt	0.14899 uV/cnt	0.03719 uV/cnt
Nominal	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt
Maximum Difference	0.3289%	0.1601%	0.1503%	0.2105%	0.3322%	0.1398%	0.1128%	0.2642%

Table 15 DC Accuracy Bit-weight: Wrangler 3052E

	Port A				Port B			
	Gain 1	Gain 4	Gain 16	Gain 64	Gain 1	Gain 4	Gain 16	Gain 64
Voltage	1.9348 V	0.50007 V	0.12082 V	31.245 mV	1.9348 V	0.50007 V	0.12082 V	31.245 mV
Chan 1/4 500 sps	2.38993 uV/cnt	0.59643 uV/cnt	0.14913 uV/cnt	0.03722 uV/cnt	2.39064 uV/cnt	0.59655 uV/cnt	0.14909 uV/cnt	0.03720 uV/cnt
Chan 2/5 500 sps	2.38978 uV/cnt	0.59635 uV/cnt	0.14908 uV/cnt	0.03720 uV/cnt	2.38933 uV/cnt	0.59628 uV/cnt	0.14905 uV/cnt	0.03720 uV/cnt
Chan 3/6 500 sps	2.38967 uV/cnt	0.59638 uV/cnt	0.14901 uV/cnt	0.03719 uV/cnt	2.39007 uV/cnt	0.59651 uV/cnt	0.14906 uV/cnt	0.03720 uV/cnt
Nominal	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt
Maximum Difference	0.2487%	0.0716%	0.0859%	0.1686%	0.2785%	0.0924%	0.0570%	0.1417%

3.4 AC Accuracy

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

3.4.1 Measurand

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

3.4.2 Configuration

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

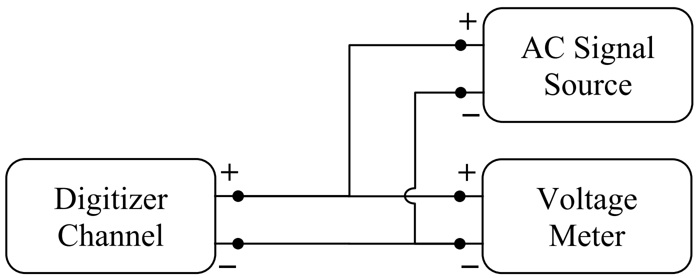

Figure 18 AC Accuracy Configuration Diagram

Table 16 AC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
Signal Source	SRS DS360	123672	Sine wave, 1.0Hz, 10% of full scale.	All
Voltage Meter	Agilent 3458A	MY45048371	10 V full scale	All

The AC Signal Source is configured to generate an AC voltage with an amplitude of 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 200 Hz, which is a minimum of 200 times the frequency of the signal of interest to negate the impact of the Agilent 3458A Meter's response roll-off at 1 Hz.

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

3.4.3 Analysis

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

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

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

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

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

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

3.4.4 Result

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

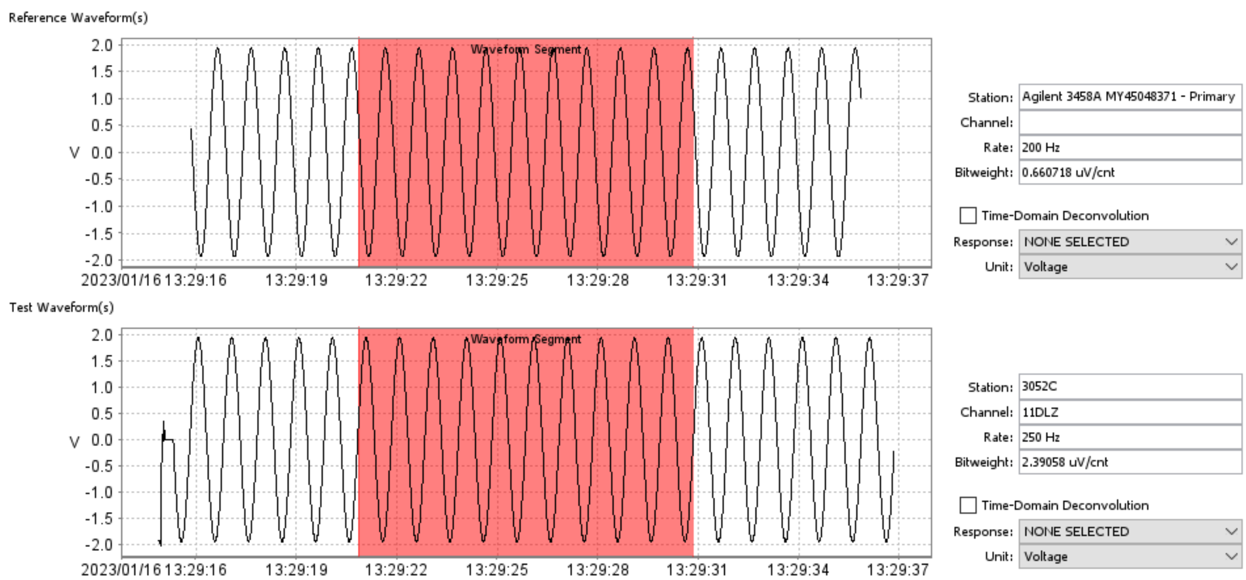

Figure 19 AC Accuracy Time Series

The following tables contain the computed bit-weights for each of the channels, sample rates, and gain levels. The measured AC bit-weights were found to be consistent with the nominal values, listed in the tables above, for all gain levels.

All measured bit-weights were within 0.36% of the nominal values of 2.384 uV/cnt, 0.596 uV/cnt, 0.149 uV/cnt, and 0.0373 uV/cnt, at gains of x1, x4, x16, and x64, respectively.

Table 17 AC Accuracy Bit-weight: Wrangler 3052C

	Port A				Port B			
	Gain 1	Gain 4	Gain 16	Gain 64	Gain 1	Gain 4	Gain 16	Gain 64
Voltage	1.93376 V	0.49978 V	0.12076 V	31.255 mV	1.93376 V	0.49978 V	0.12076 V	31.255 mV
Chan 1/4 250 sps	2.39058 uV/cnt	0.59661 uV/cnt	0.14915 uV/cnt	0.03722 uV/cnt	2.39093 uV/cnt	0.59664 uV/cnt	0.14912 uV/cnt	0.03721 uV/cnt
Chan 2/5 250 sps	2.39058 uV/cnt	0.59658 uV/cnt	0.14911 uV/cnt	0.03721 uV/cnt	2.39012 uV/cnt	0.59656 uV/cnt	0.14910 uV/cnt	0.03721 uV/cnt
Chan 3/6 250 sps	2.39106 uV/cnt	0.59673 uV/cnt	0.14918 uV/cnt	0.03723 uV/cnt	2.39086 uV/cnt	0.59666 uV/cnt	0.14916 uV/cnt	0.03722 uV/cnt
Nominal	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt
Maximum Difference	0.2961%	0.1223%	0.1228%	0.1074%	0.2907%	0.1114%	0.1067%	0.1009%

Table 18 AC Accuracy Bit-weight: Wrangler 3052D

	Port A				Port B			
	Gain 1	Gain 4	Gain 16	Gain 64	Gain 1	Gain 4	Gain 16	Gain 64
Voltage	1.93376 V	0.49978 V	0.12076 V	31.255 mV	1.93376 V	0.49978 V	0.12076 V	31.255 mV
Chan 1/4 20 sps	2.39079 uV/cnt	0.59659 uV/cnt	0.14917 uV/cnt	0.03722 uV/cnt	2.38997 uV/cnt	0.59656 uV/cnt	0.14910 uV/cnt	0.03721 uV/cnt
Chan 2/5 20 sps	2.39093 uV/cnt	0.59668 uV/cnt	0.14916 uV/cnt	0.03722 uV/cnt	2.39102 uV/cnt	0.59655 uV/cnt	0.14911 uV/cnt	0.03720 uV/cnt
Chan 3/6 20 sps	2.39042 uV/cnt	0.59664 uV/cnt	0.14915 uV/cnt	0.03723 uV/cnt	2.39016 uV/cnt	0.59653 uV/cnt	0.14906 uV/cnt	0.03720 uV/cnt
Chan 1/4 40 sps	2.39245 uV/cnt	0.59700 uV/cnt	0.14927 uV/cnt	0.03725 uV/cnt	2.39162 uV/cnt	0.59697 uV/cnt	0.14920 uV/cnt	0.03724 uV/cnt
Chan 2/5 40 sps	2.39259 uV/cnt	0.59710 uV/cnt	0.14927 uV/cnt	0.03725 uV/cnt	2.39268 uV/cnt	0.59696 uV/cnt	0.14921 uV/cnt	0.03723 uV/cnt
Chan 3/6 40 sps	2.39207 uV/cnt	0.59705 uV/cnt	0.14925 uV/cnt	0.03725 uV/cnt	2.39182 uV/cnt	0.59694 uV/cnt	0.14916 uV/cnt	0.03723 uV/cnt
Chan 1/4 100 sps	2.39052 uV/cnt	0.59652 uV/cnt	0.14915 uV/cnt	0.03722 uV/cnt	2.38969 uV/cnt	0.59649 uV/cnt	0.14908 uV/cnt	0.03721 uV/cnt
Chan 2/5 100 sps	2.39066 uV/cnt	0.59661 uV/cnt	0.14915 uV/cnt	0.03722 uV/cnt	2.39075 uV/cnt	0.59648 uV/cnt	0.14909 uV/cnt	0.03720 uV/cnt
Chan 3/6 100 sps	2.39014 uV/cnt	0.59657 uV/cnt	0.14913 uV/cnt	0.03722 uV/cnt	2.38989 uV/cnt	0.59646 uV/cnt	0.14904 uV/cnt	0.03720 uV/cnt
Chan 1/4 200 sps	2.39091 uV/cnt	0.59662 uV/cnt	0.14917 uV/cnt	0.03722 uV/cnt	2.39008 uV/cnt	0.59659 uV/cnt	0.14911 uV/cnt	0.03722 uV/cnt
Chan 2/5 200 sps	2.39105 uV/cnt	0.59671 uV/cnt	0.14917 uV/cnt	0.03722 uV/cnt	2.39114 uV/cnt	0.59658 uV/cnt	0.14912 uV/cnt	0.03720 uV/cnt
Chan 3/6 200 sps	2.39053 uV/cnt	0.59667 uV/cnt	0.14916 uV/cnt	0.03723 uV/cnt	2.39028 uV/cnt	0.59656 uV/cnt	0.14907 uV/cnt	0.03720 uV/cnt
Nominal	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt
Maximum Difference	0.3603%	0.1839%	0.1799%	0.0921%	0.3641%	0.1634%	0.1416%	0.1466%

Table 19 AC Accuracy Bit-weight: Wrangler 3052E

	Port A				Port B			
	Gain 1	Gain 4	Gain 16	Gain 64	Gain 1	Gain 4	Gain 16	Gain 64
Voltage	1.93376 V	0.49978 V	0.12076 V	31.255 mV	1.93376 V	0.49978 V	0.12076 V	31.255 mV
Chan 1/4 500 sps	2.39001 uV/cnt	0.59645 uV/cnt	0.14913 uV/cnt	0.03722 uV/cnt	2.39073 uV/cnt	0.59657 uV/cnt	0.14909 uV/cnt	0.03720 uV/cnt
Chan 2/5 500 sps	2.38985 uV/cnt	0.59637 uV/cnt	0.14909 uV/cnt	0.03720 uV/cnt	2.38939 uV/cnt	0.59630 uV/cnt	0.14905 uV/cnt	0.03720 uV/cnt
Chan 3/6 500 sps	2.38975 uV/cnt	0.59640 uV/cnt	0.14901 uV/cnt	0.03719 uV/cnt	2.39014 uV/cnt	0.59653 uV/cnt	0.14907 uV/cnt	0.03720 uV/cnt
Nominal	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt	2.3840 uV/cnt	0.5960 uV/cnt	0.1490 uV/cnt	0.0373 uV/cnt
Maximum Difference	0.2521%	0.0748%	0.0899%	0.1670%	0.2823%	0.0958%	0.0604%	0.1396%

3.5 AC Full Scale

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

3.5.1 Measurand

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

3.5.2 Configuration

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

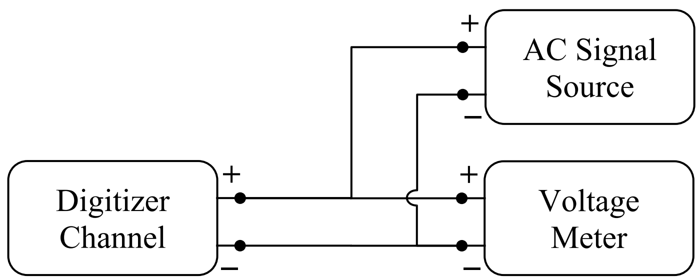

Figure 20 AC Full Scale Configuration Diagram

Table 20 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
Signal Source	SRS DS360	123672	Sine wave, 1.0Hz, 100% of full scale.	All
Voltage Meter	Agilent 3458A	MY45048371	100 V full scale	All

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 200 Hz, which is a minimum of 200 times the frequency of the signal of interest.

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

3.5.3 Analysis

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

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

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

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

3.5.4 Result

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

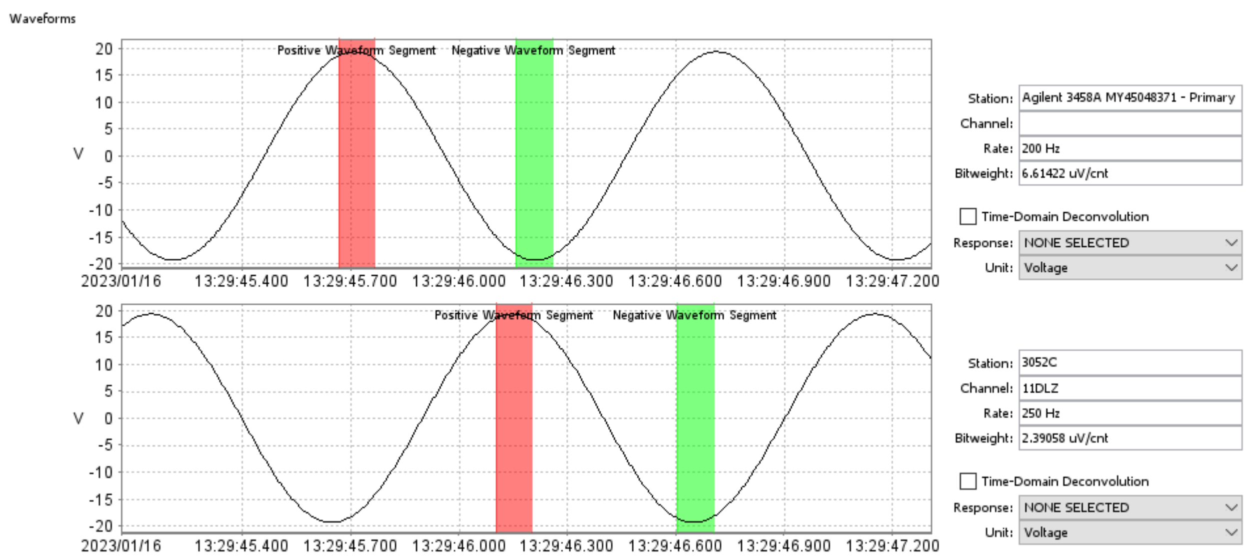

Figure 21 AC Full Scale Time Series

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

Table 21 AC Full Scale: Wrangler 3052C Port A (Ch1-3) and Port B (Ch4-6)

	Gain 1		Gain 4		Gain 16		Gain 64	
	Min	Max	Min	Max	Min	Max	Min	Max
Reference	-19.338 V	19.292 V	-5.0052 V	4.9920 V	-1.2090 V	1.2063 V	-0.31266 V	0.31175 V
Chan 1 250 sps	-19.332 V	19.285 V	-5.0032 V	4.9901 V	-1.2086 V	1.2059 V	-0.31225 V	0.31163 V
Chan 2 250 sps	-19.332 V	19.285 V	-5.0032 V	4.9902 V	-1.2086 V	1.2059 V	-0.31214 V	0.31164 V
Chan 3 250 sps	-19.332 V	19.285 V	-5.0033 V	4.9900 V	-1.2086 V	1.2059 V	-0.31232 V	0.31163 V
Chan 4 250 sps	-19.330 V	19.287 V	-5.0028 V	4.9906 V	-1.2085 V	1.2060 V	-0.31216 V	0.31166 V
Chan 5 250 sps	-19.334 V	19.283 V	-5.0037 V	4.9897 V	-1.2087 V	1.2058 V	-0.31218 V	0.31161 V
Chan 6 250 sps	-19.332 V	19.285 V	-5.0033 V	4.9901 V	-1.2086 V	1.2059 V	-0.31226 V	0.31163 V

Table 22 AC Full Scale: Wrangler 3052D Port A (Ch1-3) and Port B (Ch4-6)

	Gain 1		Gain 4		Gain 16		Gain 64	
	Min	Max	Min	Max	Min	Max	Min	Max
Reference	-19.338 V	19.292 V	-5.0052 V	4.9920 V	-1.2090 V	1.2063 V	-0.31266 V	0.31175 V
Chan 1 100 sps	-19.331 V	19.286 V	-5.0030 V	4.9904 V	-1.2085 V	1.2059 V	-0.31219 V	0.31164 V
Chan 2 100 sps	-19.332 V	19.285 V	-5.0032 V	4.9902 V	-1.2086 V	1.2059 V	-0.31221 V	0.31163 V
Chan 3 100 sps	-19.334 V	19.283 V	-5.0037 V	4.9897 V	-1.2087 V	1.2058 V	-0.31223 V	0.31160 V
Chan 4 100 sps	-19.333 V	19.285 V	-5.0033 V	4.9901 V	-1.2086 V	1.2059 V	-0.31214 V	0.31162 V
Chan 5 100 sps	-19.333 V	19.285 V	-5.0033 V	4.9902 V	-1.2086 V	1.2059 V	-0.31202 V	0.31163 V
Chan 6 100 sps	-19.335 V	19.282 V	-5.0035 V	4.9894 V	-1.2088 V	1.2057 V	-0.31202 V	0.31158 V
Chan 1 40 sps	-19.331 V	19.286 V	-5.0029 V	4.9903 V	-1.2086 V	1.2059 V	-0.31243 V	0.31164 V
Chan 2 40 sps	-19.332 V	19.285 V	-5.0031 V	4.9901 V	-1.2086 V	1.2059 V	-0.31245 V	0.31163 V
Chan 3 40 sps	-19.334 V	19.283 V	-5.0036 V	4.9897 V	-1.2087 V	1.2058 V	-0.31247 V	0.31160 V
Chan 4 40 sps	-19.333 V	19.285 V	-5.0033 V	4.9900 V	-1.2087 V	1.2059 V	-0.31240 V	0.31162 V
Chan 5 40 sps	-19.333 V	19.285 V	-5.0033 V	4.9901 V	-1.2087 V	1.2059 V	-0.31227 V	0.31163 V
Chan 6 40 sps	-19.335 V	19.282 V	-5.0039 V	4.9893 V	-1.2088 V	1.2057 V	-0.31227 V	0.31158 V
Chan 1 20 sps	-19.309 V	19.270 V	-4.9882 V	4.9726 V	-1.2085 V	1.2059 V	-0.31222 V	0.31154 V
Chan 2 20 sps	-19.310 V	19.269 V	-4.9884 V	4.9724 V	-1.2086 V	1.2058 V	-0.31225 V	0.31153 V
Chan 3 20 sps	-19.312 V	19.267 V	-4.9889 V	4.9719 V	-1.2087 V	1.2057 V	-0.31227 V	0.31150 V
Chan 4 20 sps	-19.310 V	19.269 V	-4.9886 V	4.9723 V	-1.2086 V	1.2058 V	-0.31218 V	0.31152 V
Chan 5 20 sps	-19.310 V	19.269 V	-4.9886 V	4.9723 V	-1.2086 V	1.2058 V	-0.31205 V	0.31153 V
Chan 6 20 sps	-19.313 V	19.266 V	-4.9892 V	4.9716 V	-1.2087 V	1.2057 V	-0.31205 V	0.31148 V
Chan 1 200 sps	-19.331 V	19.286 V	-5.0030 V	4.9904 V	-1.2085 V	1.2059 V	-0.31224 V	0.31165 V
Chan 2 200 sps	-19.332 V	19.285 V	-5.0033 V	4.9902 V	-1.2086 V	1.2059 V	-0.31226 V	0.31163 V
Chan 3 200 sps	-19.334 V	19.283 V	-5.0037 V	4.9897 V	-1.2087 V	1.2058 V	-0.31228 V	0.31161 V
Chan 4 200 sps	-19.333 V	19.285 V	-5.0034 V	4.9901 V	-1.2086 V	1.2059 V	-0.31220 V	0.31163 V
Chan 5 200 sps	-19.333 V	19.285 V	-5.0034 V	4.9901 V	-1.2086 V	1.2059 V	-0.31207 V	0.31163 V
Chan 6 200 sps	-19.335 V	19.282 V	-5.0040 V	4.9894 V	-1.2088 V	1.2057 V	-0.31207 V	0.31158 V

Table 23 AC Full Scale: Wrangler 3052E Port A (Ch1-3) and Port B (Ch4-6)

	Gain 1		Gain 4		Gain 16		Gain 64	
	Min	Max	Min	Max	Min	Max	Min	Max
Reference	-19.338 V	19.292 V	-5.0052 V	4.9920 V	-1.2090 V	1.2063 V	-0.31266 V	0.31175 V
Chan 1 500 sps	-19.335 V	19.287 V	-5.0034 V	4.9909 V	-1.2088 V	1.2060 V	-0.31220 V	0.31168 V
Chan 2 500 sps	-19.332 V	19.286 V	-5.0027 V	4.9904 V	-1.2086 V	1.2059 V	-0.31208 V	0.31165 V
Chan 3 500 sps	-19.335 V	19.291 V	-5.0030 V	4.9918 V	-1.2084 V	1.2059 V	-0.31195 V	0.31164 V
Chan 4 500 sps	-19.337 V	19.291 V	-5.0044 V	4.9917 V	-1.2086 V	1.2060 V	-0.31208 V	0.31167 V
Chan 5 500 sps	-19.333 V	19.286 V	-5.0021 V	4.9905 V	-1.2086 V	1.2059 V	-0.31204 V	0.31166 V
Chan 6 500 sps	-19.338 V	19.287 V	-5.0040 V	4.9909 V	-1.2089 V	1.2060 V	-0.31208 V	0.31168 V

3.6 AC Over Scale

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

3.6.1 Measurand

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

3.6.2 Configuration

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

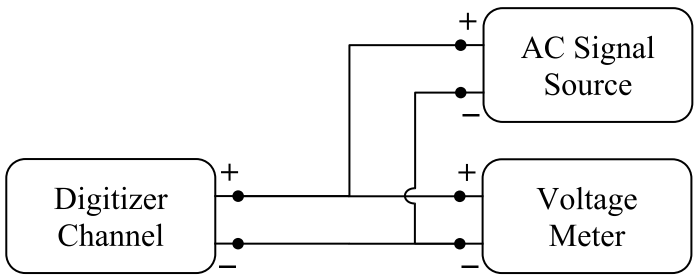

Figure 22 AC Over Scale Configuration Diagram

Table 24 AC Over Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
Signal Source	SRS DS360	123672	Sine wave, 1.0Hz, 110% of fullscale.	All
Voltage Meter	Agilent 3458A	MY45048371	100 V full scale	All

The AC Signal Source is configured to generate an AC voltage with an amplitude 110% of the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. 10 seconds of data is recorded.

Caution is taken to ensure that the voltage amplitude does not exceed the safety limits of the recording channel and that the test is short in duration to minimize the potential for damage to the equipment.

The meter and the digitizer channel record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 200 Hz, which is a minimum of 200 times the frequency of the signal of interest.

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

3.6.3 Analysis

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

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

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

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

3.6.4 Result

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

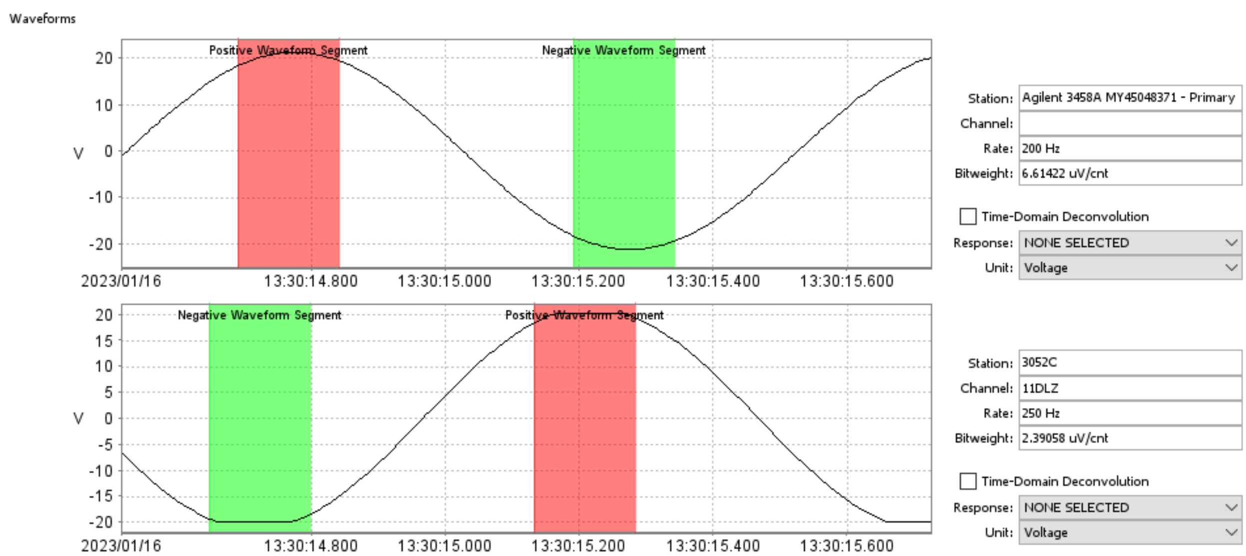

Figure 23 AC Over Scale Time Series

Note that in the figure above, the waveform recorded by the reference meter shows no sign of flattening at the positive or negative peak. The waveform recorded by the Wrangler, however, shows flattening at both the positive and negative peak indicating that the input signal has exceeded the measurement range of the digitizer and the recorded waveform has been clipped.

When the Wranglers operated with a gain of x1, they exceed the nominal clip value (40Vpp) by a minimum of 0.22%. When operated at a gain of x4, they exceeded the nominal clip value (10Vpp) by a minimum of 0.04%. When operated at a gain of x16, they exactly met the nominal clip value of 2.5Vpp. Finally, when operated at a gain of x64, the Wranglers measured clip value was slightly lower than the nominal value of 0.625Vpp. The worst-case channel had a clip value that was 0.176% less than the nominal value (i.e., it clipped at 0.624Vpp instead of the nominal value of 0.625Vpp).

These clip value results closely match the Wrangler datasheet nominal values at all sample rates and gain levels and exceed the OSI minimum requirement of 20 Vpp at a gain of x1. Although the Wrangler does not have a gain of x32, as called out in the OSI requirements, its clip level at a gain of x64 still exceeds the OSI requirement of 0.6 Vpp at a gain of x32.

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

Table 25 AC Over Scale: Wrangler 3052C Port A (Ch1-3) and Port B (Ch4-6)

	Gain 1		Gain 4		Gain 16		Gain 64	
	Min	Max	Min	Max	Min	Max	Min	Max
Reference	-21.271 V	21.223 V	-5.4729 V	5.4596 V	-1.3330 V	1.3281 V	-0.34389 V	0.34298 V
Chan 1 250 sps	-20.054 V	20.054 V	-5.0047 V	5.0047 V	-1.2512 V	1.2512 V	-0.31225 V	0.31225 V
Chan 2 250 sps	-20.054 V	20.054 V	-5.0044 V	5.0044 V	-1.2508 V	1.2508 V	-0.31214 V	0.31214 V
Chan 3 250 sps	-20.058 V	20.058 V	-5.0057 V	5.0057 V	-1.2514 V	1.2514 V	-0.31232 V	0.31232 V
Chan 4 250 sps	-20.057 V	20.057 V	-5.0050 V	5.0050 V	-1.2509 V	1.2509 V	-0.31216 V	0.31216 V
Chan 5 250 sps	-20.050 V	20.050 V	-5.0043 V	5.0043 V	-1.2508 V	1.2508 V	-0.31218 V	0.31218 V
Chan 6 250 sps	-20.056 V	20.056 V	-5.0052 V	5.0052 V	-1.2512 V	1.2512 V	-0.31226 V	0.31226 V

Table 26 AC Over Scale: Wrangler 3052D Port A (Ch1-3) and Port B (Ch4-6)

	Gain 1		Gain 4		Gain 16		Gain 64	
	Min	Max	Min	Max	Min	Max	Min	Max
Reference	-21.271 V	21.223 V	-5.4729 V	5.4596 V	-1.3330 V	1.3281 V	-0.34389 V	0.34298 V
Chan 1 100 sps	-20.053 V	20.053 V	-5.0040 V	5.0040 V	-1.2511 V	1.2511 V	-0.31219 V	0.31219 V
Chan 2 100 sps	-20.054 V	20.054 V	-5.0048 V	5.0048 V	-1.2511 V	1.2511 V	-0.31221 V	0.31221 V
Chan 3 100 sps	-20.050 V	20.050 V	-5.0044 V	5.0044 V	-1.2510 V	1.2510 V	-0.31223 V	0.31223 V
Chan 4 100 sps	-20.046 V	20.046 V	-5.0037 V	5.0037 V	-1.2506 V	1.2506 V	-0.31214 V	0.31214 V
Chan 5 100 sps	-20.055 V	20.055 V	-5.0036 V	5.0036 V	-1.2507 V	1.2507 V	-0.31202 V	0.31202 V
Chan 6 100 sps	-20.048 V	20.048 V	-5.0035 V	5.0035 V	-1.2503 V	1.2503 V	-0.31202 V	0.31202 V
Chan 1 40 sps	-20.069 V	20.069 V	-5.0080 V	5.0080 V	-1.2522 V	1.2522 V	-0.31244 V	0.31244 V
Chan 2 40 sps	-20.071 V	20.071 V	-5.0088 V	5.0088 V	-1.2521 V	1.2521 V	-0.31246 V	0.31246 V
Chan 3 40 sps	-20.066 V	20.066 V	-5.0084 V	5.0084 V	-1.2520 V	1.2520 V	-0.31248 V	0.31248 V
Chan 4 40 sps	-20.062 V	20.062 V	-5.0078 V	5.0078 V	-1.2516 V	1.2516 V	-0.31240 V	0.31240 V
Chan 5 40 sps	-20.071 V	20.071 V	-5.0077 V	5.0077 V	-1.2517 V	1.2517 V	-0.31227 V	0.31227 V
Chan 6 40 sps	-20.064 V	20.064 V	-5.0075 V	5.0075 V	-1.2513 V	1.2513 V	-0.31227 V	0.31227 V
Chan 1 20 sps	-20.055 V	20.055 V	-5.0046 V	5.0046 V	-1.2513 V	1.2513 V	-0.31222 V	0.31222 V
Chan 2 20 sps	-20.057 V	20.057 V	-5.0053 V	5.0053 V	-1.2513 V	1.2513 V	-0.31225 V	0.31225 V
Chan 3 20 sps	-20.052 V	20.052 V	-5.0050 V	5.0050 V	-1.2512 V	1.2512 V	-0.31227 V	0.31227 V
Chan 4 20 sps	-20.048 V	20.048 V	-5.0043 V	5.0043 V	-1.2507 V	1.2507 V	-0.31218 V	0.31218 V
Chan 5 20 sps	-20.057 V	20.057 V	-5.0042 V	5.0042 V	-1.2508 V	1.2508 V	-0.31205 V	0.31205 V
Chan 6 20 sps	-20.050 V	20.050 V	-5.0041 V	5.0041 V	-1.2504 V	1.2504 V	-0.31205 V	0.31205 V
Chan 1 200 sps	-20.056 V	20.056 V	-5.0048 V	5.0048 V	-1.2513 V	1.2513 V	-0.31224 V	0.31224 V
Chan 2 200 sps	-20.058 V	20.058 V	-5.0056 V	5.0056 V	-1.2513 V	1.2513 V	-0.31226 V	0.31226 V
Chan 3 200 sps	-20.053 V	20.053 V	-5.0052 V	5.0052 V	-1.2512 V	1.2512 V	-0.31228 V	0.31228 V
Chan 4 200 sps	-20.049 V	20.049 V	-5.0046 V	5.0046 V	-1.2508 V	1.2508 V	-0.31220 V	0.31220 V
Chan 5 200 sps	-20.058 V	20.058 V	-5.0045 V	5.0045 V	-1.2509 V	1.2509 V	-0.31207 V	0.31207 V
Chan 6 200 sps	-20.051 V	20.051 V	-5.0043 V	5.0043 V	-1.2505 V	1.2505 V	-0.31207 V	0.31207 V

Table 27 AC Over Scale: Wrangler 3052E Port A (Ch1-3) and Port B (Ch4-6)

	Gain 1		Gain 4		Gain 16		Gain 64	
	Min	Max	Min	Max	Min	Max	Min	Max
Reference	-21.271 V	21.223 V	-5.4729 V	5.4596 V	-1.3330 V	1.3281 V	-0.34389 V	0.34298 V
Chan 1 500 sps	-20.049 V	20.049 V	-5.0034 V	5.0034 V	-1.2510 V	1.2510 V	-0.31220 V	0.31220 V
Chan 2 500 sps	-20.048 V	20.048 V	-5.0027 V	5.0027 V	-1.2506 V	1.2506 V	-0.31208 V	0.31208 V
Chan 3 500 sps	-20.047 V	20.047 V	-5.0030 V	5.0030 V	-1.2500 V	1.2500 V	-0.31195 V	0.31195 V
Chan 4 500 sps	-20.055 V	20.055 V	-5.0044 V	5.0044 V	-1.2507 V	1.2507 V	-0.31208 V	0.31208 V
Chan 5 500 sps	-20.044 V	20.044 V	-5.0021 V	5.0021 V	-1.2504 V	1.2504 V	-0.31204 V	0.31204 V
Chan 6 500 sps	-20.050 V	20.050 V	-5.0040 V	5.0040 V	-1.2505 V	1.2505 V	-0.31208 V	0.31208 V

3.7 Input Shorted Offset

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

3.7.1 Measurand

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

3.7.2 Configuration

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

Figure 24 Input Shorted Offset Configuration Diagram

Table 28 Input Shorted Offset Testbed Equipment for x1, x4 and x16 gain levels

	Wrangler 3052C (250 sps)		Wrangler 3052D (200, 100, 40, 20 sps)		Wrangler 3052E (500 sps)	
	Port A	Port B	Port A	Port B	Port A	Port B
Channel 1 / 4	50 Ohm	50 Ohm	50 Ohm	50 Ohm	50 Ohm	50 Ohm
Channel 2 / 5	100 Ohm	100 Ohm	100 Ohm	100 Ohm	100 Ohm	100 Ohm
Channel 2 / 6	200 Ohm	200 Ohm	200 Ohm	200 Ohm	200 Ohm	200 Ohm

Table 29 Input Shorted Offset Testbed Equipment for x64 gain level

	Wrangler 3052C (250 sps)		Wrangler 3052D (200, 100, 40, 20 sps)		Wrangler 3052E (500 sps)	
	Port A	Port B	Port A	Port B	Port A	Port B
Channel 1 / 4	500 Ohm	500 Ohm	500 Ohm	500 Ohm	500 Ohm	500 Ohm
Channel 2 / 5	4k Ohm	4k Ohm	4k Ohm	4k Ohm	4k Ohm	4k Ohm
Channel 2 / 6	10k Ohm	10k Ohm	10k Ohm	10k Ohm	10k Ohm	10k Ohm

A minimum of 8 hours of data is recorded.

3.7.3 Analysis

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

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

The mean value, in volts, is calculated:

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

3.7.4 Result

The figures below show representative waveform time series for the recording made on the digitizer channels under test. The window regions bounded by the red lines indicate the segments of data used for analysis. A minimum of 8 hours of data was selected for use in analyzing the offset, chosen after the DC level of the voltage has stabilized.

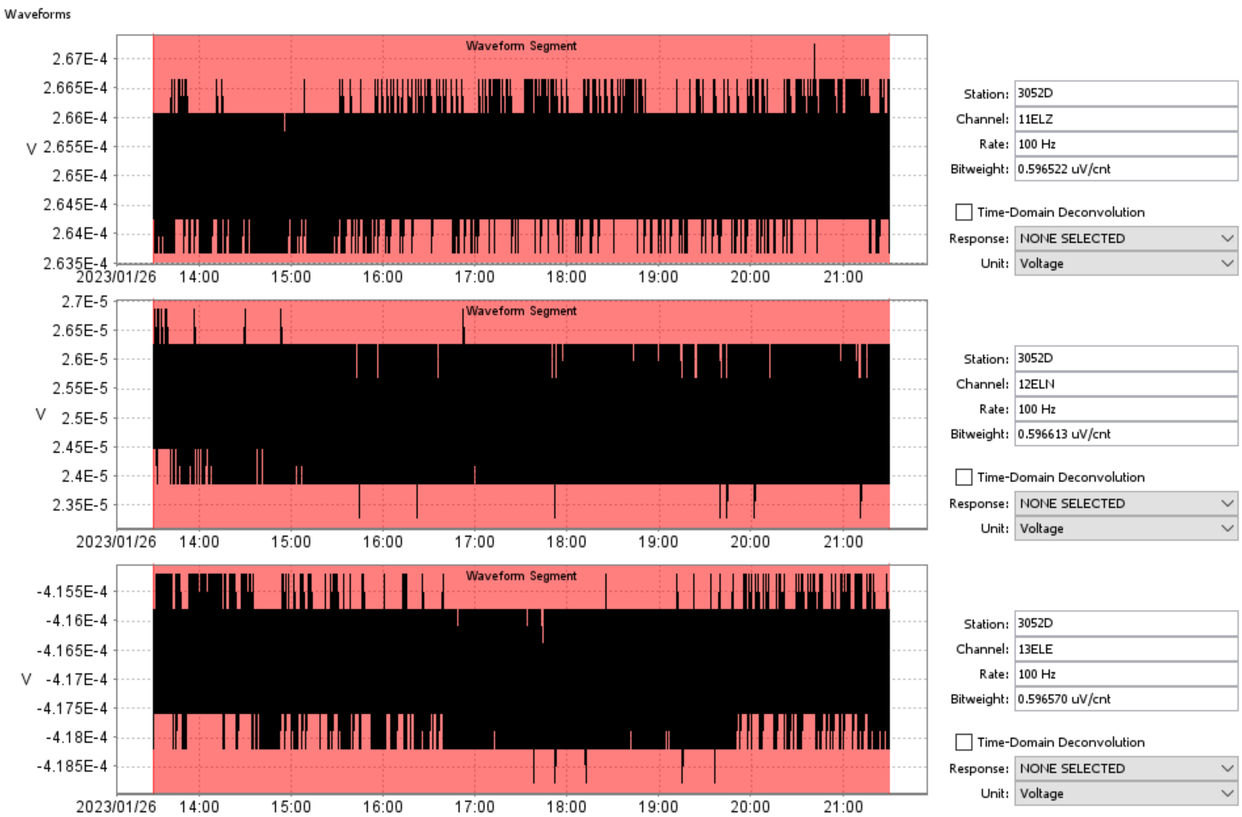

Figure 25 Input Shorted Offset: Wrangler 3052D Ch1-3, Gain 4

The following tables contain the computed DC offsets in millivolts for each of the channels and gain levels.

Table 30 Input Shorted Offset: Wrangler 3052C

Sample Rate	Channel	Gain 1	Gain 4	Gain 16	Gain 64
250	1	0.219 mV	0.054 mV	0.028 mV	0.005 mV
250	2	0.188 mV	0.051 mV	0.006 mV	0.002 mV
250	3	-0.310 mV	-0.083 mV	0.013 mV	0.013 mV
250	4	1.888 mV	0.476 mV	0.122 mV	0.031 mV
250	5	-1.730 mV	-0.429 mV	-0.096 mV	-0.023 mV
250	6	-0.107 mV	-0.032 mV	0.019 mV	0.013 mV

Table 31 Input Shorted Offset: Wrangler 3052D

Sample Rate	Channel	Gain 1	Gain 4	Gain 16	Gain 64
20	1	1.057 mV	0.265 mV	0.075 mV	0.020 mV
20	2	0.096 mV	0.025 mV	0.002 mV	0.000 mV
20	3	-1.663 mV	-0.417 mV	-0.082 mV	-0.014 mV
20	4	-0.279 mV	-0.067 mV	-0.020 mV	-0.003 mV
20	5	-0.252 mV	-0.062 mV	-0.007 mV	0.000 mV
20	6	-2.995 mV	1.548 mV	-0.131 mV	-0.032 mV
40	1	1.058 mV	0.266 mV	0.075 mV	0.020 mV
40	2	0.096 mV	0.025 mV	0.002 mV	0.000 mV
40	3	-1.666 mV	-0.418 mV	-0.082 mV	-0.014 mV
40	4	-0.279 mV	-0.067 mV	-0.020 mV	-0.003 mV
40	5	-0.253 mV	-0.062 mV	-0.007 mV	0.000 mV
40	6	-2.999 mV	1.551 mV	-0.131 mV	-0.032 mV
100	1	1.056 mV	0.265 mV	0.075 mV	0.020 mV
100	2	0.096 mV	0.025 mV	0.002 mV	0.000 mV
100	3	-1.662 mV	-0.417 mV	-0.082 mV	-0.014 mV
100	4	-0.279 mV	-0.067 mV	-0.020 mV	-0.003 mV
100	5	-0.252 mV	-0.062 mV	-0.007 mV	0.000 mV
100	6	-2.992 mV	1.547 mV	-0.131 mV	-0.032 mV
200	1	1.057 mV	0.265 mV	0.075 mV	0.020 mV
200	2	0.096 mV	0.025 mV	0.002 mV	0.000 mV
200	3	-1.663 mV	-0.417 mV	-0.082 mV	-0.014 mV
200	4	-0.279 mV	-0.067 mV	-0.020 mV	-0.003 mV
200	5	-0.252 mV	-0.062 mV	-0.007 mV	0.000 mV
200	6	-2.995 mV	1.548 mV	-0.131 mV	-0.032 mV

Table 32 Input Shorted Offset: Wrangler 3052E

Sample Rate	Channel	Gain 1	Gain 4	Gain 16	Gain 64
500	1	0.104 mV	0.023 mV	0.026 mV	0.003 mV
500	2	0.670 mV	0.170 mV	0.048 mV	0.012 mV
500	3	2.325 mV	0.578 mV	0.163 mV	0.045 mV
500	4	0.955 mV	0.237 mV	0.083 mV	0.018 mV
500	5	-0.076 mV	-0.015 mV	0.008 mV	0.003 mV
500	6	-1.362 mV	-0.336 mV	-0.081 mV	-0.021 mV

The observed offsets were all less than 3 mV, in some cases significantly less. The offset generally scales in an inversely proportional manner with the gain setting, indicating that the offset is relatively constant per channel in units of counts.

3.8 Self-Noise

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

3.8.1 Measurand

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

3.8.2 Configuration

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

Figure 26 Self Noise Configuration Diagram

For the self-noise tests, the digitizer channels were initially operated at a gain of x1 and with similar valued terminating resistors to establish a baseline noise level and to determine if there were any bad channels. The table below shows the resistor configuration for the initial baseline test.

Table 33 Digitizer Self-Noise Terminator Configuration for Baseline

	Wrangler 3052C (250 sps)		Wrangler 3052D (200, 100, 40, 20 sps)		Wrangler 3052E (500 sps)	
	Port A	Port B	Port A	Port B	Port A	Port B
Channel 1 / 4	50 Ohm	100 Ohm	50 Ohm	50 Ohm	100 Ohm	100 Ohm
Channel 2 / 5	50 Ohm	100 Ohm	50 Ohm	50 Ohm	100 Ohm	100 Ohm
Channel 2 / 6	50 Ohm	100 Ohm	50 Ohm	50 Ohm	100 Ohm	100 Ohm

After the baseline test was completed, self-noise tests were conducted at each of the four gain levels (1, 4, 16 and 64). Higher resistance terminators were used for the x64 gain test since this gain stage is generally used with passive sensors that have a higher output impedance. The tables below summarize the termination resistors used for the tests.

Table 34 Digitizer Self-Noise Terminator Configuration for x1, x4 and x16 Gain Tests

	Wrangler 3052C (250 sps)		Wrangler 3052D (200, 100, 40, 20 sps)		Wrangler 3052E (500 sps)	
	Port A	Port B	Port A	Port B	Port A	Port B
Channel 1 / 4	50 Ohm	50 Ohm	50 Ohm	50 Ohm	50 Ohm	50 Ohm
Channel 2 / 5	100 Ohm	100 Ohm	100 Ohm	100 Ohm	100 Ohm	100 Ohm
Channel 2 / 6	200 Ohm	200 Ohm	200 Ohm	200 Ohm	200 Ohm	200 Ohm

Table 35 Digitizer Self-Noise Terminator Configuration for x64 Gain Test

	Wrangler 3052C (250 sps)		Wrangler 3052D (200, 100, 40, 20 sps)		Wrangler 3052E (500 sps)	
	Port A	Port B	Port A	Port B	Port A	Port B
Channel 1 / 4	500 Ohm	500 Ohm	500 Ohm	500 Ohm	500 Ohm	500 Ohm
Channel 2 / 5	4k Ohm	4k Ohm	4k Ohm	4k Ohm	4k Ohm	4k Ohm
Channel 2 / 6	10k Ohm	10k Ohm	10k Ohm	10k Ohm	10k Ohm	10k Ohm

3.8.3 Analysis

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

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

The PSD is computed (Merchant, 2011) from the time series using a Hann window of length 4k, 8k, and 16k for the 20 Hz, 40 Hz, and 100 Hz sample rates, respectively. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation passband of 0.01 Hz and the 90% confidence interval is less than 0.6 dB.

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

Over frequencies (in Hertz):

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

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

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

Where:

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

In addition, the total RMS noise is calculated over an application passband:

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

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

3.8.4 Result

3.8.4.1 Baseline Analysis at gain 1x

The figures below show PSDs of the baseline noise test that was generated with 23 hours of data.

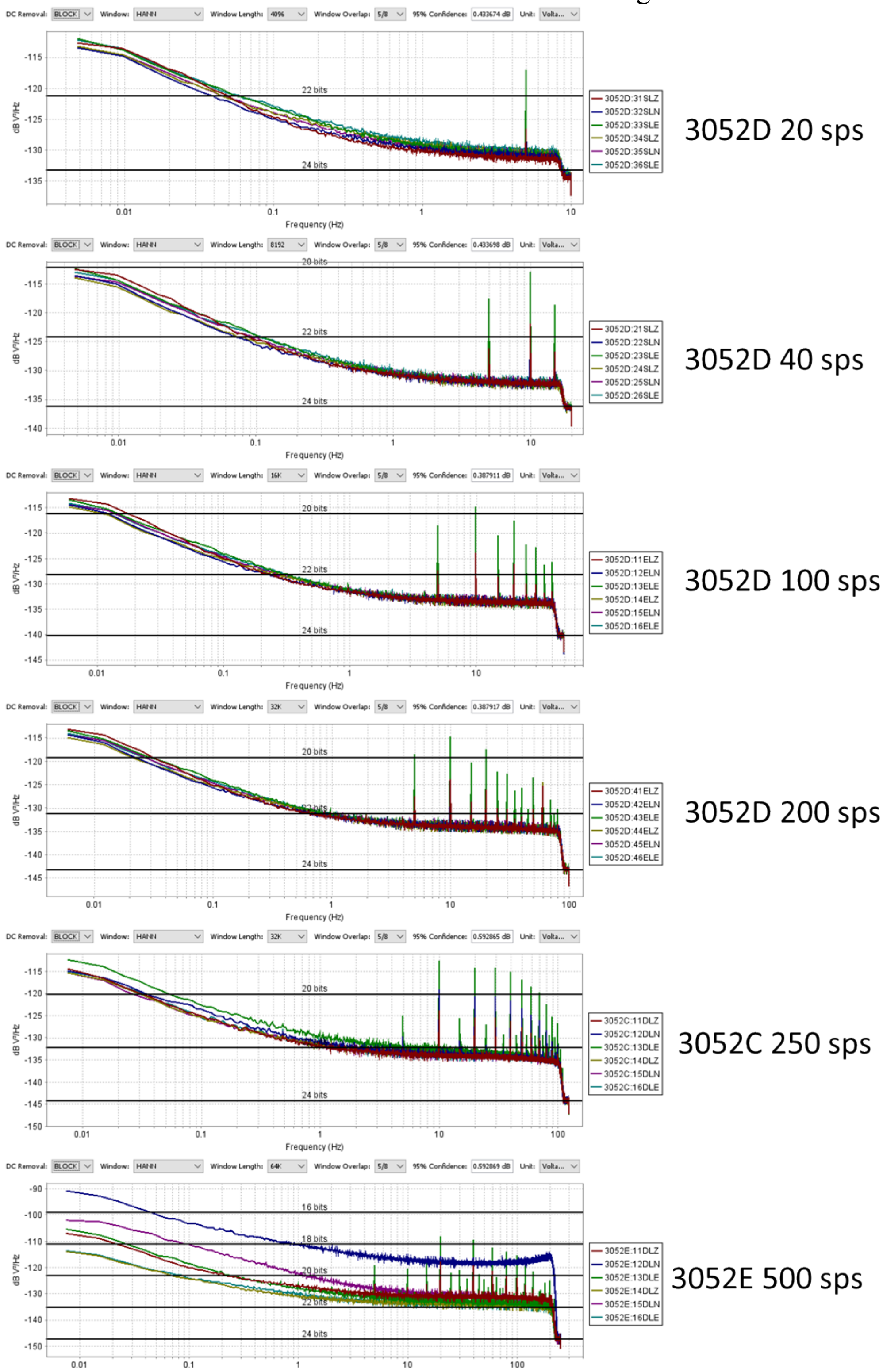

Figure 27 Self Noise Time Series for the Baseline Test

The PSDs for Wranglers 3052D show good agreement in noise levels for all channels and sample rates. The PSDs for 3052C show good agreement as well although Channel 3 of 3052C is a few dB noisier than the other channels at frequencies below about 5 Hz. The baseline PSD for 3052E, however, shows a large spread in noise levels for the different channels. Channel 2 is significantly noisier than all other channels. Based on discussions with Reftek it was determined that this channel likely had a hardware defect. As a result, the noise level of this channel will not be shown in subsequent figures. The other channels of 3052E show good agreement at high frequencies but there is deviation in noise levels at frequencies below about 5 Hz. Channel 5 is noisier than all other channels and channels 1 and 3 are a few dB noisier than channels 4 and 6 at low frequencies.

After the suite of self-noise tests were complete, 3052E was returned to Reftek who determined that a bad op-amp component was responsible for the significantly higher noise level of channel 2. This component was replaced, and the unit was returned to Sandia. In November 2023, channel 2 of 3052E was revaluated and the noise level was found to be significantly improved. A plot showing this improvement can be found in section 3.8.4.4.

As would be expected, for the same gain level all the channels had similar self-noise levels at lower frequencies, below approximately 1 Hz, where generally the contribution of analog electronics is the primary contributor to self-noise. At higher frequencies, above 1 Hz, we observe that the measured self-noise decreases as sampling rate increases, up to the measured rate of 500 sps. This indicates that the self-noise at these frequencies is likely due to amplitude quantization and the noise power is being distributed over a larger frequency passband.

3.8.4.2 Gain 1, 4 and 16 Analysis

Due to the larger number of iterations of self-noise measurements made over various sample rates and gain levels, the self-noise power spectra are summarized in the following figures, with a separate figure for each Wrangler port (either channels 1-3 or channels 4-5), and for each terminator impedance level. Traces are organized by gain and channel. For a x1 gain, a triangle is used as the marker. For a x4 gain, a circle marker is used. For x16 gain a star marker is used. A given channel is plotted with the same line color regardless of the gain setting.

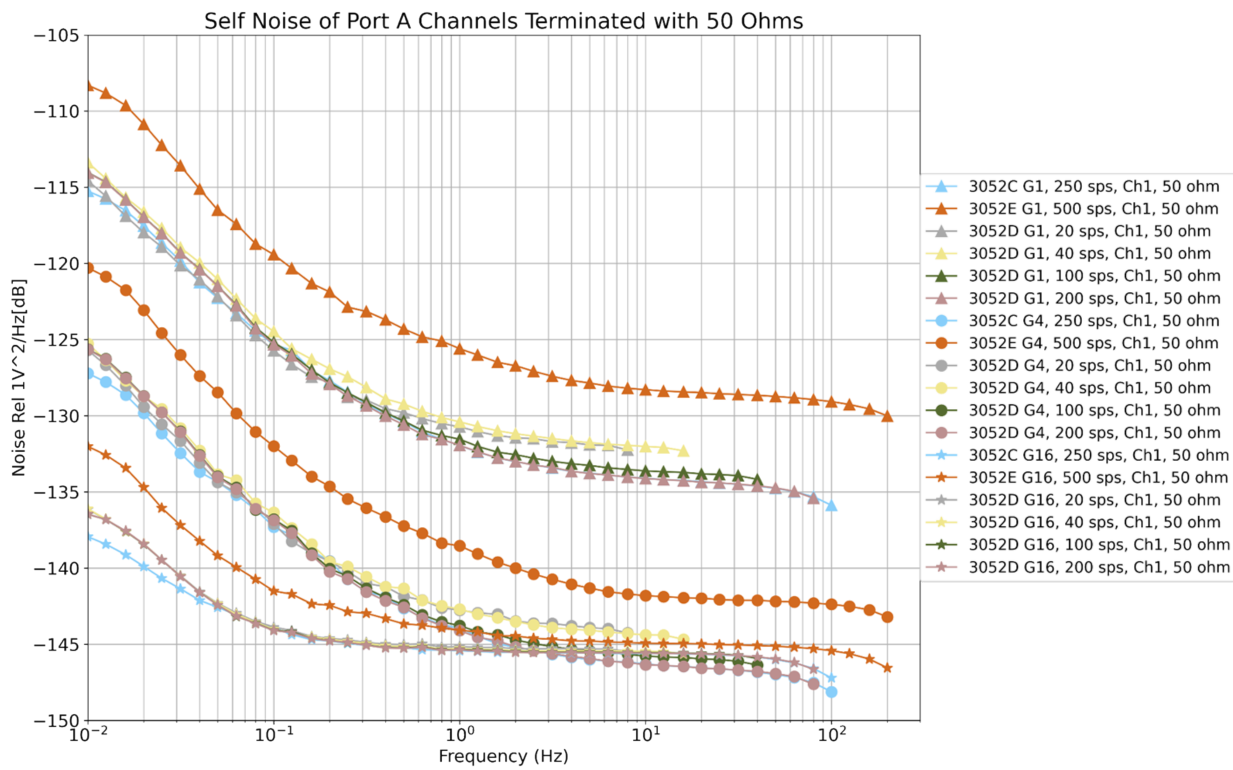

Figure 28 Self Noise Power Spectra, Port A, 50 ohms

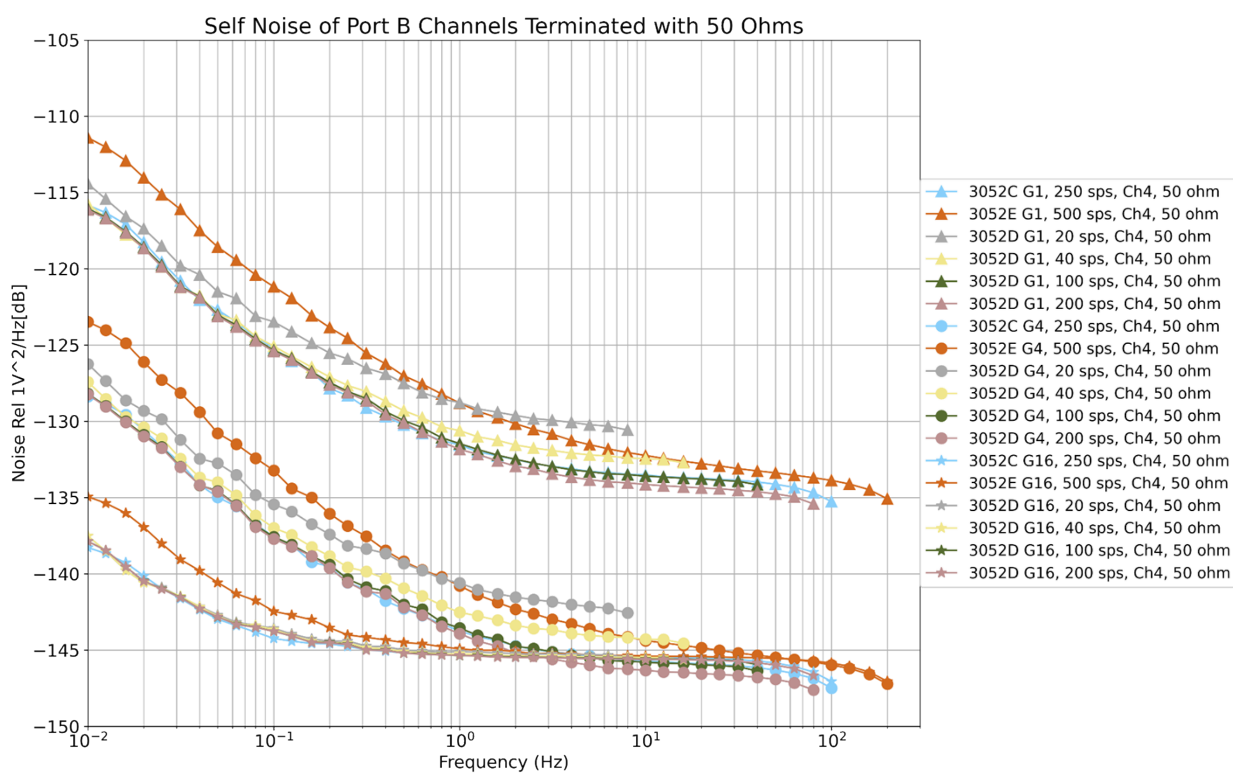

Figure 29 Self Noise Power Spectra, Port B, 50 ohms

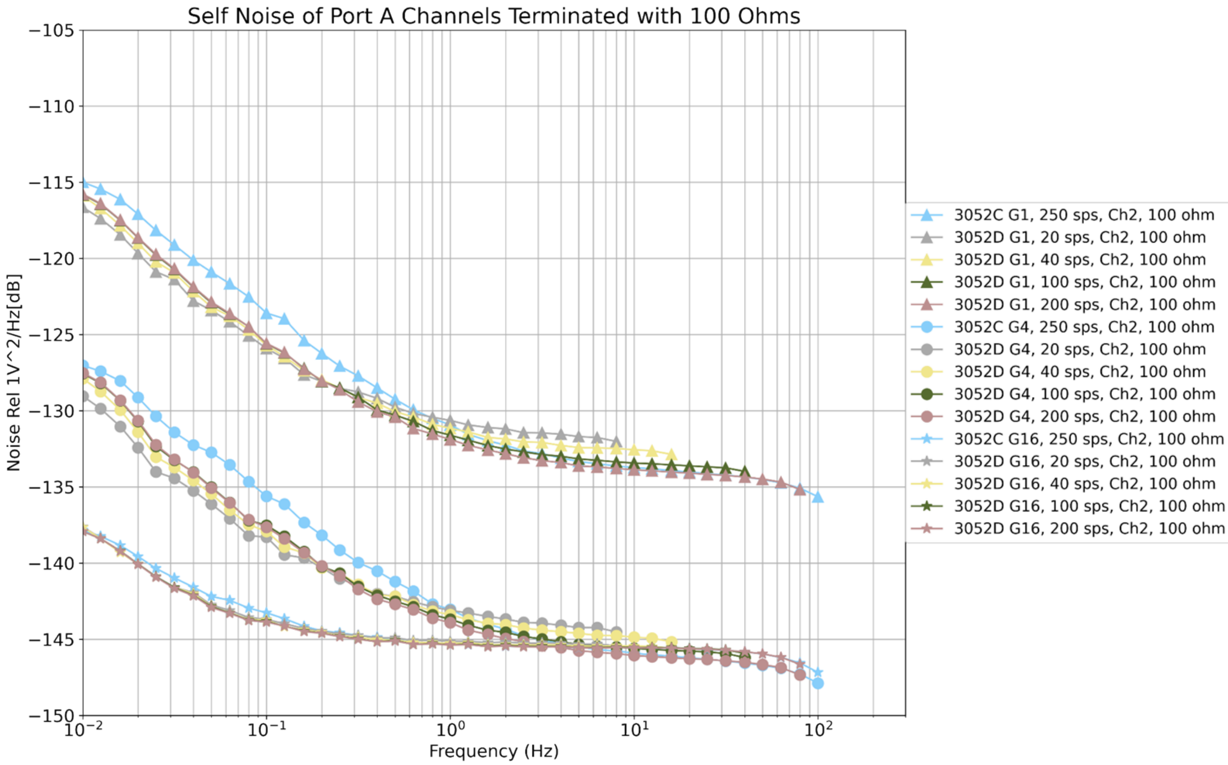

Figure 30 Self Noise Power Spectra, Port A, 100 ohms

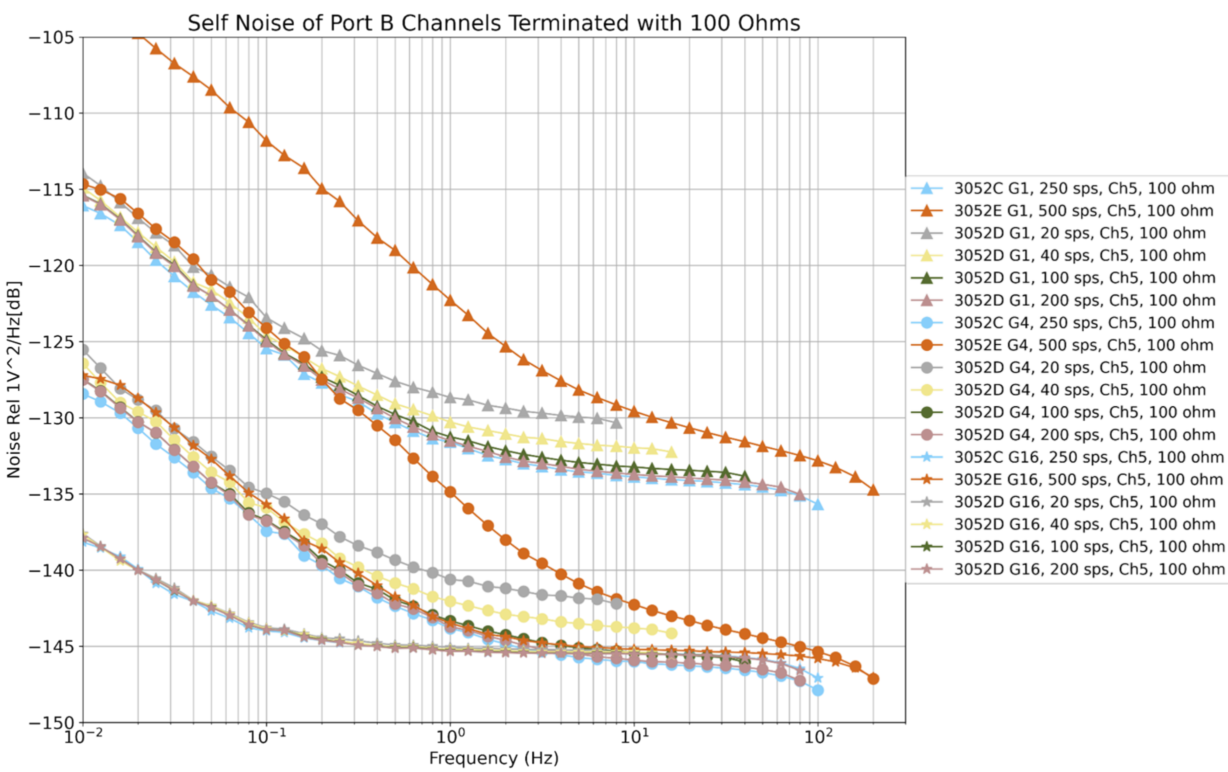

Figure 31 Self Noise Power Spectra, Port B, 100 ohms

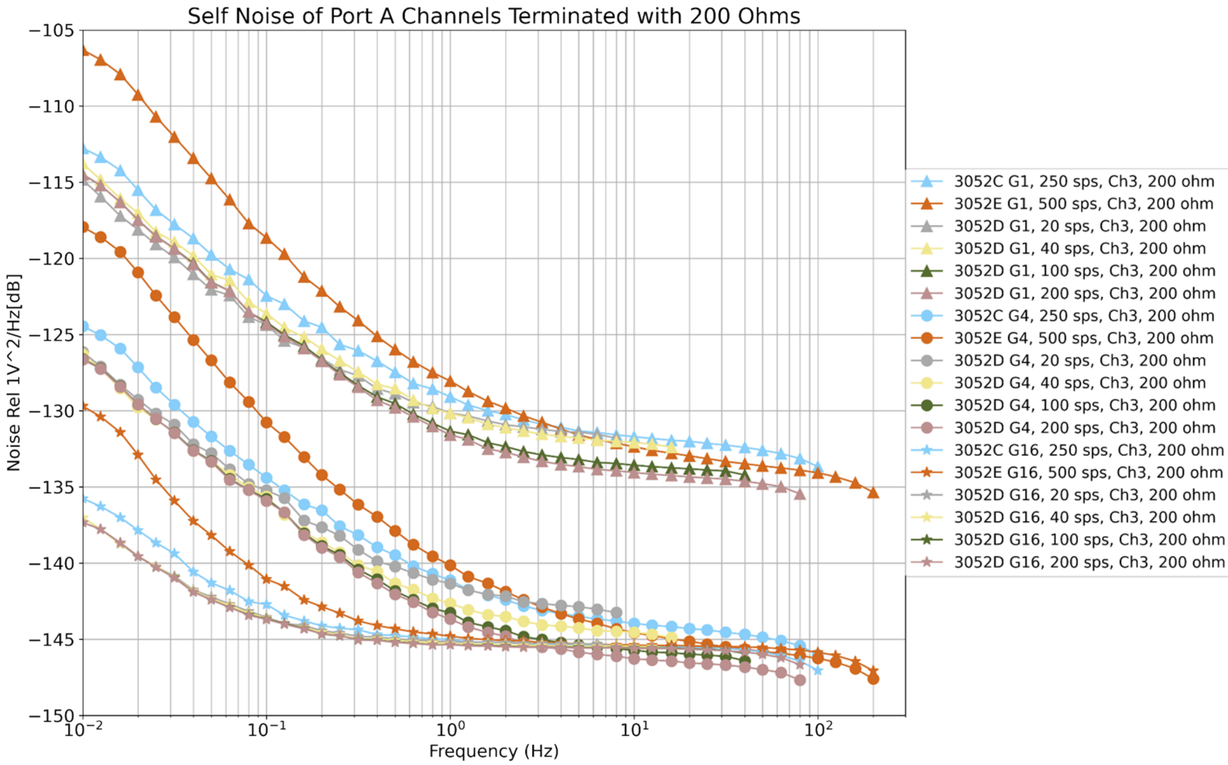

Figure 32 Self Noise Power Spectra, Port A, 200 ohms

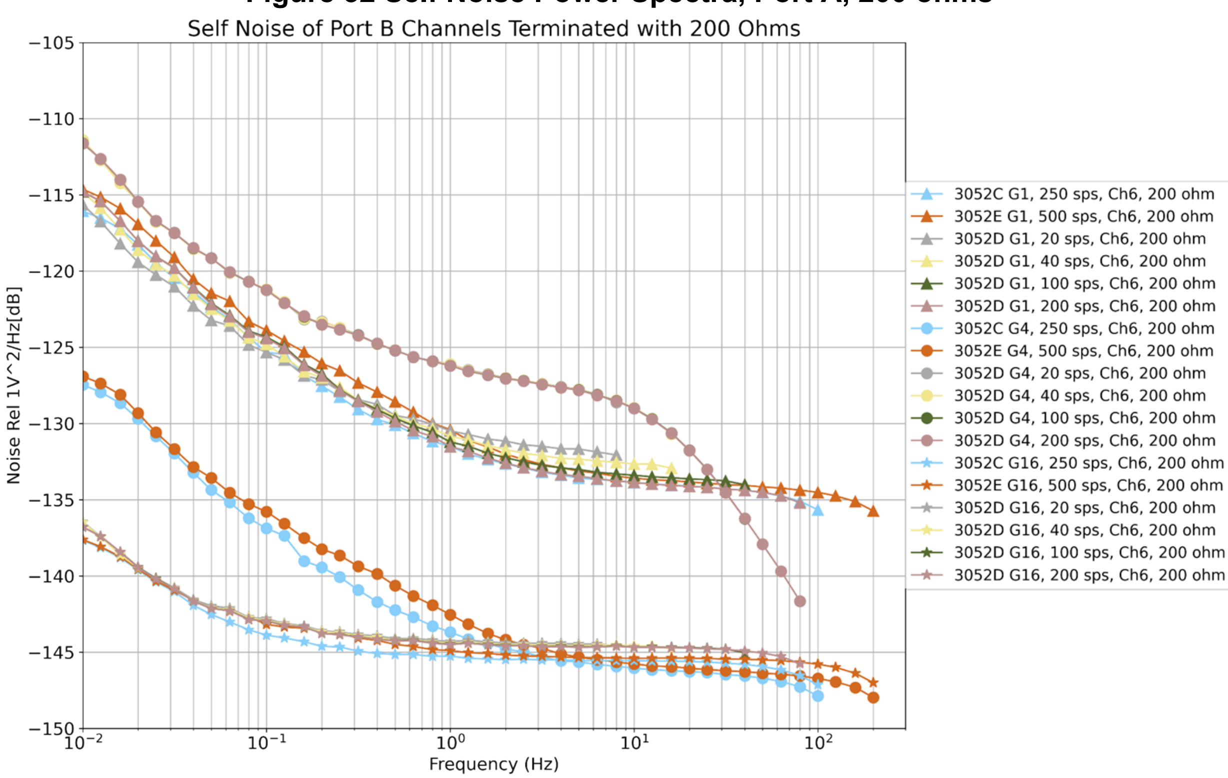

Figure 33 Self Noise Power Spectra, Port B, 200 ohms

For the x1 and x4 gain levels, the expected relationship between noise and gain can be clearly seen. As gain increases, the noise level decrease. This relationship only partially holds for the x16 gain level. For frequencies below about 0.1Hz, the noise level of the x16 gain channels is lower than the noise level for the x4 gain channels. For higher frequencies, however, there is very little difference in the noise levels. This means that the x16 gain level would only be advantageous if one is interested in signals with frequencies below about 0.1Hz. For higher frequency signals, the x4 gain option will provide the same noise floor but with a larger clip value and, as a result, a higher dynamic range.

3052E is significantly noisier than the other two Wranglers in all cases except for its sixth channel (Ch6). Interesting this channel has very similar noise levels to the other two Wranglers. This could imply that the noise issue with the unit is mostly likely related to a hardware defect and not the fact that it is operated at a higher sample rate than the two other units.

Figure 32 shows that Ch6 of 3052D is very noisy when the unit is operated at a x4 gain. This was a repeatable finding – when the unit operated at the other gain values its noise levels closely matched the other channels. When placed in x4 gain operation, however, noise increased dramatically. This implies that there is likely a hardware issue with the x4 gain stage of the unit's sixth channel.

3.8.4.3 Gain 64 Analysis

The following plots show noise PSD data for when the three Wranglers were operated at the x64 gain level. Because there are fewer traces to include, the following plots show channels from both port A and B that were terminated with the same value of resistor.

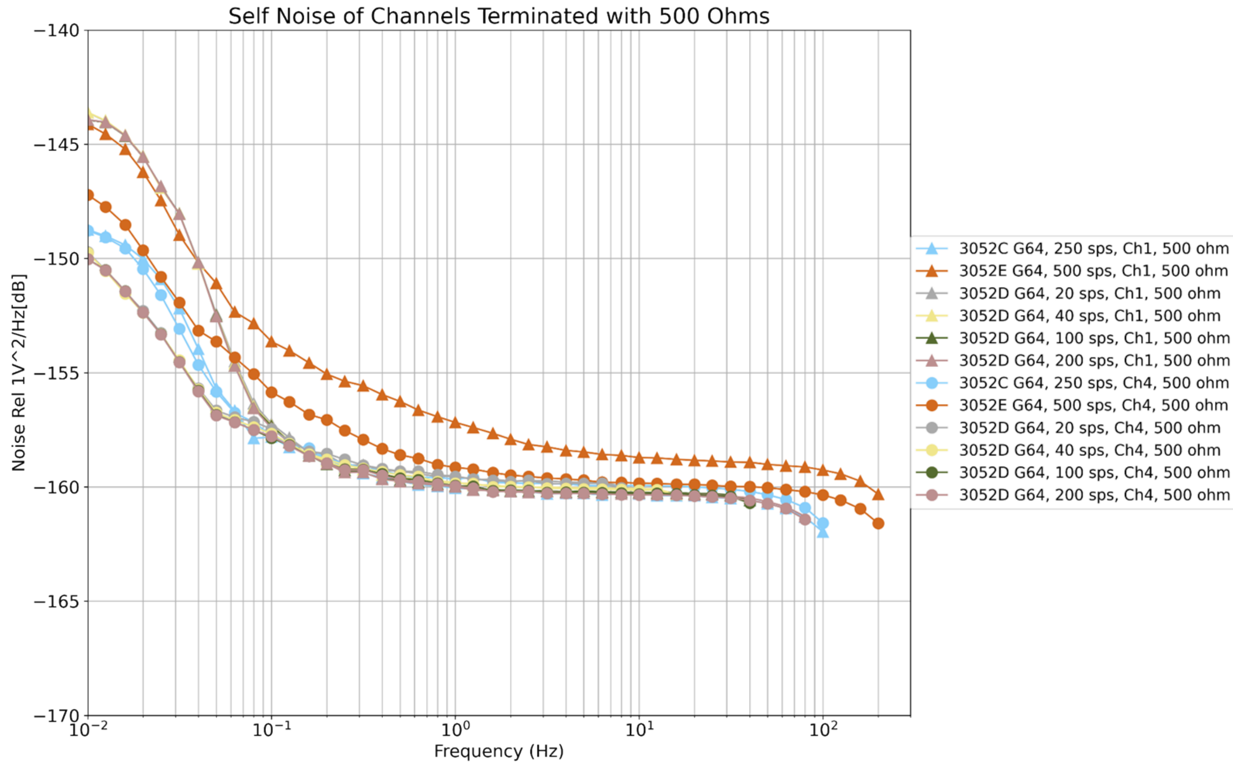

Figure 34 Self Noise Power Spectra 500 ohms

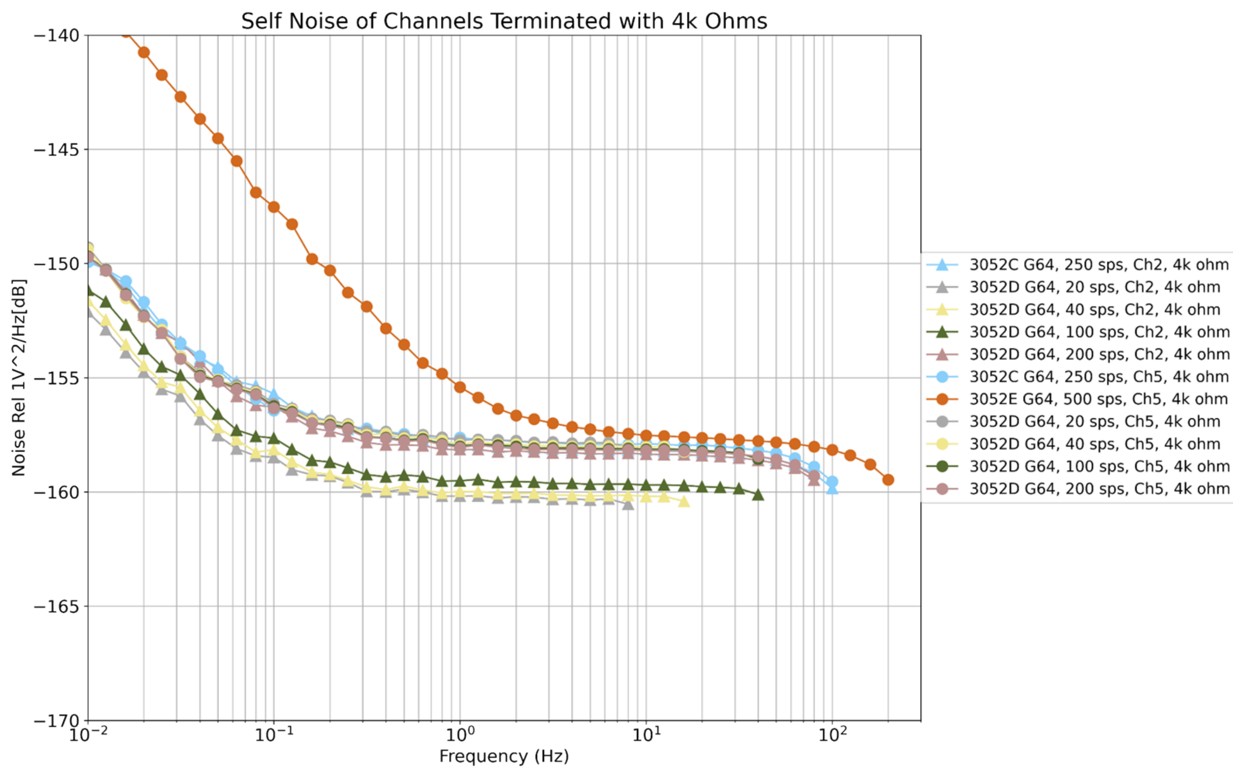

Figure 35 Self Noise Power Spectra 4k ohms

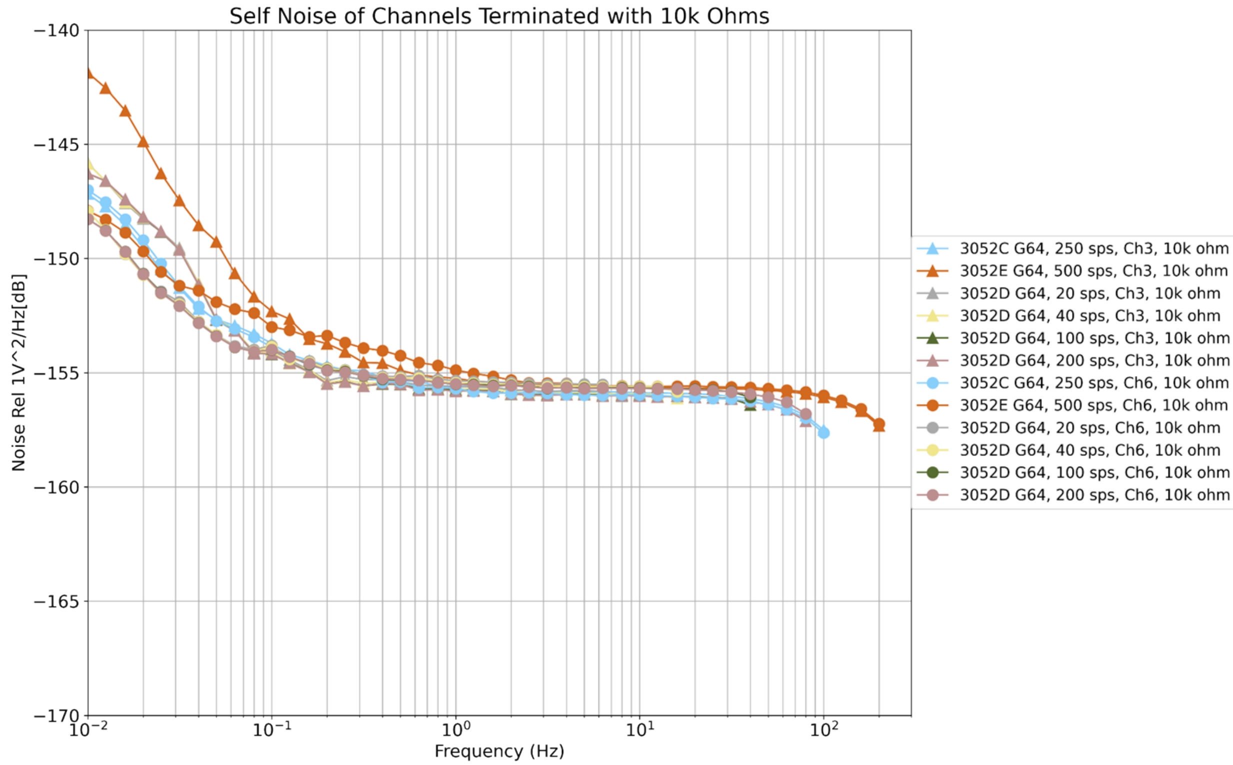

Figure 36 Self Noise Power Spectra 10k ohms

The above figures show that there is a considerable decrease in noise when the Wranglers are operated at x64 gain. The decrease in noise is across the entire bandwidth.

Noise levels are similar when a 500 ohm and 4k ohm termination resistor are used although some channels are a few dB noisier when terminated with a 4k resistor. All channels are noisier when terminated with a 10k ohm resistor. This is not unique to the Wrangler. In general, dataloggers will be noisier when connected to a sensor with a large output impedance.

The following tables contain the total noise power computed from each of the digitizer self-noise PSDs for each combination of digitizer, gain, sample rates, and input termination impedance.

Table 36 Self-Noise RMS: Wrangler 3052C

		Volts (uV rms)				Counts (cnt rms)			
Channel	Input Terminator	0.01 Hz to Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz to Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
Gain 1									
1 - 250sps	50 ohms	1.94	0.54	0.88	0.81	0.81	0.23	0.37	0.34
2 - 250sps	100 ohms	2.02	0.61	0.95	0.87	0.85	0.25	0.40	0.36
3 - 250sps	200 ohms	2.57	0.74	1.21	1.13	1.07	0.31	0.51	0.47
4 - 250sps	50 ohms	2.07	0.55	0.92	0.86	0.86	0.23	0.38	0.36
5 - 250sps	100 ohms	1.97	0.55	0.89	0.83	0.83	0.23	0.37	0.35
6 - 250sps	200 ohms	1.98	0.55	0.90	0.83	0.83	0.23	0.38	0.35
Gain 4									
1 - 250sps	50 ohms	0.48	0.13	0.22	0.20	0.80	0.22	0.36	0.33
2 - 250sps	100 ohms	0.50	0.15	0.23	0.21	0.83	0.25	0.39	0.36
3 - 250sps	200 ohms	0.63	0.19	0.30	0.28	1.05	0.31	0.50	0.46
4 - 250sps	50 ohms	0.52	0.14	0.23	0.21	0.87	0.23	0.38	0.36
5 - 250sps	100 ohms	0.49	0.14	0.22	0.21	0.82	0.23	0.37	0.34
6 - 250sps	200 ohms	0.49	0.14	0.22	0.21	0.82	0.23	0.37	0.35
Gain 16									
1 - 250sps	50 ohms	0.51	0.11	0.21	0.21	3.42	0.72	1.42	1.39
2 - 250sps	100 ohms	0.51	0.11	0.21	0.21	3.43	0.73	1.43	1.40
3 - 250sps	200 ohms	0.52	0.11	0.22	0.21	3.49	0.76	1.46	1.43
4 - 250sps	50 ohms	0.53	0.11	0.21	0.21	3.54	0.73	1.44	1.41
5 - 250sps	100 ohms	0.52	0.11	0.21	0.21	3.47	0.73	1.44	1.41
6 - 250sps	200 ohms	0.51	0.11	0.21	0.21	3.44	0.73	1.43	1.40
Gain 64									
1 - 250sps	500 ohms	0.10	0.02	0.04	0.04	2.61	0.55	1.05	1.02
2 - 250sps	4k ohms	0.18	0.03	0.05	0.05	4.86	0.69	1.34	1.31
3 - 250sps	10k ohms	0.24	0.03	0.07	0.06	6.49	0.90	1.75	1.71
4 - 250sps	500 ohms	0.15	0.02	0.04	0.04	4.13	0.57	1.10	1.07
5 - 250sps	4k ohms	0.28	0.03	0.05	0.05	7.46	0.71	1.38	1.35
6 - 20sps	10k ohms	0.64	0.03	0.06	0.06	1	0.88	1.72	1.69

Table 37 Self-Noise RMS: Wrangler 3052D

		Volts (uV rms)				Counts (cnt rms)			
Channel	Input Terminator	0.01 Hz to Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz to Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
Gain 1									
1 - 20sps	50 ohms	0.85	0.60			0.35	0.25		
2 - 20sps	100 ohms	0.85	0.60			0.36	0.25		
3 - 20sps	200 ohms	0.91	0.65			0.38	0.27		
4 - 20sps	50 ohms	1.03	0.74			0.43	0.31		
5 - 20sps	100 ohms	1.06	0.76			0.44	0.32		
6 - 20sps	200 ohms	0.86	0.62			0.36	0.26		
1 - 40sps	50 ohms	1.16	0.64	1.08	1.02	0.48	0.27	0.45	0.43
2 - 40sps	100 ohms	1.07	0.58	1.00	0.95	0.45	0.24	0.42	0.40
3 - 40sps	200 ohms	1.18	0.66	1.12	1.05	0.50	0.27	0.47	0.44
4 - 40sps	50 ohms	1.09	0.60	1.03	0.97	0.46	0.25	0.43	0.41
5 - 40sps	100 ohms	1.16	0.64	1.09	1.03	0.48	0.27	0.45	0.43
6 - 40sps	200 ohms	1.08	0.60	1.01	0.95	0.45	0.25	0.42	0.40
1 - 100sps	50 ohms	1.43	0.56	0.92	0.86	0.60	0.23	0.39	0.36
2 - 100sps	100 ohms	1.44	0.55	0.93	0.87	0.60	0.23	0.39	0.36
3 - 100sps	200 ohms	1.47	0.58	0.97	0.90	0.61	0.24	0.40	0.38
4 - 100sps	50 ohms	1.42	0.56	0.92	0.86	0.59	0.23	0.38	0.36
5 - 100sps	100 ohms	1.48	0.58	0.95	0.89	0.62	0.24	0.40	0.37
6 - 100sps	200 ohms	1.46	0.58	0.95	0.88	0.61	0.24	0.40	0.37
1 - 200sps	50 ohms	1.79	0.54	0.88	0.81	0.75	0.23	0.37	0.34
2 - 200sps	100 ohms	1.83	0.54	0.89	0.83	0.76	0.22	0.37	0.35
3 - 200sps	200 ohms	1.82	0.57	0.93	0.86	0.76	0.24	0.39	0.36
4 - 200sps	50 ohms	1.78	0.54	0.87	0.81	0.74	0.22	0.36	0.34
5 - 200sps	100 ohms	1.86	0.56	0.91	0.85	0.78	0.23	0.38	0.36
6 - 200sps	200 ohms	6.07	0.57	0.91	0.84	2.54	0.24	0.38	0.35
Gain 4									
1 - 20sps	50 ohms	0.21	0.15			0.36	0.26		
2 - 20sps	100 ohms	0.20	0.14			0.34	0.24		
3 - 20sps	200 ohms	0.24	0.18			0.41	0.30		
4 - 20sps	50 ohms	0.26	0.19			0.44	0.32		
5 - 20sps	100 ohms	0.27	0.20			0.45	0.33		
6 - 20sps	200 ohms	1.32	0.99			2.21	1.66		
1 - 40sps	50 ohms	0.28	0.15	0.26	0.25	0.47	0.26	0.44	0.41
2 - 40sps	100 ohms	0.26	0.14	0.24	0.23	0.43	0.23	0.41	0.39
3 - 40sps	200 ohms	0.28	0.16	0.27	0.25	0.47	0.26	0.44	0.42
4 - 40sps	50 ohms	0.28	0.16	0.26	0.25	0.47	0.26	0.44	0.42
5 - 40sps	100 ohms	0.30	0.16	0.28	0.26	0.50	0.28	0.47	0.44
6 - 40sps	200 ohms	1.63	0.99	1.59	1.51	2.73	1.66	2.67	2.53
1 - 100sps	50 ohms	0.35	0.14	0.23	0.21	0.59	0.23	0.38	0.36
2 - 100sps	100 ohms	0.36	0.14	0.23	0.22	0.60	0.23	0.38	0.36
3 - 100sps	200 ohms	0.36	0.15	0.24	0.22	0.61	0.24	0.40	0.37
4 - 100sps	50 ohms	0.35	0.14	0.23	0.21	0.59	0.23	0.38	0.35
5 - 100sps	100 ohms	0.36	0.14	0.24	0.22	0.61	0.24	0.40	0.37
6 - 100sps	200 ohms	1.94	0.99	1.59	1.50	3.26	1.65	2.66	2.52
1 - 200sps	50 ohms	0.44	0.13	0.22	0.20	0.74	0.23	0.36	0.34
2 - 200sps	100 ohms	0.45	0.13	0.22	0.20	0.75	0.22	0.37	0.34
3 - 200sps	200 ohms	0.45	0.14	0.23	0.21	0.75	0.24	0.38	0.35

		Volts (uV rms)				Counts (cnt rms)			
4 - 200sps	50 ohms	0.44	0.13	0.21	0.20	0.74	0.22	0.36	0.33
5 - 200sps	100 ohms	0.46	0.14	0.23	0.21	0.77	0.23	0.38	0.35
6 - 200sps	200 ohms	60.45	0.99	1.59	1.50	101.32	1.65	2.66	2.52
Gain 16									
1 - 20sps	50 ohms	0.16	0.11			1.08	0.74		
2 - 20sps	100 ohms	0.16	0.11			1.08	0.75		
3 - 20sps	200 ohms	0.16	0.11			1.09	0.75		
4 - 20sps	50 ohms	0.16	0.11			1.08	0.75		
5 - 20sps	100 ohms	0.16	0.11			1.09	0.75		
6 - 20sps	200 ohms	0.18	0.12			1.20	0.82		
1 - 40sps	50 ohms	0.22	0.11	0.21	0.21	1.49	0.73	1.44	1.41
2 - 40sps	100 ohms	0.22	0.11	0.22	0.21	1.49	0.73	1.44	1.41
3 - 40sps	200 ohms	0.22	0.11	0.22	0.21	1.50	0.74	1.44	1.41
4 - 40sps	50 ohms	0.22	0.11	0.21	0.21	1.49	0.73	1.44	1.41
5 - 40sps	100 ohms	0.22	0.11	0.22	0.21	1.50	0.74	1.45	1.42
6 - 40sps	200 ohms	0.25	0.12	0.24	0.23	1.65	0.81	1.60	1.57
1 - 100sps	50 ohms	0.34	0.11	0.21	0.21	2.30	0.73	1.43	1.40
2 - 100sps	100 ohms	0.34	0.11	0.21	0.21	2.30	0.73	1.43	1.40
3 - 100sps	200 ohms	0.34	0.11	0.21	0.21	2.30	0.73	1.43	1.40
4 - 100sps	50 ohms	0.34	0.11	0.21	0.21	2.30	0.73	1.42	1.40
5 - 100sps	100 ohms	0.35	0.11	0.21	0.21	2.32	0.73	1.44	1.41
6 - 100sps	200 ohms	0.38	0.12	0.24	0.23	2.55	0.81	1.58	1.55
1 - 200sps	50 ohms	0.47	0.11	0.21	0.21	3.15	0.72	1.42	1.39
2 - 200sps	100 ohms	0.47	0.11	0.21	0.21	3.14	0.73	1.42	1.40
3 - 200sps	200 ohms	0.47	0.11	0.21	0.21	3.13	0.73	1.42	1.40
4 - 200sps	50 ohms	0.47	0.11	0.21	0.21	3.15	0.73	1.42	1.39
5 - 200sps	100 ohms	0.47	0.11	0.21	0.21	3.17	0.73	1.43	1.40
6 - 200sps	200 ohms	6.29	0.12	0.24	0.23	42.18	0.81	1.58	1.55
Gain 64									
1 - 20sps	500 ohms	0.03	0.02			0.85	0.59		
2 - 20sps	4k ohms	0.03	0.02			0.78	0.53		
3 - 20sps	10k ohms	0.05	0.03			1.30	0.89		
4 - 20sps	500 ohms	0.03	0.02			0.82	0.57		
5 - 20sps	4k ohms	0.04	0.03			1.03	0.71		
6 - 20sps	10k ohms	0.05	0.03			1.34	0.92		
1 - 40sps	500 ohms	0.04	0.02	0.04	0.04	1.16	0.57	1.11	1.08
2 - 40sps	4k ohms	0.04	0.02	0.04	0.04	1.10	0.54	1.06	1.04
3 - 40sps	10k ohms	0.07	0.03	0.06	0.06	1.80	0.88	1.73	1.70
4 - 40sps	500 ohms	0.04	0.02	0.04	0.04	1.12	0.55	1.07	1.05
5 - 40sps	4k ohms	0.05	0.03	0.05	0.05	1.41	0.69	1.36	1.33
6 - 40sps	10k ohms	0.07	0.03	0.07	0.07	1.85	0.91	1.79	1.76
1 - 100sps	500 ohms	0.07	0.02	0.04	0.04	1.78	0.57	1.09	1.06
2 - 100sps	4k ohms	0.07	0.02	0.04	0.04	1.81	0.57	1.12	1.10
3 - 100sps	10k ohms	0.10	0.03	0.06	0.06	2.77	0.88	1.72	1.69
4 - 100sps	500 ohms	0.06	0.02	0.04	0.04	1.70	0.54	1.06	1.03
5 - 100sps	4k ohms	0.08	0.03	0.05	0.05	2.17	0.69	1.35	1.32
6 - 100sps	10k ohms	0.11	0.03	0.07	0.06	2.87	0.91	1.78	1.75
1 - 200sps	500 ohms	0.10	0.02	0.04	0.04	2.59	0.56	1.09	1.05
2 - 200sps	4k ohms	0.43	0.02	0.05	0.05	11.57	0.67	1.31	1.29
3 - 200sps	10k ohms	0.40	0.03	0.06	0.06	10.87	0.88	1.72	1.68

		Volts (uV rms)				Counts (cnt rms)			
4 - 200sps	500 ohms	0.09	0.02	0.04	0.04	2.55	0.54	1.05	1.03
5 - 200sps	4k ohms	0.18	0.03	0.05	0.05	4.92	0.68	1.34	1.31
6 - 200sps	10k ohms	0.25	0.03	0.07	0.06	6.71	0.90	1.78	1.74

Table 38 Self-Noise RMS: Wrangler 3052E

		Volts (uV rms)				Counts (cnt rms)			
Channel	Input Terminator	0.01 Hz to Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz to Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
Gain 1									
1 - 500sps	50 ohms	5.20	1.09	1.73	1.61	2.18	0.46	0.73	0.67
2 - 500sps	100 ohms	15.36	7.14	8.66	6.80	6.43	2.99	3.62	2.85
3 - 500sps	200 ohms	3.16	0.95	1.29	1.09	1.32	0.40	0.54	0.45
4 - 500sps	50 ohms	3.06	0.79	1.16	1.04	1.28	0.33	0.49	0.44
5 - 500sps	100 ohms	3.92	1.85	2.20	1.63	1.64	0.77	0.92	0.68
6 - 500sps	200 ohms	2.78	0.62	0.96	0.88	1.16	0.26	0.40	0.37
Gain 4									
1 - 500sps	50 ohms	1.13	0.25	0.38	0.34	1.89	0.41	0.63	0.58
2 - 500sps	100 ohms	3.73	1.73	2.10	1.66	6.25	2.90	3.53	2.79
3 - 500sps	200 ohms	0.78	0.24	0.32	0.27	1.31	0.40	0.54	0.45
4 - 500sps	50 ohms	0.76	0.19	0.29	0.26	1.27	0.33	0.48	0.44
5 - 500sps	100 ohms	0.93	0.44	0.52	0.38	1.56	0.74	0.87	0.64
6 - 500sps	200 ohms	0.68	0.15	0.24	0.22	1.14	0.26	0.40	0.36
Gain 16									
1 - 500sps	50 ohms	0.77	0.13	0.23	0.23	5.20	0.84	1.57	1.52
2 - 500sps	100 ohms	1.21	0.46	0.59	0.48	8.10	3.11	3.93	3.22
3 - 500sps	200 ohms	0.74	0.12	0.22	0.21	4.95	0.80	1.49	1.44
4 - 500sps	50 ohms	0.73	0.12	0.22	0.21	4.92	0.77	1.47	1.43
5 - 500sps	100 ohms	0.75	0.15	0.24	0.22	5.01	1.00	1.63	1.50
6 - 500sps	200 ohms	0.74	0.11	0.22	0.21	4.95	0.76	1.46	1.43
Gain 64									
1 - 500sps	500 ohms	0.17	0.03	0.05	0.05	4.59	0.74	1.32	1.27
2 - 500sps	4k ohms	0.43	0.12	0.16	0.13	11.48	3.35	4.22	3.43
3 - 500sps	10k ohms	0.68	0.04	0.07	0.07	18.40	0.95	1.82	1.77
4 - 500sps	500 ohms	0.15	0.02	0.04	0.04	3.93	0.60	1.13	1.09
5 - 500sps	4k ohms	0.23	0.04	0.06	0.05	6.31	1.01	1.60	1.47
6 - 500sps	10k ohms	0.38	0.04	0.07	0.07	10.13	0.96	1.82	1.78

Digitizer self-noise values are reported in the tables below in units of dB relative to 1 V^2/Hz at the defined third-octave frequencies. The 90% uncertainty of the provided estimates are less than +/- 0.6 dB based upon the number of time-windows and the resulting spectral averaging that was performed when computing the power spectral densities.

Table 39 Self-Noise PSD, Wrangler 3052C, Gains 1 and 4

250sps												
	Gain 1						Gain 4					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm
0.01	-115.25	-114.99	-112.76	-115.83	-116.07	-116.07	-127.21	-127.02	-124.45	-128.38	-128.44	-127.46
0.0125	-115.77	-115.44	-113.34	-116.32	-116.59	-116.52	-127.78	-127.41	-125.04	-128.85	-128.94	-127.94
0.016	-116.53	-116.12	-114.22	-117.09	-117.37	-117.21	-128.63	-128.04	-125.92	-129.57	-129.69	-128.67
0.02	-117.54	-117.10	-115.51	-118.26	-118.48	-118.27	-129.82	-129.13	-127.15	-130.59	-130.68	-129.70
0.025	-118.66	-118.16	-116.81	-119.55	-119.66	-119.45	-131.16	-130.36	-128.47	-131.66	-131.73	-130.83
0.0315	-119.84	-119.11	-117.76	-120.81	-120.71	-120.45	-132.45	-131.42	-129.61	-132.73	-132.62	-131.96
0.04	-121.27	-120.12	-118.69	-122.05	-121.75	-121.36	-133.69	-132.25	-130.73	-134.17	-133.59	-133.23
0.05	-122.27	-120.89	-119.75	-122.70	-122.59	-122.35	-134.35	-132.73	-131.69	-134.98	-134.63	-134.36
0.063	-123.28	-121.65	-120.71	-123.49	-123.41	-123.18	-135.20	-133.55	-132.63	-135.58	-135.30	-135.18
0.08	-124.42	-122.52	-121.38	-124.47	-124.45	-124.35	-136.16	-134.65	-133.54	-136.76	-136.36	-136.22
0.1	-125.33	-123.59	-122.46	-125.18	-125.47	-125.33	-137.30	-135.61	-134.39	-137.57	-137.45	-136.88
0.125	-125.70	-123.96	-123.00	-126.05	-125.87	-125.45	-137.85	-136.13	-135.23	-138.11	-137.63	-137.36
0.16	-127.04	-125.38	-124.11	-126.77	-127.13	-126.87	-138.88	-137.34	-136.15	-139.23	-139.06	-139.03
0.2	-127.69	-126.24	-124.52	-127.85	-127.70	-127.54	-139.55	-138.18	-136.53	-139.52	-139.69	-139.44
0.25	-128.45	-127.07	-125.65	-128.31	-128.47	-128.26	-140.74	-139.14	-137.58	-140.58	-140.55	-140.07
0.315	-129.25	-127.71	-126.05	-129.13	-128.94	-129.08	-141.56	-139.96	-138.16	-141.02	-141.07	-140.93
0.4	-129.86	-128.50	-126.75	-129.69	-129.74	-129.72	-141.88	-140.53	-138.97	-141.78	-141.81	-141.70
0.5	-130.39	-129.24	-127.47	-130.23	-130.31	-130.09	-142.65	-141.21	-139.47	-142.28	-142.37	-142.24
0.63	-131.05	-129.94	-128.21	-130.78	-130.87	-130.65	-143.22	-141.84	-140.20	-142.74	-142.85	-142.70
0.8	-131.56	-130.50	-128.57	-131.27	-131.36	-131.17	-143.73	-142.69	-140.71	-143.29	-143.29	-143.29
1	-131.94	-130.93	-129.09	-131.55	-131.60	-131.50	-143.93	-143.04	-141.13	-143.74	-143.84	-143.68
1.25	-132.39	-131.54	-129.62	-131.99	-132.02	-132.00	-144.47	-143.61	-141.74	-144.13	-144.10	-144.14
1.6	-132.77	-131.97	-130.00	-132.27	-132.48	-132.37	-144.97	-144.03	-142.11	-144.38	-144.55	-144.43
2	-133.02	-132.26	-130.24	-132.51	-132.73	-132.64	-145.21	-144.34	-142.41	-144.73	-144.85	-144.79
2.5	-133.22	-132.64	-130.60	-132.77	-133.01	-132.91	-145.40	-144.78	-142.81	-144.97	-145.17	-144.99
3.15	-133.43	-132.81	-130.88	-132.95	-133.18	-133.20	-145.67	-145.04	-143.11	-145.11	-145.34	-145.33
4	-133.66	-133.11	-131.09	-133.11	-133.40	-133.38	-145.86	-145.31	-143.31	-145.26	-145.56	-145.56
5	-133.77	-133.33	-131.32	-133.28	-133.55	-133.58	-146.00	-145.49	-143.50	-145.37	-145.74	-145.65
6.3	-133.90	-133.48	-131.43	-133.37	-133.63	-133.67	-146.12	-145.69	-143.67	-145.56	-145.86	-145.80
8	-134.03	-133.63	-131.58	-133.47	-133.79	-133.75	-146.17	-145.77	-143.82	-145.64	-145.97	-145.94
10	-134.10	-133.73	-131.70	-133.51	-133.88	-133.88	-146.29	-145.92	-143.96	-145.71	-146.02	-146.04
12.5	-134.20	-133.81	-131.82	-133.63	-133.97	-133.96	-146.41	-146.03	-144.09	-145.77	-146.14	-146.16
16	-134.25	-133.93	-131.94	-133.69	-134.06	-134.05	-146.46	-146.11	-144.17	-145.86	-146.22	-146.21
20	-134.33	-134.02	-132.01	-133.74	-134.12	-134.11	-146.55	-146.22	-144.31	-145.90	-146.29	-146.28
25	-134.41	-134.14	-132.14	-133.81	-134.18	-134.19	-146.62	-146.31	-144.39	-145.96	-146.35	-146.34
31.5	-134.50	-134.22	-132.26	-133.87	-134.28	-134.29	-146.71	-146.44	-144.54	-146.03	-146.44	-146.47
40	-134.62	-134.35	-132.40	-133.98	-134.39	-134.38	-146.83	-146.56	-144.69	-146.16	-146.57	-146.56
50	-134.76	-134.51	-132.59	-134.13	-134.54	-134.53	-146.99	-146.72	-144.87	-146.31	-146.72	-146.70
63	-134.98	-134.73	-132.81	-134.33	-134.76	-134.75	-147.18	-146.91	-145.09	-146.54	-146.95	-146.93
80	-135.31	-135.08	-133.14	-134.68	-135.12	-135.09	-147.53	-147.29	-145.43	-146.86	-147.30	-147.27
100	-135.88	-135.65	-133.67	-135.26	-135.68	-135.66	-148.12	-147.88	-146.02	-147.49	-147.88	-147.87

Table 40 Self-Noise PSD, Wrangler 3052C, Gains 16 and 64

250sps												
	Gain 16						Gain 64					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 500 ohm	Chan 2 4k ohm	Chan 3 10k ohm	Chan 4 500 ohm	Chan 5 4k ohm	Chan 6 10k ohm
0.01	-137.94	-137.83	-135.76	-138.27	-138.16	-137.67	-148.74	-149.82	-147.17	-148.78	-149.94	-147.00
0.0125	-138.43	-138.24	-136.28	-138.67	-138.55	-138.14	-149.01	-150.29	-147.74	-149.07	-150.25	-147.54
0.016	-139.12	-138.83	-137.01	-139.27	-139.12	-138.81	-149.42	-150.98	-148.54	-149.56	-150.77	-148.29
0.02	-139.89	-139.57	-137.85	-140.13	-139.94	-139.61	-150.02	-151.98	-149.51	-150.46	-151.68	-149.20
0.025	-140.67	-140.35	-138.67	-140.98	-140.87	-140.39	-150.91	-152.91	-150.49	-151.61	-152.67	-150.22
0.0315	-141.36	-140.97	-139.36	-141.62	-141.59	-141.03	-152.20	-153.52	-151.29	-153.08	-153.48	-151.22
0.04	-142.12	-141.58	-140.58	-142.36	-142.06	-141.93	-153.96	-154.17	-152.20	-154.66	-154.05	-152.11
0.05	-142.57	-142.19	-141.30	-142.98	-142.69	-142.53	-155.69	-154.52	-152.67	-155.83	-154.65	-152.74
0.063	-143.07	-142.45	-141.79	-143.40	-143.16	-143.02	-156.67	-155.17	-152.94	-156.76	-155.37	-153.09
0.08	-143.55	-142.96	-142.53	-143.82	-143.79	-143.54	-157.87	-155.35	-153.30	-157.17	-155.93	-153.45
0.1	-143.92	-143.27	-142.72	-144.24	-143.99	-143.89	-157.81	-155.70	-153.72	-157.75	-156.44	-153.89
0.125	-144.37	-143.65	-143.42	-144.41	-144.09	-144.07	-158.27	-156.30	-154.21	-158.17	-156.46	-154.31
0.16	-144.70	-144.15	-143.80	-144.57	-144.46	-144.32	-158.51	-156.68	-154.47	-158.31	-156.93	-154.65
0.2	-144.78	-144.45	-144.12	-144.60	-144.63	-144.62	-158.74	-156.92	-154.70	-158.77	-157.12	-154.90
0.25	-144.96	-144.58	-144.28	-144.76	-144.78	-144.66	-159.14	-157.25	-154.89	-158.96	-157.13	-154.97
0.315	-145.07	-144.75	-144.38	-144.98	-144.88	-144.94	-159.41	-157.23	-154.92	-159.18	-157.22	-155.10
0.4	-145.19	-144.87	-144.70	-145.08	-144.98	-145.09	-159.58	-157.54	-155.21	-159.27	-157.36	-155.43
0.5	-145.21	-145.02	-144.76	-145.19	-145.03	-145.15	-159.75	-157.62	-155.35	-159.50	-157.46	-155.40
0.63	-145.36	-145.21	-144.85	-145.16	-145.13	-145.15	-159.90	-157.72	-155.39	-159.59	-157.56	-155.66
0.8	-145.38	-145.30	-144.98	-145.28	-145.22	-145.28	-159.96	-157.85	-155.59	-159.59	-157.72	-155.64
1	-145.43	-145.27	-145.02	-145.23	-145.22	-145.26	-160.05	-157.96	-155.58	-159.66	-157.62	-155.70
1.25	-145.47	-145.36	-145.19	-145.37	-145.33	-145.40	-160.10	-157.95	-155.62	-159.59	-157.71	-155.82
1.6	-145.54	-145.37	-145.21	-145.34	-145.40	-145.45	-160.11	-158.03	-155.66	-159.81	-157.73	-155.89
2	-145.51	-145.46	-145.20	-145.39	-145.38	-145.49	-160.21	-157.98	-155.76	-159.82	-157.80	-155.89
2.5	-145.50	-145.48	-145.26	-145.40	-145.39	-145.46	-160.22	-158.09	-155.78	-159.85	-157.83	-155.87
3.15	-145.56	-145.49	-145.33	-145.46	-145.42	-145.52	-160.29	-158.12	-155.84	-159.85	-157.85	-155.90
4	-145.58	-145.50	-145.35	-145.42	-145.45	-145.49	-160.28	-158.17	-155.80	-159.87	-157.91	-155.96
5	-145.58	-145.58	-145.36	-145.45	-145.46	-145.56	-160.28	-158.12	-155.86	-159.94	-157.91	-155.98
6.3	-145.59	-145.56	-145.39	-145.46	-145.49	-145.55	-160.35	-158.18	-155.82	-159.94	-157.92	-155.99
8	-145.60	-145.54	-145.43	-145.45	-145.47	-145.55	-160.30	-158.18	-155.85	-159.95	-157.92	-155.96
10	-145.61	-145.56	-145.40	-145.45	-145.46	-145.55	-160.30	-158.17	-155.89	-159.92	-157.90	-155.98
12.5	-145.61	-145.59	-145.44	-145.49	-145.50	-145.58	-160.38	-158.22	-155.87	-159.96	-157.92	-156.01
16	-145.63	-145.58	-145.48	-145.50	-145.53	-145.59	-160.39	-158.23	-155.92	-159.96	-157.96	-156.04
20	-145.65	-145.62	-145.51	-145.51	-145.54	-145.61	-160.38	-158.27	-155.91	-160.00	-157.94	-156.07
25	-145.71	-145.68	-145.54	-145.57	-145.60	-145.65	-160.46	-158.29	-155.97	-160.05	-158.01	-156.13
31.5	-145.76	-145.73	-145.60	-145.62	-145.63	-145.73	-160.50	-158.36	-156.03	-160.11	-158.09	-156.15
40	-145.85	-145.83	-145.70	-145.71	-145.74	-145.80	-160.58	-158.45	-156.13	-160.20	-158.18	-156.25
50	-146.00	-145.97	-145.84	-145.85	-145.86	-145.95	-160.72	-158.59	-156.28	-160.34	-158.30	-156.40
63	-146.22	-146.20	-146.07	-146.07	-146.09	-146.16	-160.95	-158.81	-156.50	-160.55	-158.53	-156.61
80	-146.59	-146.56	-146.43	-146.44	-146.47	-146.54	-161.32	-159.18	-156.87	-160.91	-158.90	-156.99
100	-147.21	-147.18	-147.04	-147.06	-147.09	-147.14	-161.96	-159.84	-157.51	-161.58	-159.55	-157.64

Table 41 Self-Noise PSD, Wrangler 3052D, 20 sps, Gains 1 and 4

20sps												
	Gain 1						Gain 4					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm
0.01	-114.57	-116.64	-114.84	-114.42	-113.94	-115.63	-125.70	-129.04	-126.15	-126.24	-125.53	-111.41
0.0125	-115.58	-117.38	-115.93	-115.43	-114.77	-116.74	-126.67	-129.86	-127.09	-127.36	-126.74	-112.71
0.016	-116.89	-118.44	-117.21	-116.56	-115.86	-118.20	-128.02	-131.03	-128.28	-128.63	-128.09	-114.23
0.02	-117.97	-119.66	-118.12	-117.36	-116.89	-119.41	-129.43	-132.42	-129.28	-129.31	-128.82	-115.46
0.025	-118.93	-120.88	-119.07	-118.50	-117.86	-120.24	-130.56	-134.01	-130.18	-129.86	-129.51	-116.77
0.0315	-120.13	-121.38	-119.93	-119.79	-118.69	-121.02	-131.65	-134.43	-130.90	-131.22	-130.71	-117.48
0.04	-121.08	-122.79	-121.04	-120.40	-120.09	-122.27	-133.09	-135.25	-132.20	-132.45	-131.59	-118.55
0.05	-122.17	-123.41	-122.04	-121.51	-120.63	-123.23	-134.36	-136.12	-132.78	-132.76	-132.55	-119.14
0.063	-123.41	-124.15	-122.42	-121.94	-121.41	-123.59	-135.03	-137.08	-133.84	-133.52	-133.46	-120.11
0.08	-124.72	-125.07	-123.84	-123.11	-122.09	-124.84	-135.90	-138.21	-134.81	-134.83	-134.57	-120.69
0.1	-125.73	-125.91	-124.36	-123.48	-123.44	-125.33	-137.10	-138.29	-135.23	-135.44	-134.97	-121.21
0.125	-126.63	-126.55	-125.41	-124.13	-124.12	-125.81	-138.24	-139.45	-135.73	-135.91	-135.52	-122.02
0.16	-127.46	-127.64	-125.84	-124.89	-124.80	-126.86	-139.05	-139.67	-137.21	-136.75	-136.39	-123.16
0.2	-127.80	-128.08	-126.57	-125.52	-125.60	-127.13	-139.55	-140.30	-137.65	-137.42	-136.98	-123.31
0.25	-128.79	-128.53	-127.30	-125.90	-125.91	-127.88	-140.23	-141.03	-138.20	-138.15	-137.81	-123.71
0.315	-128.98	-128.77	-127.70	-126.52	-126.55	-128.43	-141.01	-141.47	-139.12	-138.37	-138.40	-124.18
0.4	-129.54	-129.19	-128.56	-126.89	-127.10	-128.74	-141.22	-142.02	-139.89	-138.66	-138.84	-124.76
0.5	-129.80	-129.77	-128.88	-127.51	-127.60	-129.47	-141.86	-142.18	-140.22	-139.32	-139.34	-125.22
0.63	-130.18	-130.17	-129.45	-128.12	-128.00	-129.70	-142.11	-142.55	-140.66	-139.78	-139.81	-125.62
0.8	-130.51	-130.43	-129.72	-128.55	-128.32	-130.04	-142.62	-142.87	-141.09	-140.33	-140.17	-125.90
1	-130.73	-130.64	-130.15	-128.76	-128.67	-130.49	-142.76	-143.11	-141.34	-140.60	-140.61	-126.10
1.25	-131.04	-130.93	-130.34	-129.18	-128.82	-130.72	-142.94	-143.28	-141.78	-141.04	-140.73	-126.48
1.6	-131.31	-131.10	-130.67	-129.41	-129.18	-131.02	-143.03	-143.50	-142.06	-141.31	-141.07	-126.76
2	-131.44	-131.19	-130.92	-129.62	-129.36	-131.16	-143.48	-143.68	-142.16	-141.53	-141.20	-127.00
2.5	-131.51	-131.44	-131.06	-129.82	-129.58	-131.40	-143.62	-143.89	-142.55	-141.70	-141.40	-127.18
3.15	-131.70	-131.46	-131.21	-129.93	-129.70	-131.50	-143.64	-143.95	-142.66	-141.83	-141.63	-127.38
4	-131.77	-131.54	-131.37	-130.07	-129.85	-131.65	-143.79	-144.08	-142.78	-142.02	-141.69	-127.59
5	-131.92	-131.70	-131.40	-130.23	-129.95	-131.68	-143.91	-144.24	-142.87	-142.15	-141.85	-127.76
6.3	-131.94	-131.76	-131.55	-130.32	-130.04	-131.87	-143.98	-144.24	-143.03	-142.27	-141.91	-128.08
8	-132.24	-132.01	-131.79	-130.57	-130.33	-132.06	-144.26	-144.52	-143.25	-142.56	-142.21	-128.61

Table 42 Self-Noise PSD, Wrangler 3052D, 20 sps, Gains 16 and 64

20sps												
	Gain 16						Gain 64					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 500 ohm	Chan 2 4k ohm	Chan 3 10k ohm	Chan 4 500 ohm	Chan 5 4k ohm	Chan 6 10k ohm
0.01	-136.14	-137.61	-137.02	-137.51	-137.60	-136.45	-143.61	-152.12	-145.84	-149.73	-149.30	-147.93
0.0125	-136.80	-138.37	-137.78	-138.52	-138.43	-137.41	-143.98	-152.90	-146.62	-150.51	-150.24	-148.75
0.016	-137.63	-139.30	-138.75	-139.78	-139.38	-138.60	-144.61	-153.90	-147.58	-151.47	-151.46	-149.82
0.02	-138.41	-140.07	-139.57	-140.54	-139.98	-139.46	-145.51	-154.75	-148.26	-152.29	-152.35	-150.71
0.025	-139.46	-140.90	-140.22	-140.90	-140.56	-140.14	-146.91	-155.51	-148.82	-153.27	-152.96	-151.44
0.0315	-140.50	-141.59	-140.86	-141.49	-141.17	-140.78	-148.04	-155.81	-149.54	-154.53	-154.08	-151.90
0.04	-141.56	-141.94	-141.77	-142.15	-141.98	-141.56	-150.20	-156.82	-151.07	-155.69	-154.78	-152.76
0.05	-142.31	-142.75	-142.22	-142.69	-142.34	-141.96	-152.43	-157.53	-152.66	-156.66	-155.15	-153.34
0.063	-142.96	-143.11	-142.69	-143.18	-142.86	-142.11	-154.51	-158.11	-153.12	-156.95	-155.32	-153.83
0.08	-143.50	-143.57	-143.17	-143.38	-143.43	-142.72	-156.34	-158.43	-154.09	-157.16	-155.57	-153.99
0.1	-143.87	-143.69	-143.56	-143.58	-143.79	-142.81	-157.24	-158.48	-154.01	-157.46	-156.14	-153.81
0.125	-144.11	-143.98	-143.97	-143.95	-143.87	-143.11	-157.85	-159.03	-154.45	-157.98	-156.34	-154.42
0.16	-144.49	-144.29	-144.10	-144.27	-144.18	-143.28	-158.50	-159.25	-154.89	-158.45	-156.78	-154.49
0.2	-144.62	-144.48	-144.45	-144.43	-144.45	-143.60	-158.59	-159.31	-155.35	-158.55	-156.87	-154.79
0.25	-144.71	-144.66	-144.59	-144.41	-144.52	-143.68	-159.04	-159.59	-155.17	-158.80	-157.03	-154.88
0.315	-144.88	-144.75	-144.82	-144.74	-144.64	-143.85	-159.04	-159.98	-155.30	-159.05	-157.33	-155.08
0.4	-145.00	-144.91	-144.85	-144.78	-144.80	-143.93	-159.27	-160.00	-155.30	-159.20	-157.36	-155.16
0.5	-145.02	-144.91	-144.98	-145.00	-144.92	-144.12	-159.31	-159.88	-155.40	-159.31	-157.55	-155.18
0.63	-144.97	-145.09	-145.04	-145.07	-144.93	-144.09	-159.42	-160.01	-155.54	-159.32	-157.50	-155.12
0.8	-145.19	-145.07	-145.13	-145.14	-145.00	-144.21	-159.55	-160.18	-155.58	-159.47	-157.61	-155.29
1	-145.15	-145.13	-145.15	-145.10	-145.08	-144.31	-159.52	-160.19	-155.63	-159.54	-157.74	-155.35
1.25	-145.21	-145.13	-145.20	-145.14	-145.14	-144.22	-159.68	-160.17	-155.61	-159.65	-157.70	-155.38
1.6	-145.20	-145.23	-145.20	-145.18	-145.14	-144.33	-159.67	-160.26	-155.63	-159.71	-157.73	-155.42
2	-145.28	-145.18	-145.23	-145.23	-145.18	-144.39	-159.75	-160.21	-155.75	-159.77	-157.76	-155.42
2.5	-145.30	-145.26	-145.28	-145.26	-145.20	-144.41	-159.73	-160.23	-155.78	-159.72	-157.84	-155.47
3.15	-145.28	-145.24	-145.27	-145.26	-145.22	-144.41	-159.74	-160.32	-155.83	-159.86	-157.82	-155.51
4	-145.28	-145.25	-145.29	-145.30	-145.23	-144.43	-159.79	-160.30	-155.79	-159.85	-157.87	-155.49
5	-145.31	-145.32	-145.31	-145.29	-145.27	-144.47	-159.80	-160.35	-155.78	-159.85	-157.84	-155.51
6.3	-145.31	-145.32	-145.32	-145.33	-145.24	-144.46	-159.79	-160.31	-155.82	-159.84	-157.85	-155.52
8	-145.47	-145.44	-145.44	-145.47	-145.40	-144.58	-159.97	-160.53	-156.03	-160.05	-158.04	-155.70

Table 43 Self-Noise PSD, Wrangler 3052D, 40 sps, Gains 1 and 4

40sps												
	Gain 1						Gain 4					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm
0.01	-113.36	-115.88	-113.77	-115.74	-114.90	-114.80	-125.28	-127.89	-126.29	-127.42	-126.43	-111.41
0.0125	-114.43	-116.71	-114.84	-116.67	-115.74	-115.86	-126.34	-128.73	-127.24	-128.53	-127.69	-112.72
0.016	-115.67	-117.84	-116.08	-117.76	-116.84	-117.27	-127.70	-129.95	-128.53	-129.73	-129.02	-114.22
0.02	-116.61	-119.01	-117.03	-118.62	-117.83	-118.61	-128.71	-131.41	-129.77	-130.39	-129.61	-115.45
0.025	-117.69	-120.21	-118.25	-119.88	-118.79	-119.56	-129.55	-133.03	-130.57	-131.12	-130.25	-116.77
0.0315	-118.95	-120.94	-118.92	-121.23	-119.77	-120.28	-130.83	-133.72	-131.45	-132.45	-131.46	-117.51
0.04	-119.96	-122.16	-119.83	-121.76	-121.11	-121.51	-132.28	-134.57	-132.65	-133.69	-132.58	-118.54
0.05	-121.04	-123.18	-121.06	-122.98	-121.60	-122.48	-133.84	-135.45	-133.29	-134.00	-133.58	-119.15
0.063	-122.33	-123.78	-121.45	-123.37	-122.45	-123.25	-134.23	-136.52	-134.22	-134.86	-134.23	-120.11
0.08	-123.62	-124.68	-122.87	-124.43	-123.45	-124.36	-135.75	-137.48	-135.03	-136.17	-135.57	-120.68
0.1	-124.47	-125.71	-123.63	-125.07	-124.61	-124.79	-136.35	-137.92	-135.63	-137.00	-135.91	-121.20
0.125	-125.60	-126.43	-124.54	-125.74	-125.23	-125.62	-137.38	-138.94	-136.82	-137.45	-136.84	-122.01
0.16	-126.29	-127.37	-125.18	-126.46	-126.05	-126.58	-138.43	-139.33	-137.95	-138.23	-137.63	-123.11
0.2	-126.92	-127.97	-125.96	-127.10	-126.77	-127.00	-139.59	-140.31	-138.65	-138.84	-138.24	-123.35
0.25	-127.44	-128.52	-126.71	-127.65	-127.30	-127.61	-139.91	-140.67	-139.30	-139.57	-139.23	-123.71
0.315	-128.13	-129.12	-127.45	-128.05	-127.92	-128.47	-140.57	-141.39	-140.14	-139.86	-139.81	-124.23
0.4	-128.90	-129.51	-128.26	-128.69	-128.51	-129.02	-141.22	-142.09	-140.55	-140.31	-140.41	-124.77
0.5	-129.23	-130.05	-128.55	-129.30	-129.08	-129.52	-141.33	-142.19	-141.34	-140.93	-140.86	-125.19
0.63	-129.71	-130.41	-129.30	-129.77	-129.46	-129.99	-142.12	-142.73	-141.75	-141.46	-141.23	-125.63
0.8	-130.11	-130.88	-129.85	-130.36	-129.87	-130.34	-142.47	-143.16	-142.32	-142.06	-141.75	-125.92
1	-130.40	-131.16	-130.17	-130.61	-130.28	-130.85	-142.70	-143.39	-142.64	-142.54	-142.05	-126.11
1.25	-130.70	-131.39	-130.45	-131.01	-130.60	-131.06	-143.02	-143.72	-143.07	-142.76	-142.34	-126.51
1.6	-130.99	-131.75	-130.89	-131.26	-130.84	-131.46	-143.25	-143.95	-143.39	-143.05	-142.65	-126.79
2	-131.18	-131.85	-131.10	-131.55	-131.06	-131.70	-143.51	-144.05	-143.51	-143.37	-142.90	-127.01
2.5	-131.34	-132.04	-131.33	-131.75	-131.28	-131.95	-143.73	-144.27	-143.82	-143.59	-143.05	-127.17
3.15	-131.50	-132.08	-131.54	-131.91	-131.37	-132.10	-143.91	-144.41	-144.06	-143.67	-143.20	-127.39
4	-131.65	-132.28	-131.70	-132.09	-131.57	-132.28	-144.02	-144.51	-144.14	-143.91	-143.41	-127.62
5	-131.76	-132.42	-131.78	-132.20	-131.69	-132.34	-144.08	-144.62	-144.26	-144.04	-143.51	-127.76
6.3	-131.88	-132.43	-131.93	-132.28	-131.80	-132.45	-144.21	-144.75	-144.43	-144.13	-143.64	-128.12
8	-131.94	-132.48	-132.01	-132.39	-131.87	-132.54	-144.29	-144.76	-144.49	-144.18	-143.72	-128.48
10	-132.01	-132.56	-132.08	-132.46	-131.97	-132.65	-144.39	-144.87	-144.54	-144.29	-143.81	-128.97
12.5	-132.08	-132.63	-132.19	-132.50	-132.03	-132.66	-144.40	-144.93	-144.67	-144.31	-143.89	-129.67
16	-132.30	-132.87	-132.38	-132.72	-132.25	-132.93	-144.68	-145.17	-144.89	-144.57	-144.15	-130.70

Table 44 Self-Noise PSD, 3052D, 40 sps, Gains 16 and 64

40sps												
	Gain 16						Gain 64					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 500 ohm	Chan 2 4k ohm	Chan 3 10k ohm	Chan 4 500 ohm	Chan 5 4k ohm	Chan 6 10k ohm
0.01	-136.11	-137.64	-137.03	-137.51	-137.67	-136.49	-143.61	-151.62	-145.85	-149.75	-149.37	-147.94
0.0125	-136.78	-138.39	-137.78	-138.51	-138.49	-137.44	-143.97	-152.46	-146.61	-150.55	-150.32	-148.75
0.016	-137.62	-139.30	-138.75	-139.77	-139.41	-138.61	-144.60	-153.55	-147.54	-151.54	-151.52	-149.81
0.02	-138.40	-140.05	-139.55	-140.60	-140.01	-139.47	-145.52	-154.46	-148.21	-152.38	-152.36	-150.73
0.025	-139.47	-140.92	-140.22	-140.97	-140.63	-140.17	-146.92	-155.20	-148.83	-153.31	-152.90	-151.53
0.0315	-140.52	-141.59	-140.93	-141.47	-141.29	-140.80	-148.03	-155.42	-149.60	-154.46	-154.08	-152.01
0.04	-141.60	-142.02	-141.83	-142.17	-141.99	-141.65	-150.23	-156.44	-151.08	-155.73	-154.87	-152.77
0.05	-142.35	-142.84	-142.34	-142.78	-142.36	-142.09	-152.49	-157.18	-152.67	-156.75	-155.08	-153.34
0.063	-143.04	-143.26	-142.77	-143.27	-142.91	-142.21	-154.60	-157.70	-153.08	-157.07	-155.44	-153.89
0.08	-143.56	-143.70	-143.28	-143.40	-143.48	-142.76	-156.47	-158.27	-154.13	-157.38	-155.64	-154.06
0.1	-144.02	-143.73	-143.61	-143.66	-143.86	-142.91	-157.30	-158.15	-154.06	-157.67	-156.31	-153.87
0.125	-144.25	-144.18	-144.01	-144.05	-144.02	-143.16	-158.00	-158.67	-154.60	-158.11	-156.41	-154.41
0.16	-144.52	-144.38	-144.22	-144.40	-144.24	-143.34	-158.62	-159.14	-154.88	-158.56	-156.89	-154.54
0.2	-144.68	-144.55	-144.54	-144.53	-144.53	-143.67	-158.86	-159.23	-155.44	-158.79	-156.96	-154.82
0.25	-144.81	-144.78	-144.69	-144.53	-144.67	-143.74	-159.17	-159.50	-155.32	-159.04	-157.08	-154.91
0.315	-144.94	-144.87	-145.01	-144.85	-144.81	-143.93	-159.22	-159.78	-155.46	-159.19	-157.50	-155.15
0.4	-145.11	-145.04	-144.97	-144.92	-144.95	-144.02	-159.48	-159.90	-155.43	-159.34	-157.45	-155.21
0.5	-145.16	-145.05	-145.06	-145.10	-145.04	-144.22	-159.57	-159.75	-155.48	-159.48	-157.65	-155.23
0.63	-145.11	-145.21	-145.17	-145.17	-145.02	-144.19	-159.66	-159.92	-155.68	-159.54	-157.60	-155.23
0.8	-145.33	-145.21	-145.23	-145.26	-145.13	-144.33	-159.74	-160.04	-155.65	-159.78	-157.75	-155.38
1	-145.28	-145.28	-145.29	-145.23	-145.23	-144.40	-159.79	-159.98	-155.72	-159.84	-157.93	-155.43
1.25	-145.34	-145.22	-145.32	-145.29	-145.22	-144.36	-159.94	-159.99	-155.70	-159.85	-157.80	-155.46
1.6	-145.35	-145.37	-145.34	-145.35	-145.27	-144.43	-159.91	-160.07	-155.71	-160.00	-157.89	-155.52
2	-145.42	-145.34	-145.38	-145.37	-145.28	-144.51	-160.01	-160.07	-155.83	-159.99	-157.91	-155.50
2.5	-145.44	-145.38	-145.41	-145.40	-145.34	-144.50	-160.03	-160.06	-155.88	-160.01	-157.99	-155.58
3.15	-145.43	-145.38	-145.41	-145.40	-145.36	-144.54	-160.00	-160.13	-155.91	-160.06	-157.98	-155.61
4	-145.42	-145.38	-145.44	-145.43	-145.37	-144.55	-160.04	-160.14	-155.88	-160.07	-158.01	-155.57
5	-145.45	-145.44	-145.46	-145.46	-145.38	-144.58	-160.04	-160.17	-155.89	-160.10	-158.00	-155.60
6.3	-145.45	-145.46	-145.48	-145.47	-145.37	-144.55	-160.04	-160.16	-155.93	-160.11	-158.00	-155.61
8	-145.45	-145.43	-145.44	-145.48	-145.38	-144.52	-160.07	-160.15	-155.92	-160.11	-158.00	-155.60
10	-145.46	-145.44	-145.48	-145.50	-145.39	-144.59	-160.07	-160.19	-155.93	-160.15	-158.03	-155.60
12.5	-145.48	-145.47	-145.49	-145.49	-145.43	-144.59	-160.10	-160.19	-155.97	-160.13	-158.01	-155.62
16	-145.65	-145.60	-145.63	-145.65	-145.58	-144.77	-160.31	-160.41	-156.12	-160.35	-158.24	-155.84

Table 45 Self-Noise PSD, Wrangler 3052D, 100 sps, Gains 1 and 4

100sps												
	Gain 1						Gain 4					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm
0.01	-114.03	-115.81	-114.49	-116.06	-115.39	-114.80	-125.63	-127.56	-126.61	-128.19	-127.47	-111.62
0.0125	-114.66	-116.42	-115.20	-116.62	-115.96	-115.42	-126.26	-128.18	-127.21	-128.99	-128.24	-112.64
0.016	-115.81	-117.50	-116.31	-117.56	-116.96	-116.71	-127.49	-129.34	-128.39	-130.00	-129.32	-114.01
0.02	-116.95	-118.65	-117.48	-118.58	-118.05	-118.02	-128.69	-130.70	-129.59	-130.89	-130.27	-115.44
0.025	-118.01	-119.78	-118.53	-119.76	-119.13	-119.03	-129.78	-132.33	-130.55	-131.69	-130.99	-116.70
0.0315	-119.30	-120.72	-119.35	-121.15	-119.98	-119.79	-131.03	-133.24	-131.43	-132.98	-132.10	-117.51
0.04	-120.38	-121.89	-120.32	-121.84	-121.29	-121.05	-132.58	-134.03	-132.60	-134.19	-133.20	-118.49
0.05	-121.48	-122.91	-121.55	-123.02	-122.00	-122.11	-133.98	-135.02	-133.30	-134.57	-134.26	-119.15
0.063	-122.73	-123.66	-122.14	-123.70	-122.90	-122.91	-134.71	-136.02	-134.47	-135.49	-135.00	-120.07
0.08	-124.21	-124.48	-123.52	-124.61	-123.93	-123.94	-136.17	-137.20	-135.19	-136.83	-136.25	-120.70
0.1	-125.17	-125.60	-124.18	-125.35	-124.89	-124.33	-136.79	-137.52	-135.78	-137.58	-136.72	-121.24
0.125	-125.95	-126.20	-125.01	-125.87	-125.77	-124.96	-137.54	-138.25	-136.67	-138.09	-137.48	-122.09
0.16	-126.99	-127.22	-125.74	-126.75	-126.47	-126.11	-139.03	-139.24	-138.06	-138.84	-138.27	-122.98
0.2	-127.83	-128.07	-126.68	-127.46	-127.32	-126.73	-140.04	-140.23	-138.88	-139.41	-139.37	-123.51
0.25	-128.49	-128.50	-127.50	-128.04	-127.87	-127.78	-140.54	-140.67	-139.46	-140.35	-140.00	-123.84
0.315	-129.13	-129.10	-128.34	-128.51	-128.54	-128.50	-141.33	-141.54	-140.42	-140.88	-140.85	-124.20
0.4	-129.80	-129.95	-129.10	-129.37	-129.24	-129.08	-141.94	-142.12	-141.06	-141.13	-141.26	-124.75
0.5	-130.34	-130.28	-129.53	-129.95	-129.78	-129.65	-142.41	-142.50	-141.83	-142.02	-141.98	-125.20
0.63	-130.95	-130.70	-130.23	-130.42	-130.24	-130.14	-143.08	-142.87	-142.41	-142.32	-142.37	-125.64
0.8	-131.29	-131.30	-130.81	-131.08	-130.89	-130.58	-143.53	-143.39	-142.98	-143.17	-142.95	-125.92
1	-131.54	-131.61	-131.34	-131.46	-131.25	-131.22	-143.78	-143.69	-143.27	-143.56	-143.34	-126.20
1.25	-132.01	-131.93	-131.58	-131.84	-131.51	-131.48	-144.19	-144.08	-143.89	-144.03	-143.66	-126.57
1.6	-132.39	-132.28	-132.10	-132.22	-131.89	-131.95	-144.38	-144.41	-144.19	-144.30	-144.01	-126.82
2	-132.55	-132.52	-132.36	-132.50	-132.16	-132.24	-144.72	-144.54	-144.44	-144.76	-144.25	-127.04
2.5	-132.79	-132.70	-132.67	-132.74	-132.40	-132.51	-144.96	-144.82	-144.84	-144.89	-144.50	-127.21
3.15	-132.99	-132.88	-132.90	-132.97	-132.60	-132.75	-145.16	-144.98	-145.02	-145.12	-144.77	-127.44
4	-133.15	-132.99	-133.07	-133.18	-132.79	-132.91	-145.33	-145.17	-145.23	-145.35	-144.95	-127.64
5	-133.26	-133.16	-133.20	-133.31	-132.93	-133.01	-145.43	-145.34	-145.38	-145.50	-145.11	-127.80
6.3	-133.42	-133.25	-133.39	-133.45	-133.04	-133.20	-145.56	-145.46	-145.50	-145.69	-145.21	-128.14
8	-133.52	-133.36	-133.46	-133.49	-133.17	-133.31	-145.66	-145.52	-145.62	-145.74	-145.31	-128.51
10	-133.62	-133.43	-133.57	-133.60	-133.23	-133.40	-145.78	-145.60	-145.73	-145.80	-145.41	-129.00
12.5	-133.67	-133.48	-133.67	-133.66	-133.32	-133.50	-145.84	-145.66	-145.84	-145.87	-145.51	-129.70
16	-133.72	-133.55	-133.75	-133.73	-133.39	-133.56	-145.88	-145.73	-145.90	-145.89	-145.57	-130.63
20	-133.81	-133.62	-133.81	-133.79	-133.45	-133.64	-145.96	-145.78	-145.97	-145.98	-145.60	-131.76
25	-133.86	-133.68	-133.89	-133.87	-133.51	-133.68	-146.01	-145.83	-146.05	-146.02	-145.67	-133.01
31.5	-133.93	-133.75	-133.95	-133.94	-133.59	-133.76	-146.12	-145.94	-146.12	-146.10	-145.75	-134.52
40	-134.18	-133.98	-134.22	-134.16	-133.84	-134.01	-146.37	-146.20	-146.41	-146.37	-146.04	-136.25

Table 46 Self-Noise PSD, Wrangler 3052D, 100 sps, Gains 16 and 64

100sps												
	Gain 16						Gain 64					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 500 ohm	Chan 2 4k ohm	Chan 3 10k ohm	Chan 4 500 ohm	Chan 5 4k ohm	Chan 6 10k ohm
0.01	-136.46	-137.93	-137.34	-137.87	-137.90	-136.79	-143.94	-151.16	-146.28	-150.03	-149.69	-148.28
0.0125	-136.82	-138.40	-137.77	-138.46	-138.46	-137.40	-144.04	-151.67	-146.61	-150.51	-150.29	-148.78
0.016	-137.58	-139.20	-138.67	-139.55	-139.25	-138.42	-144.63	-152.69	-147.42	-151.43	-151.36	-149.70
0.02	-138.44	-140.06	-139.56	-140.47	-140.02	-139.42	-145.56	-153.73	-148.19	-152.36	-152.30	-150.67
0.025	-139.48	-140.89	-140.28	-140.99	-140.66	-140.17	-146.84	-154.52	-148.84	-153.31	-153.04	-151.49
0.0315	-140.55	-141.61	-140.95	-141.54	-141.35	-140.83	-148.05	-154.89	-149.62	-154.54	-154.17	-152.08
0.04	-141.59	-142.12	-141.89	-142.30	-142.02	-141.66	-150.17	-155.70	-151.15	-155.79	-154.90	-152.82
0.05	-142.42	-142.86	-142.42	-142.84	-142.45	-142.13	-152.51	-156.58	-152.69	-156.84	-155.14	-153.40
0.063	-143.17	-143.27	-142.91	-143.30	-142.97	-142.28	-154.70	-157.29	-153.16	-157.16	-155.47	-153.88
0.08	-143.62	-143.75	-143.40	-143.50	-143.61	-142.85	-156.54	-157.56	-154.14	-157.51	-155.72	-154.08
0.1	-144.09	-143.83	-143.67	-143.77	-143.93	-142.96	-157.34	-157.64	-154.20	-157.86	-156.25	-154.00
0.125	-144.18	-144.14	-143.97	-144.09	-143.96	-143.24	-158.03	-158.13	-154.56	-158.17	-156.49	-154.28
0.16	-144.61	-144.46	-144.29	-144.49	-144.37	-143.35	-158.63	-158.61	-154.96	-158.65	-156.99	-154.64
0.2	-144.76	-144.61	-144.66	-144.51	-144.57	-143.78	-159.01	-158.69	-155.50	-158.96	-157.05	-154.89
0.25	-144.90	-144.81	-144.78	-144.62	-144.74	-143.84	-159.27	-158.95	-155.39	-159.23	-157.19	-154.95
0.315	-145.05	-144.98	-145.02	-144.98	-144.94	-143.99	-159.36	-159.24	-155.58	-159.23	-157.60	-155.15
0.4	-145.23	-145.17	-145.05	-145.01	-145.00	-144.16	-159.65	-159.34	-155.49	-159.44	-157.62	-155.29
0.5	-145.24	-145.07	-145.19	-145.20	-145.11	-144.25	-159.70	-159.26	-155.52	-159.63	-157.75	-155.31
0.63	-145.17	-145.35	-145.26	-145.24	-145.08	-144.22	-159.80	-159.32	-155.71	-159.69	-157.68	-155.33
0.8	-145.38	-145.28	-145.36	-145.31	-145.21	-144.40	-159.87	-159.53	-155.71	-159.84	-157.89	-155.43
1	-145.35	-145.38	-145.36	-145.37	-145.30	-144.47	-159.95	-159.51	-155.75	-159.95	-158.01	-155.51
1.25	-145.40	-145.32	-145.42	-145.36	-145.32	-144.40	-160.11	-159.45	-155.76	-159.97	-157.91	-155.52
1.6	-145.43	-145.44	-145.42	-145.42	-145.36	-144.51	-160.11	-159.58	-155.80	-160.17	-157.95	-155.56
2	-145.50	-145.40	-145.47	-145.45	-145.39	-144.56	-160.17	-159.55	-155.93	-160.15	-158.01	-155.55
2.5	-145.52	-145.46	-145.51	-145.47	-145.43	-144.57	-160.18	-159.56	-155.97	-160.16	-158.09	-155.60
3.15	-145.52	-145.47	-145.51	-145.48	-145.45	-144.63	-160.17	-159.63	-155.97	-160.25	-158.07	-155.68
4	-145.52	-145.46	-145.51	-145.53	-145.45	-144.61	-160.22	-159.63	-155.95	-160.24	-158.08	-155.64
5	-145.54	-145.54	-145.54	-145.53	-145.49	-144.66	-160.17	-159.67	-155.94	-160.25	-158.09	-155.68
6.3	-145.53	-145.55	-145.57	-145.55	-145.47	-144.65	-160.22	-159.66	-155.99	-160.26	-158.12	-155.67
8	-145.55	-145.52	-145.53	-145.57	-145.47	-144.59	-160.23	-159.66	-155.99	-160.27	-158.10	-155.66
10	-145.56	-145.54	-145.57	-145.59	-145.50	-144.67	-160.24	-159.70	-155.99	-160.31	-158.13	-155.67
12.5	-145.58	-145.54	-145.59	-145.58	-145.51	-144.67	-160.26	-159.70	-156.05	-160.28	-158.12	-155.69
16	-145.58	-145.55	-145.58	-145.59	-145.52	-144.68	-160.25	-159.72	-156.02	-160.31	-158.15	-155.71
20	-145.62	-145.61	-145.63	-145.64	-145.57	-144.71	-160.30	-159.77	-156.07	-160.35	-158.21	-155.73
25	-145.65	-145.63	-145.66	-145.65	-145.58	-144.75	-160.30	-159.80	-156.09	-160.38	-158.23	-155.77
31.5	-145.72	-145.70	-145.73	-145.72	-145.66	-144.80	-160.36	-159.85	-156.13	-160.42	-158.29	-155.83
40	-145.93	-145.93	-145.93	-145.95	-145.87	-145.04	-160.60	-160.11	-156.42	-160.71	-158.56	-156.08

Table 47 Self-Noise PSD, Wrangler 3052D, 200 sps, Gains 1 and 4

200sps												
	Gain 1						Gain 4					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm
0.01	-114.05	-115.77	-114.48	-116.14	-115.42	-114.78	-125.65	-127.52	-126.64	-128.24	-127.50	-111.61
0.0125	-114.68	-116.40	-115.19	-116.70	-116.00	-115.41	-126.30	-128.14	-127.25	-129.04	-128.28	-112.63
0.016	-115.83	-117.47	-116.31	-117.63	-117.00	-116.71	-127.54	-129.31	-128.42	-130.07	-129.36	-114.00
0.02	-116.97	-118.63	-117.49	-118.66	-118.09	-118.03	-128.72	-130.65	-129.59	-130.98	-130.29	-115.44
0.025	-118.03	-119.73	-118.55	-119.87	-119.18	-119.04	-129.77	-132.24	-130.52	-131.76	-130.97	-116.69
0.0315	-119.32	-120.67	-119.36	-121.21	-120.05	-119.81	-131.07	-133.20	-131.47	-133.01	-132.11	-117.50
0.04	-120.40	-121.86	-120.39	-121.89	-121.34	-121.09	-132.63	-134.06	-132.63	-134.18	-133.21	-118.48
0.05	-121.49	-122.85	-121.58	-123.12	-121.97	-122.17	-134.04	-135.06	-133.35	-134.63	-134.25	-119.15
0.063	-122.78	-123.62	-122.14	-123.80	-122.92	-122.98	-134.80	-136.05	-134.54	-135.54	-135.10	-120.06
0.08	-124.29	-124.49	-123.49	-124.70	-123.96	-124.01	-136.12	-137.16	-135.21	-136.93	-136.36	-120.69
0.1	-125.32	-125.58	-124.31	-125.43	-124.98	-124.41	-136.85	-137.64	-135.92	-137.71	-136.78	-121.25
0.125	-126.05	-126.16	-125.12	-125.98	-125.84	-125.07	-137.70	-138.39	-136.67	-138.22	-137.58	-122.10
0.16	-127.23	-127.26	-125.90	-126.83	-126.58	-126.18	-139.16	-139.32	-138.15	-138.85	-138.40	-122.95
0.2	-127.94	-128.03	-126.73	-127.61	-127.50	-126.88	-140.23	-140.18	-138.99	-139.63	-139.60	-123.52
0.25	-128.70	-128.62	-127.63	-128.12	-128.12	-127.83	-140.72	-140.84	-139.60	-140.56	-140.14	-123.83
0.315	-129.34	-129.42	-128.45	-128.67	-128.71	-128.55	-141.57	-141.72	-140.61	-141.17	-141.03	-124.22
0.4	-130.02	-130.07	-129.31	-129.56	-129.38	-129.22	-142.15	-142.37	-141.33	-141.31	-141.51	-124.75
0.5	-130.59	-130.41	-129.79	-130.09	-130.04	-129.86	-142.57	-142.70	-142.05	-142.20	-142.22	-125.21
0.63	-131.23	-131.17	-130.40	-130.72	-130.59	-130.46	-143.29	-143.06	-142.57	-142.71	-142.54	-125.63
0.8	-131.55	-131.53	-131.03	-131.35	-131.11	-130.86	-143.79	-143.62	-143.25	-143.45	-143.11	-125.92
1	-131.95	-131.89	-131.58	-131.84	-131.51	-131.52	-144.10	-143.91	-143.68	-143.92	-143.72	-126.21
1.25	-132.36	-132.26	-131.89	-132.17	-131.87	-131.82	-144.54	-144.41	-144.20	-144.41	-143.96	-126.56
1.6	-132.77	-132.58	-132.51	-132.60	-132.22	-132.27	-144.78	-144.69	-144.56	-144.75	-144.35	-126.83
2	-133.00	-132.82	-132.72	-132.95	-132.57	-132.60	-145.17	-144.96	-144.80	-145.18	-144.62	-127.05
2.5	-133.25	-133.08	-133.04	-133.14	-132.85	-132.88	-145.40	-145.16	-145.26	-145.38	-144.93	-127.21
3.15	-133.39	-133.28	-133.32	-133.44	-133.00	-133.13	-145.62	-145.43	-145.51	-145.59	-145.20	-127.43
4	-133.65	-133.40	-133.53	-133.67	-133.19	-133.35	-145.80	-145.54	-145.64	-145.81	-145.36	-127.65
5	-133.79	-133.62	-133.67	-133.83	-133.38	-133.45	-145.94	-145.75	-145.85	-145.99	-145.52	-127.81
6.3	-133.90	-133.69	-133.85	-133.97	-133.51	-133.62	-146.11	-145.86	-146.00	-146.19	-145.69	-128.15
8	-134.02	-133.79	-133.94	-134.04	-133.63	-133.77	-146.20	-145.95	-146.11	-146.25	-145.79	-128.52
10	-134.13	-133.87	-134.05	-134.14	-133.72	-133.86	-146.34	-146.06	-146.29	-146.33	-145.92	-129.02
12.5	-134.19	-133.94	-134.17	-134.23	-133.82	-133.98	-146.40	-146.14	-146.36	-146.43	-146.01	-129.72
16	-134.27	-134.03	-134.25	-134.30	-133.87	-134.05	-146.46	-146.21	-146.44	-146.47	-146.05	-130.64
20	-134.36	-134.10	-134.34	-134.37	-133.95	-134.12	-146.57	-146.29	-146.55	-146.55	-146.12	-131.78
25	-134.40	-134.18	-134.41	-134.42	-134.02	-134.19	-146.61	-146.32	-146.62	-146.59	-146.19	-133.03
31.5	-134.49	-134.25	-134.49	-134.53	-134.10	-134.29	-146.70	-146.42	-146.69	-146.68	-146.27	-134.54
40	-134.60	-134.35	-134.63	-134.61	-134.21	-134.38	-146.79	-146.51	-146.83	-146.79	-146.38	-136.24
50	-134.74	-134.48	-134.79	-134.76	-134.36	-134.51	-146.93	-146.66	-146.99	-146.92	-146.53	-137.92
63	-134.96	-134.69	-134.98	-134.96	-134.56	-134.74	-147.13	-146.86	-147.19	-147.15	-146.75	-139.69
80	-135.41	-135.17	-135.46	-135.42	-135.03	-135.21	-147.62	-147.35	-147.68	-147.61	-147.25	-141.66

Table 48 Self-Noise PSD, Wrangler 3052D, 200 sps, Gains 16 and 64

200sps												
	Gain 16						Gain 64					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 500 ohm	Chan 2 4k ohm	Chan 3 10k ohm	Chan 4 500 ohm	Chan 5 4k ohm	Chan 6 10k ohm
0.01	-136.46	-137.92	-137.34	-137.87	-137.89	-136.78	-143.93	-149.71	-146.28	-150.04	-149.72	-148.28
0.0125	-136.81	-138.39	-137.77	-138.46	-138.46	-137.39	-144.03	-150.23	-146.60	-150.52	-150.32	-148.79
0.016	-137.57	-139.22	-138.67	-139.55	-139.26	-138.43	-144.62	-151.22	-147.42	-151.44	-151.38	-149.72
0.02	-138.42	-140.08	-139.55	-140.47	-140.02	-139.45	-145.56	-152.25	-148.18	-152.37	-152.32	-150.70
0.025	-139.47	-140.92	-140.27	-141.01	-140.65	-140.20	-146.85	-153.05	-148.82	-153.33	-153.03	-151.52
0.0315	-140.54	-141.66	-140.97	-141.56	-141.32	-140.84	-148.06	-153.44	-149.62	-154.55	-154.17	-152.08
0.04	-141.60	-142.14	-141.90	-142.29	-142.03	-141.67	-150.17	-154.30	-151.15	-155.83	-154.97	-152.83
0.05	-142.43	-142.91	-142.40	-142.82	-142.45	-142.14	-152.53	-155.12	-152.66	-156.87	-155.17	-153.41
0.063	-143.15	-143.30	-142.91	-143.32	-142.98	-142.29	-154.71	-155.81	-153.16	-157.17	-155.52	-153.88
0.08	-143.65	-143.77	-143.43	-143.51	-143.59	-142.87	-156.56	-156.21	-154.16	-157.50	-155.75	-154.08
0.1	-144.10	-143.88	-143.70	-143.78	-143.92	-142.95	-157.43	-156.28	-154.17	-157.79	-156.34	-153.99
0.125	-144.24	-144.13	-144.01	-144.07	-143.97	-143.22	-158.06	-156.70	-154.58	-158.20	-156.55	-154.31
0.16	-144.62	-144.50	-144.32	-144.50	-144.41	-143.35	-158.64	-157.21	-154.98	-158.66	-156.98	-154.61
0.2	-144.78	-144.61	-144.65	-144.54	-144.61	-143.77	-158.97	-157.34	-155.50	-158.96	-157.11	-154.92
0.25	-144.88	-144.83	-144.77	-144.65	-144.75	-143.87	-159.37	-157.57	-155.41	-159.26	-157.26	-154.98
0.315	-145.07	-145.00	-145.05	-145.00	-144.93	-144.00	-159.36	-157.84	-155.58	-159.26	-157.62	-155.12
0.4	-145.24	-145.17	-145.07	-145.03	-145.03	-144.16	-159.66	-157.94	-155.46	-159.50	-157.65	-155.26
0.5	-145.26	-145.12	-145.21	-145.20	-145.14	-144.27	-159.76	-157.94	-155.50	-159.69	-157.78	-155.30
0.63	-145.21	-145.34	-145.28	-145.27	-145.12	-144.24	-159.85	-157.97	-155.77	-159.78	-157.75	-155.34
0.8	-145.41	-145.31	-145.38	-145.33	-145.24	-144.42	-159.93	-158.14	-155.74	-159.87	-157.93	-155.43
1	-145.36	-145.39	-145.36	-145.34	-145.34	-144.51	-159.99	-158.15	-155.81	-159.96	-158.06	-155.50
1.25	-145.45	-145.35	-145.43	-145.41	-145.33	-144.42	-160.13	-158.14	-155.80	-160.05	-157.95	-155.55
1.6	-145.47	-145.49	-145.45	-145.46	-145.40	-144.53	-160.16	-158.25	-155.82	-160.21	-158.05	-155.59
2	-145.54	-145.45	-145.50	-145.49	-145.42	-144.59	-160.21	-158.21	-155.92	-160.19	-158.10	-155.56
2.5	-145.56	-145.50	-145.53	-145.50	-145.45	-144.58	-160.24	-158.25	-155.99	-160.20	-158.15	-155.63
3.15	-145.55	-145.51	-145.52	-145.50	-145.47	-144.65	-160.19	-158.29	-155.99	-160.29	-158.14	-155.68
4	-145.55	-145.49	-145.53	-145.54	-145.47	-144.64	-160.24	-158.28	-155.96	-160.29	-158.15	-155.66
5	-145.57	-145.56	-145.58	-145.57	-145.50	-144.69	-160.24	-158.33	-155.96	-160.29	-158.15	-155.70
6.3	-145.56	-145.59	-145.59	-145.58	-145.50	-144.66	-160.27	-158.33	-156.01	-160.31	-158.18	-155.68
8	-145.58	-145.54	-145.56	-145.59	-145.48	-144.62	-160.29	-158.30	-156.01	-160.34	-158.15	-155.68
10	-145.58	-145.56	-145.60	-145.63	-145.51	-144.69	-160.28	-158.35	-156.01	-160.36	-158.19	-155.69
12.5	-145.60	-145.58	-145.61	-145.62	-145.54	-144.70	-160.32	-158.36	-156.06	-160.35	-158.18	-155.71
16	-145.61	-145.58	-145.61	-145.62	-145.55	-144.70	-160.30	-158.37	-156.03	-160.37	-158.20	-155.71
20	-145.65	-145.64	-145.66	-145.67	-145.60	-144.74	-160.35	-158.41	-156.08	-160.40	-158.27	-155.75
25	-145.68	-145.66	-145.70	-145.68	-145.61	-144.78	-160.35	-158.46	-156.11	-160.44	-158.29	-155.79
31.5	-145.74	-145.72	-145.76	-145.75	-145.69	-144.82	-160.41	-158.51	-156.15	-160.48	-158.35	-155.84
40	-145.83	-145.83	-145.85	-145.84	-145.77	-144.93	-160.48	-158.61	-156.27	-160.59	-158.44	-155.94
50	-145.97	-145.96	-145.98	-145.99	-145.91	-145.06	-160.64	-158.75	-156.40	-160.73	-158.58	-156.07
63	-146.19	-146.19	-146.21	-146.21	-146.14	-145.28	-160.87	-158.96	-156.62	-160.95	-158.81	-156.29
80	-146.64	-146.65	-146.67	-146.68	-146.59	-145.76	-161.29	-159.48	-157.12	-161.43	-159.30	-156.80

Table 49 Self-Noise PSD, Wrangler 3052E, 500 sps, Gains 1 and 4

500sps												
	Gain 1						Gain 4					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm
0.01	-108.30	-89.22	-106.31	-111.41	-103.18	-114.63	-120.29	-101.76	-117.94	-123.47	-114.66	-126.90
0.0125	-108.82	-89.85	-106.95	-112.02	-103.45	-115.14	-120.87	-102.45	-118.59	-124.03	-115.03	-127.37
0.016	-109.63	-90.80	-107.91	-112.91	-103.90	-115.90	-121.76	-103.44	-119.56	-124.88	-115.62	-128.11
0.02	-110.86	-92.09	-109.25	-114.02	-104.76	-116.92	-123.07	-104.72	-120.93	-126.11	-116.59	-129.32
0.025	-112.23	-93.45	-110.70	-115.13	-105.76	-118.01	-124.57	-106.17	-122.43	-127.28	-117.60	-130.58
0.0315	-113.58	-94.66	-112.02	-116.10	-106.74	-119.09	-126.01	-107.48	-123.85	-128.14	-118.48	-131.68
0.04	-115.12	-96.10	-113.41	-117.49	-107.61	-120.53	-127.39	-108.67	-125.35	-129.40	-119.59	-132.85
0.05	-116.50	-97.63	-114.74	-118.58	-108.47	-121.44	-128.46	-109.88	-126.70	-130.78	-120.95	-133.57
0.063	-117.42	-98.73	-116.14	-119.44	-109.63	-121.98	-129.84	-111.32	-128.14	-131.50	-121.74	-134.53
0.08	-118.72	-100.10	-117.70	-120.41	-110.60	-123.31	-131.06	-112.12	-129.41	-132.42	-123.09	-135.28
0.1	-119.42	-100.93	-118.65	-121.17	-111.82	-123.89	-132.00	-113.49	-130.77	-133.22	-124.11	-135.79
0.125	-120.32	-102.05	-119.71	-121.92	-112.77	-124.58	-132.94	-114.51	-131.72	-134.41	-125.14	-136.58
0.16	-121.32	-103.07	-121.21	-123.07	-113.61	-125.31	-133.99	-115.39	-133.04	-135.00	-126.01	-137.51
0.2	-121.87	-104.11	-122.12	-123.85	-114.95	-126.06	-134.64	-116.49	-134.22	-136.06	-127.48	-138.25
0.25	-122.87	-105.11	-123.18	-124.56	-115.80	-126.53	-135.47	-117.20	-135.17	-136.87	-128.75	-138.66
0.315	-123.15	-106.00	-124.08	-125.54	-117.06	-127.33	-136.06	-117.82	-136.16	-137.55	-129.50	-139.37
0.4	-123.70	-106.74	-125.12	-126.24	-118.18	-127.94	-136.64	-118.68	-136.96	-138.47	-130.52	-139.86
0.5	-124.30	-107.45	-125.98	-127.01	-119.01	-128.56	-137.23	-120.05	-137.88	-139.19	-131.46	-140.64
0.63	-124.82	-108.41	-126.78	-127.56	-120.13	-129.25	-137.71	-120.82	-138.79	-139.75	-132.66	-141.31
0.8	-125.10	-109.40	-127.49	-128.21	-121.25	-129.99	-138.36	-121.34	-139.55	-140.21	-133.86	-141.92
1	-125.60	-110.00	-128.05	-128.80	-122.28	-130.40	-138.54	-122.33	-140.14	-140.78	-134.87	-142.54
1.25	-126.01	-110.93	-128.74	-129.34	-123.27	-131.10	-139.07	-123.05	-140.89	-141.38	-135.96	-143.16
1.6	-126.49	-111.67	-129.38	-129.76	-124.46	-131.54	-139.62	-123.86	-141.33	-141.88	-137.08	-143.78
2	-126.72	-112.37	-129.82	-130.17	-125.32	-132.00	-140.00	-124.81	-141.87	-142.32	-138.03	-144.19
2.5	-127.08	-113.20	-130.33	-130.53	-126.18	-132.37	-140.40	-125.42	-142.42	-142.62	-138.90	-144.50
3.15	-127.41	-114.04	-130.75	-130.84	-126.89	-132.68	-140.74	-126.24	-142.89	-142.99	-139.55	-144.76
4	-127.68	-114.82	-131.21	-131.25	-127.58	-132.90	-141.07	-127.09	-143.33	-143.28	-140.27	-145.12
5	-127.85	-115.46	-131.58	-131.53	-128.18	-133.12	-141.32	-127.67	-143.68	-143.61	-140.89	-145.33
6.3	-128.05	-116.18	-131.89	-131.81	-128.67	-133.26	-141.56	-128.36	-143.96	-143.93	-141.42	-145.50
8	-128.19	-116.78	-132.14	-132.05	-129.16	-133.46	-141.70	-129.00	-144.32	-144.14	-141.89	-145.65
10	-128.29	-117.34	-132.37	-132.24	-129.58	-133.59	-141.82	-129.57	-144.57	-144.38	-142.26	-145.78
12.5	-128.38	-117.85	-132.60	-132.43	-129.96	-133.69	-141.87	-130.04	-144.76	-144.53	-142.65	-145.90
16	-128.43	-118.34	-132.79	-132.63	-130.33	-133.75	-141.95	-130.62	-144.99	-144.70	-143.02	-145.95
20	-128.48	-118.72	-132.96	-132.77	-130.66	-133.83	-141.98	-131.00	-145.14	-144.86	-143.31	-146.05
25	-128.55	-119.09	-133.14	-132.93	-130.97	-133.92	-142.06	-131.33	-145.33	-145.02	-143.63	-146.15
31.5	-128.61	-119.42	-133.33	-133.11	-131.28	-134.01	-142.11	-131.68	-145.50	-145.20	-143.91	-146.22
40	-128.66	-119.69	-133.48	-133.25	-131.57	-134.06	-142.11	-131.94	-145.65	-145.34	-144.18	-146.28
50	-128.73	-120.02	-133.62	-133.38	-131.87	-134.16	-142.18	-132.31	-145.80	-145.48	-144.45	-146.38
63	-128.82	-120.40	-133.75	-133.54	-132.16	-134.24	-142.22	-132.65	-145.92	-145.62	-144.72	-146.45
80	-128.93	-120.81	-133.90	-133.70	-132.48	-134.37	-142.30	-133.07	-146.08	-145.78	-145.03	-146.56
100	-129.08	-121.24	-134.08	-133.88	-132.82	-134.52	-142.38	-133.53	-146.26	-145.98	-145.36	-146.73
125	-129.26	-121.69	-134.34	-134.11	-133.25	-134.74	-142.51	-133.98	-146.51	-146.21	-145.74	-146.95
160	-129.55	-122.13	-134.73	-134.49	-133.88	-135.12	-142.75	-134.45	-146.93	-146.60	-146.32	-147.32
200	-130.01	-122.57	-135.35	-135.09	-134.72	-135.73	-143.20	-134.97	-147.60	-147.22	-147.13	-147.97

Table 50 Self-Noise PSD, Wrangler 3052E, 500 sps, Gains 16 and 64

500sps												
	Gain 16						Gain 64					
Frequency	Chan 1 50 ohm	Chan 2 100 ohm	Chan 3 200 ohm	Chan 4 50 ohm	Chan 5 100 ohm	Chan 6 200 ohm	Chan 1 500 ohm	Chan 2 4k ohm	Chan 3 10k ohm	Chan 4 500 ohm	Chan 5 4k ohm	Chan 6 10k ohm
0.01	-132.01	-112.90	-129.70	-134.94	-127.21	-137.62	-144.12	-124.50	-141.87	-147.22	-139.03	-147.91
0.0125	-132.58	-113.58	-130.39	-135.37	-127.45	-138.08	-144.56	-125.17	-142.54	-147.75	-139.35	-148.30
0.016	-133.43	-114.62	-131.42	-136.02	-127.87	-138.74	-145.22	-126.17	-143.53	-148.53	-139.86	-148.87
0.02	-134.70	-116.11	-132.91	-136.95	-128.72	-139.54	-146.22	-127.58	-144.88	-149.64	-140.75	-149.68
0.025	-136.05	-117.70	-134.51	-138.03	-129.66	-140.34	-147.46	-129.16	-146.28	-150.81	-141.75	-150.59
0.0315	-137.18	-119.15	-135.91	-139.06	-130.65	-140.94	-148.97	-130.62	-147.46	-151.93	-142.70	-151.20
0.04	-138.22	-120.62	-137.23	-139.80	-131.83	-141.61	-150.19	-132.01	-148.55	-153.16	-143.67	-151.40
0.05	-139.18	-121.71	-138.17	-140.57	-132.71	-141.99	-151.09	-133.04	-149.26	-153.64	-144.52	-151.91
0.063	-139.94	-122.67	-139.23	-141.30	-133.82	-142.32	-152.34	-133.98	-150.65	-154.34	-145.51	-152.22
0.08	-140.74	-123.75	-140.13	-141.77	-134.93	-142.69	-152.84	-135.18	-151.66	-155.06	-146.89	-152.38
0.1	-141.51	-124.98	-141.06	-142.46	-135.70	-143.18	-153.64	-136.36	-152.31	-155.86	-147.53	-153.00
0.125	-141.71	-125.97	-141.52	-142.71	-136.63	-143.35	-154.03	-137.38	-152.65	-156.27	-148.28	-153.14
0.16	-142.35	-127.39	-142.42	-143.01	-138.09	-143.43	-154.57	-138.53	-153.53	-156.84	-149.80	-153.43
0.2	-142.44	-127.88	-142.86	-143.54	-138.60	-143.67	-155.07	-139.12	-153.73	-157.06	-150.30	-153.37
0.25	-142.87	-128.72	-143.29	-144.01	-139.51	-143.77	-155.38	-140.17	-154.09	-157.53	-151.27	-153.69
0.315	-142.97	-129.45	-143.80	-144.17	-140.21	-144.08	-155.57	-140.91	-154.55	-157.93	-151.89	-153.93
0.4	-143.32	-130.50	-144.10	-144.33	-141.01	-144.23	-155.96	-141.73	-154.58	-158.33	-152.85	-154.03
0.5	-143.66	-131.35	-144.31	-144.51	-141.76	-144.49	-156.26	-142.83	-154.90	-158.60	-153.54	-154.26
0.63	-143.75	-132.04	-144.53	-144.59	-142.30	-144.63	-156.64	-143.26	-155.10	-158.76	-154.35	-154.56
0.8	-143.94	-132.99	-144.65	-144.78	-143.04	-144.84	-156.93	-144.38	-155.19	-159.03	-154.82	-154.68
1	-144.09	-133.63	-144.80	-144.93	-143.49	-144.89	-157.18	-144.98	-155.24	-159.15	-155.41	-154.89
1.25	-144.18	-134.37	-144.94	-145.01	-143.83	-145.04	-157.40	-145.76	-155.37	-159.22	-155.87	-155.03
1.6	-144.44	-135.17	-145.04	-145.01	-144.23	-145.08	-157.65	-146.74	-155.42	-159.38	-156.36	-155.17
2	-144.46	-135.88	-145.09	-145.09	-144.37	-145.19	-157.91	-147.33	-155.44	-159.49	-156.65	-155.33
2.5	-144.61	-136.50	-145.12	-145.24	-144.62	-145.25	-158.14	-147.99	-155.49	-159.55	-156.82	-155.44
3.15	-144.67	-137.23	-145.21	-145.22	-144.78	-145.27	-158.25	-148.72	-155.54	-159.61	-157.00	-155.46
4	-144.78	-137.88	-145.25	-145.24	-144.91	-145.33	-158.40	-149.33	-155.55	-159.65	-157.16	-155.47
5	-144.79	-138.42	-145.30	-145.31	-145.02	-145.35	-158.47	-149.96	-155.58	-159.71	-157.26	-155.54
6.3	-144.85	-139.06	-145.32	-145.35	-145.08	-145.37	-158.58	-150.51	-155.55	-159.80	-157.37	-155.57
8	-144.89	-139.52	-145.37	-145.35	-145.15	-145.39	-158.62	-151.05	-155.67	-159.81	-157.45	-155.58
10	-144.93	-139.95	-145.39	-145.39	-145.21	-145.40	-158.71	-151.50	-155.61	-159.84	-157.52	-155.60
12.5	-144.95	-140.28	-145.40	-145.42	-145.23	-145.40	-158.73	-151.89	-155.63	-159.85	-157.55	-155.61
16	-144.96	-140.65	-145.41	-145.42	-145.27	-145.39	-158.79	-152.28	-155.69	-159.88	-157.60	-155.59
20	-144.98	-140.90	-145.43	-145.43	-145.29	-145.40	-158.83	-152.58	-155.67	-159.89	-157.63	-155.58
25	-145.03	-141.14	-145.47	-145.46	-145.35	-145.41	-158.87	-152.80	-155.69	-159.93	-157.68	-155.62
31.5	-145.05	-141.36	-145.48	-145.49	-145.38	-145.46	-158.91	-153.03	-155.70	-159.98	-157.72	-155.63
40	-145.09	-141.56	-145.50	-145.51	-145.41	-145.46	-158.92	-153.27	-155.73	-159.99	-157.77	-155.65
50	-145.13	-141.77	-145.55	-145.55	-145.48	-145.51	-159.01	-153.49	-155.77	-160.04	-157.82	-155.70
63	-145.20	-142.02	-145.62	-145.61	-145.55	-145.56	-159.08	-153.75	-155.83	-160.12	-157.90	-155.76
80	-145.29	-142.30	-145.71	-145.71	-145.64	-145.66	-159.13	-154.05	-155.92	-160.21	-158.02	-155.84
100	-145.42	-142.59	-145.86	-145.86	-145.81	-145.79	-159.26	-154.36	-156.07	-160.35	-158.16	-156.00
125	-145.62	-142.95	-146.07	-146.07	-146.03	-146.00	-159.43	-154.69	-156.29	-160.58	-158.40	-156.21
160	-145.98	-143.36	-146.45	-146.44	-146.42	-146.39	-159.75	-155.08	-156.67	-160.96	-158.79	-156.59
200	-146.56	-143.88	-147.06	-147.06	-147.05	-147.00	-160.31	-155.58	-157.33	-161.59	-159.46	-157.24

3.8.4.4 Reevaluation of Wrangler 3052E's Self Noise

The noise level of Channel 2 of Wrangler 3052E was reevaluated in November 2023 after the unit was repaired by Reftek. The noise level of the channel is greatly improved compared to when it was first evaluated. Figure 37 shows a direct comparison of the channel before and after the repair.

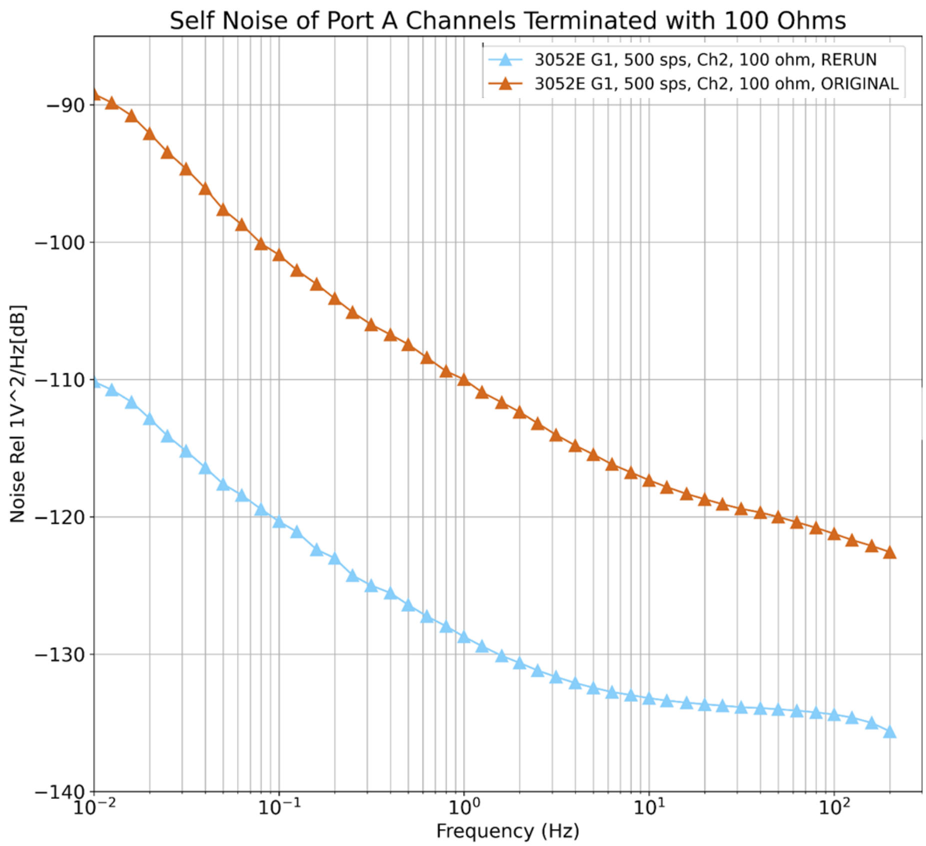

Figure 37 Reevaluation of 3052E Channel 2 self noise

3.9 Dynamic Range

Dynamic Range is defined as the ratio between the power of the largest and smallest signals that can be measured on the digitizer channel.

3.9.1 Measurand

The Dynamic Range is measured in dB as the ratio between the power in the largest and smallest signals. The largest signal is defined to be a sinusoid with amplitude equal to the full-scale input of the digitizer channel. The smallest signal is defined to have power equal to the self-noise of the digitizer channel. This definition of dynamic range is consistent with the definition of signal-to-noise and distortion ratio (SINAD) for digitizers (IEEE Std 1241-2010 section 9.2).

3.9.2 Configuration

There is no test configuration for the dynamic range test.

3.9.3 Analysis

The dynamic range over a given passband is:

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

Where

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

Note that full scale peak-to-peak values must be divided by 2 to convert them to full scale peak values. The passband over which the noise is integrated should be selected to be consistent with the application passband and the sampling rate that is being used.

3.9.4 Result

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

Table 51 Dynamic Range: Wrangler 3052C

Channel	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
	Gain 1				**Gain 4**			
1 - 250sps	137.30	148.37	144.18	144.84	137.44	148.46	144.30	144.97
2 - 250sps	136.91	147.36	143.47	144.25	137.04	147.42	143.57	144.36
3 - 250sps	134.85	145.60	141.37	142.01	135.04	145.63	141.49	142.17
4 - 250sps	136.73	148.16	143.77	144.34	136.66	148.24	143.87	144.44
5 - 250sps	137.12	148.28	144.03	144.63	137.23	148.29	144.10	144.73
6 - 250sps	137.10	148.16	143.98	144.61	137.20	148.13	144.03	144.70
	Gain 16				**Gain 64**			
1 - 250sps	124.79	138.29	132.44	132.61	127.15	140.72	135.05	135.27
2 - 250sps	124.75	138.15	132.37	132.56	121.73	138.70	132.93	133.11
3 - 250sps	124.60	137.89	132.17	132.37	119.22	136.41	130.61	130.79
4 - 250sps	124.48	138.18	132.31	132.48	123.14	140.39	134.67	134.87
5 - 250sps	124.67	138.15	132.31	132.48	118.01	138.49	132.68	132.86
6 - 250sps	124.74	138.20	132.38	132.56	110.81	136.53	130.75	130.93

Table 52 Dynamic Range: Wrangler 3052D

Channel	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
	Gain 1				**Gain 4**			
1 - 20sps	144.48	147.44	N/A	N/A	144.35	147.30	N/A	N/A
2 - 20sps	144.40	147.43	N/A	N/A	144.84	147.89	N/A	N/A
3 - 20sps	143.89	146.79	N/A	N/A	143.20	146.02	N/A	N/A
4 - 20sps	142.79	145.60	N/A	N/A	142.62	145.39	N/A	N/A
5 - 20sps	142.54	145.37	N/A	N/A	142.36	145.17	N/A	N/A
6 - 20sps	144.33	147.24	N/A	N/A	128.59	131.06	N/A	N/A
	Gain 16				**Gain 64**			
1 - 20sps	134.77	138.03	N/A	N/A	136.85	140.08	N/A	N/A
2 - 20sps	134.76	138.01	N/A	N/A	137.65	140.98	N/A	N/A
3 - 20sps	134.75	138.00	N/A	N/A	133.20	136.43	N/A	N/A
4 - 20sps	134.77	138.01	N/A	N/A	137.15	140.39	N/A	N/A
5 - 20sps	134.71	137.95	N/A	N/A	135.23	138.49	N/A	N/A
6 - 20sps	133.90	137.14	N/A	N/A	132.94	136.18	N/A	N/A
	Gain 1				**Gain 4**			
1 - 40sps	141.79	146.95	142.34	142.85	142.05	147.21	142.61	143.13
2 - 40sps	142.47	147.83	143.03	143.46	142.70	148.08	143.26	143.68
3 - 40sps	141.57	146.70	142.08	142.63	141.99	147.13	142.51	143.06
4 - 40sps	142.27	147.41	142.81	143.28	142.01	147.10	142.54	143.03
5 - 40sps	141.79	146.92	142.32	142.81	141.56	146.64	142.08	142.59
6 - 40sps	142.40	147.50	142.95	143.45	126.73	131.08	126.95	127.41

Channel	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
	Gain 16				**Gain 64**			
1 - 40sps	131.99	138.17	132.30	132.47	134.17	140.30	134.54	134.81
2 - 40sps	131.98	138.14	132.29	132.46	134.61	140.81	134.96	135.13
3 - 40sps	131.97	138.13	132.28	132.45	130.38	136.53	130.69	130.87
4 - 40sps	132.00	138.14	132.31	132.49	134.51	140.62	134.85	135.04
5 - 40sps	131.93	138.08	132.24	132.41	132.48	138.63	132.79	132.97
6 - 40sps	131.10	137.25	131.40	131.57	130.10	136.27	130.40	130.57
	Gain 1				**Gain 4**			
1 - 100sps	139.93	148.07	143.74	144.36	140.00	148.12	143.82	144.45
2 - 100sps	139.84	148.22	143.70	144.22	139.95	148.34	143.81	144.32
3 - 100sps	139.71	147.69	143.32	143.96	139.80	147.74	143.40	144.05
4 - 100sps	139.98	148.12	143.79	144.36	140.09	148.19	143.91	144.49
5 - 100sps	139.64	147.77	143.44	144.01	139.74	147.83	143.53	144.12
6 - 100sps	139.76	147.73	143.51	144.13	125.20	131.09	126.97	127.43
	Gain 16				**Gain 64**			
1 - 100sps	128.22	138.25	132.38	132.55	130.43	140.41	134.68	134.95
2 - 100sps	128.22	138.22	132.37	132.54	130.29	140.29	134.45	134.63
3 - 100sps	128.23	138.21	132.36	132.54	126.60	136.58	130.75	130.93
4 - 100sps	128.24	138.22	132.40	132.57	130.84	140.76	135.00	135.19
5 - 100sps	128.17	138.16	132.32	132.49	128.74	138.72	132.89	133.06
6 - 100sps	127.32	137.31	131.47	131.64	126.29	136.32	130.45	130.62
	Gain 1				**Gain 4**			
1 - 200sps	137.99	148.37	144.18	144.84	138.07	148.42	144.27	144.95
2 - 200sps	137.81	148.47	144.08	144.64	137.92	148.60	144.20	144.75
3 - 200sps	137.85	147.94	143.69	144.38	137.97	148.00	143.78	144.48
4 - 200sps	138.04	148.43	144.25	144.86	138.12	148.50	144.36	144.99
5 - 200sps	137.65	148.05	143.84	144.46	137.73	148.10	143.93	144.57
6 - 200sps	127.37	147.98	143.90	144.56	95.35	131.10	126.98	127.44
	Gain 16				**Gain 64**			
1 - 200sps	125.50	138.27	132.41	132.58	127.21	140.46	134.73	135.00
2 - 200sps	125.53	138.25	132.40	132.57	114.20	138.94	133.11	133.28
3 - 200sps	125.55	138.24	132.39	132.56	114.74	136.60	130.76	130.94
4 - 200sps	125.51	138.25	132.43	132.60	127.33	140.80	135.05	135.24
5 - 200sps	125.45	138.19	132.34	132.52	121.63	138.78	132.95	133.12
6 - 200sps	102.96	137.33	131.50	131.67	118.93	136.33	130.47	130.64

Table 53 Dynamic Range: Wrangler 3052E

Channel	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz	0.01 Hz - Nyquist	0.02 - 4 Hz	0.02 - 16 Hz	0.5 - 16 Hz
	Gain 1				**Gain 4**			
1 - 500sps	128.71	142.24	138.25	138.91	129.93	143.14	139.46	140.26
2 - 500sps	119.30	125.95	124.28	126.38	119.54	126.22	124.51	126.55
3 - 500sps	133.05	143.52	140.80	142.31	133.12	143.44	140.79	142.36
4 - 500sps	133.33	145.14	141.74	142.66	133.36	145.18	141.77	142.69
5 - 500sps	131.15	137.69	136.20	138.77	131.58	138.04	136.64	139.40
6 - 500sps	134.15	147.13	143.37	144.13	134.30	147.25	143.51	144.27
	Gain 16				**Gain 64**			
1 - 500sps	121.15	136.96	131.57	131.82	122.22	138.02	133.06	133.41
2 - 500sps	117.30	125.62	123.57	125.31	114.27	124.95	122.96	124.75
3 - 500sps	121.58	137.41	132.01	132.29	110.17	135.88	130.28	130.52
4 - 500sps	121.62	137.72	132.12	132.34	123.58	139.83	134.43	134.69
5 - 500sps	121.47	135.45	131.23	131.95	119.47	135.39	131.36	132.14
6 - 500sps	121.58	137.83	132.15	132.35	115.35	135.81	130.25	130.47

Dynamic range can vary considerably depending upon the spectral level of the self-noise, passband over which the noise is integrated, sample rate, gain settings, and terminating resistor. In general, dynamic range levels were between 138 dB and 148 dB at x1 gain levels depending on the sample rate and frequency passband. Channels operated at 200 sps and higher were able to record 60Hz power line noise which sometimes resulted in significantly lower dynamic range values for the 0.01Hz to Nyquist passband case.

Dynamic range tended to be similar when the Wranglers were operated at x1 or x4 gain. When the units were operated at x16 gain, however, dynamic range was noticeably less than the x1 and x4 gain cases. This is likely due to the elevated noise at frequencies above about 1Hz when the x16 gain stage is used. The x64 gain stage tended to have better dynamic range than the x16 stage but not as much as the x1 and x4 stages. Some of this drop is likely due to the larger valued termination resistors that were used for the x64 test.

The Wrangler datasheet specifies > 140 dB of dynamic range at 100 sps. In this testing, at 100 sps the measured dynamic range was between 127 and 148 dB, depending on the gain level and frequency passband for computing noise power.

For IMS Seismic and Infrasound applications, the measured dynamic range well exceeded the requirements of 120 dB and 108 dB, respectively, at the appropriate sample rates of 20 and 40 sps.

For the OSI applications, where the minimum requirement is 135 dB at 100 sps, measured dynamic range ranged for the 0.01 Hz to Nyquist passband were approximately 140 dB at gains of x1 and x4 and between 126 and 131 dB at gains of x16 and x64.

3.10 System Noise

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

3.10.1 Measurand

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

3.10.2 Configuration

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

3.10.3 Result

The PSD of the system noise is shown in the plots below. The terminated noise data was used to match the sensor output impedance and the desired sample rate for the application passband. Where available, sensor self-noise and background noise models are provided for comparison.

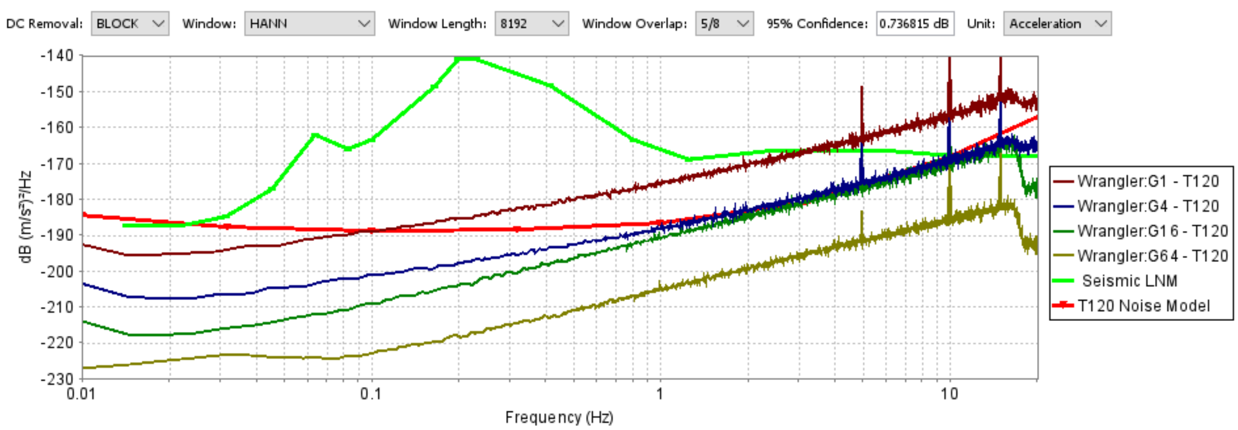

Figure 38 Seismic System Noise for Trillium 120

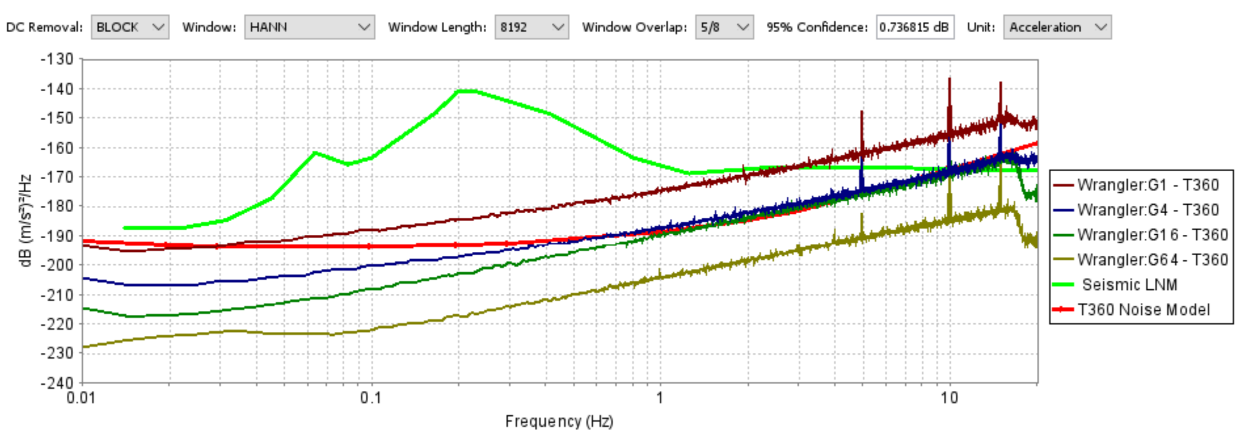

Figure 39 Seismic System Noise for Trillium 360

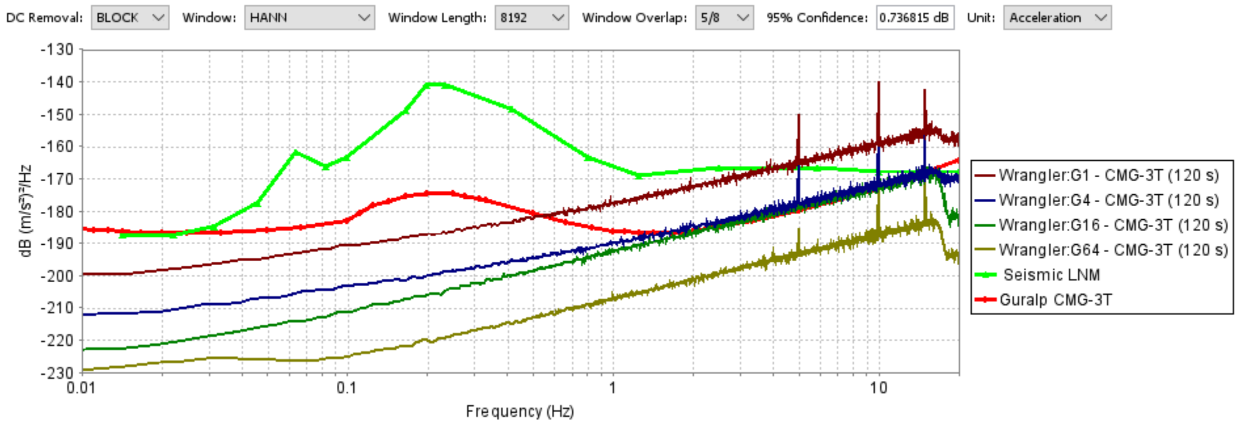

Figure 40 Seismic System Noise for Guralp CMG-3T (1500 V/(m/s) and 120 sec corner)

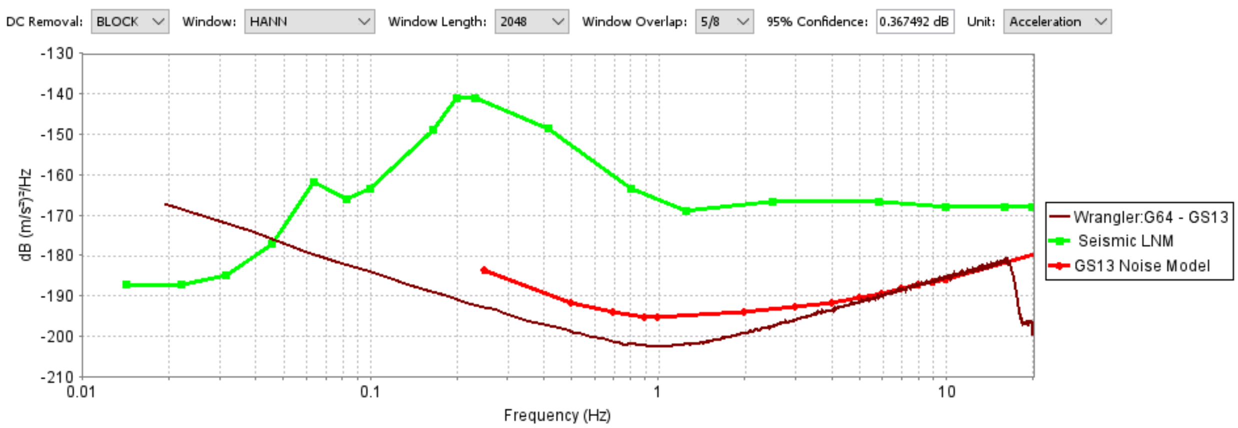

Figure 41 Seismic System Noise for Geotech GS13

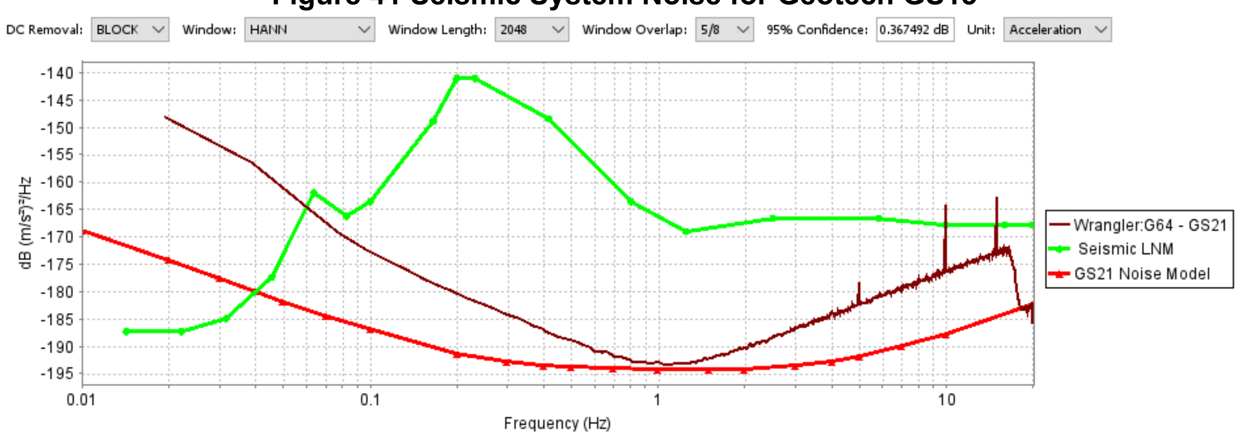

Figure 42 Seismic System Noise for Geotech GS21

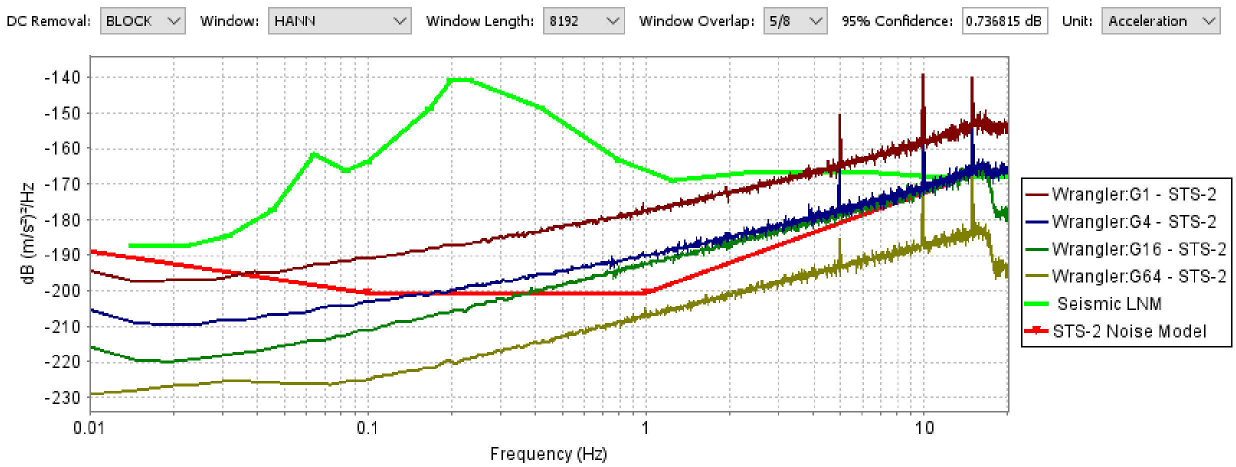

Figure 43 Seismic System Noise for STS-2

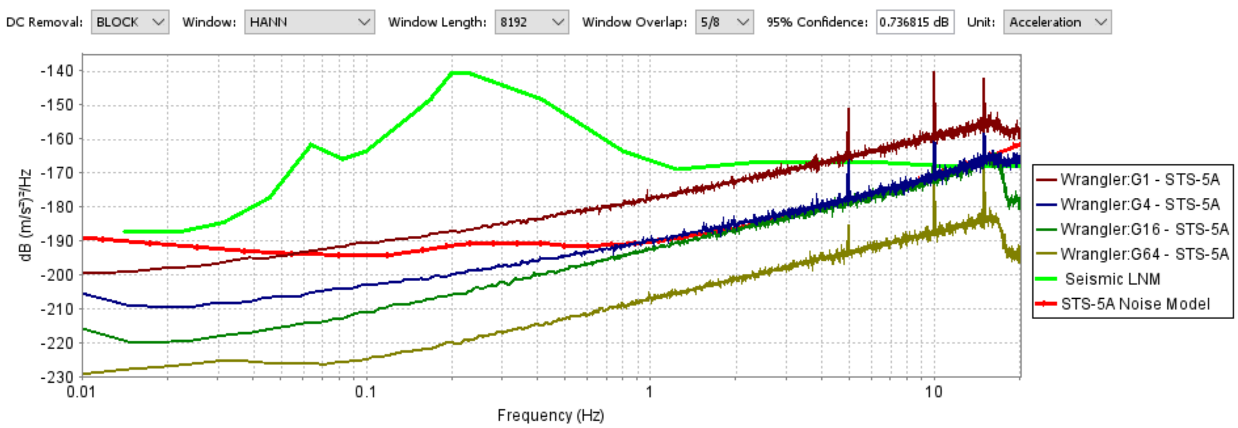

Figure 44 Seismic System Noise for Kinemetrics STS-5A

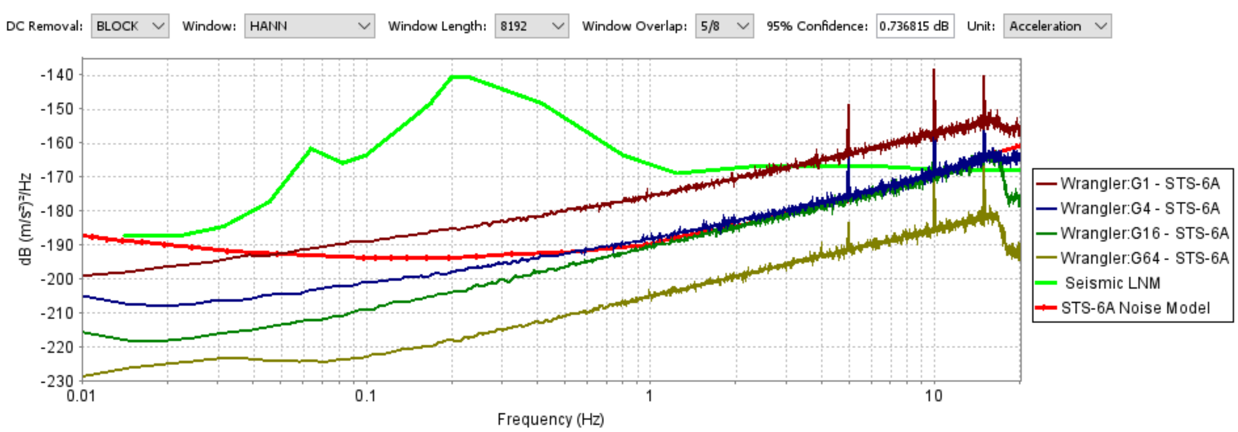

Figure 45 Seismic System Noise for Kinemetrics STS-6A

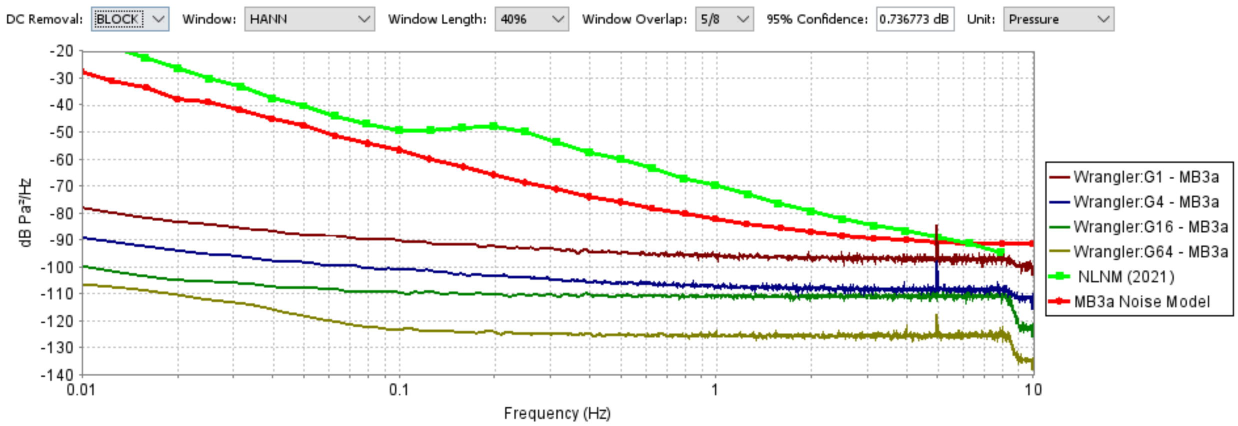

Figure 46 Infrasound System Noise for MB3a (20 mV/Pa)

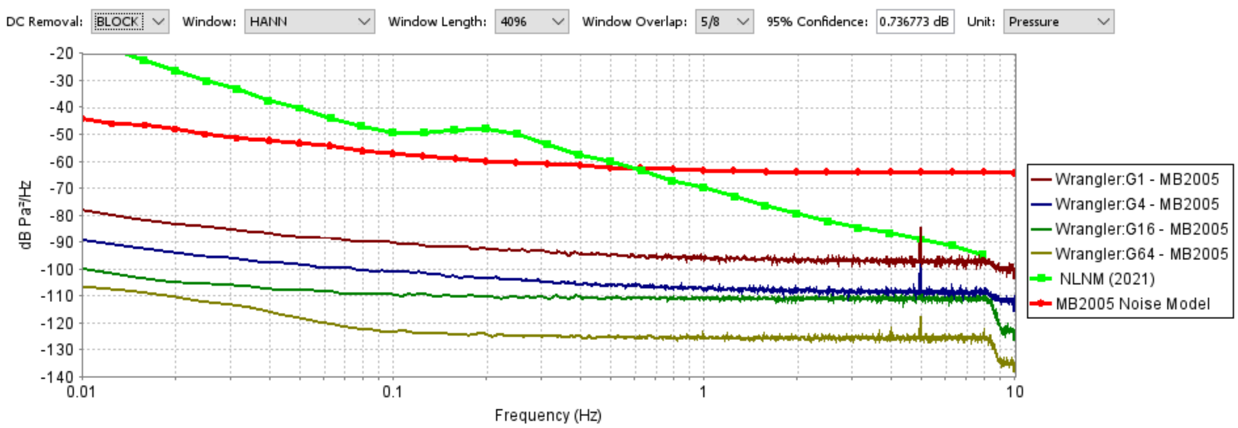

Figure 47 Infrasound System Noise for MB2005 (20 mV/Pa)

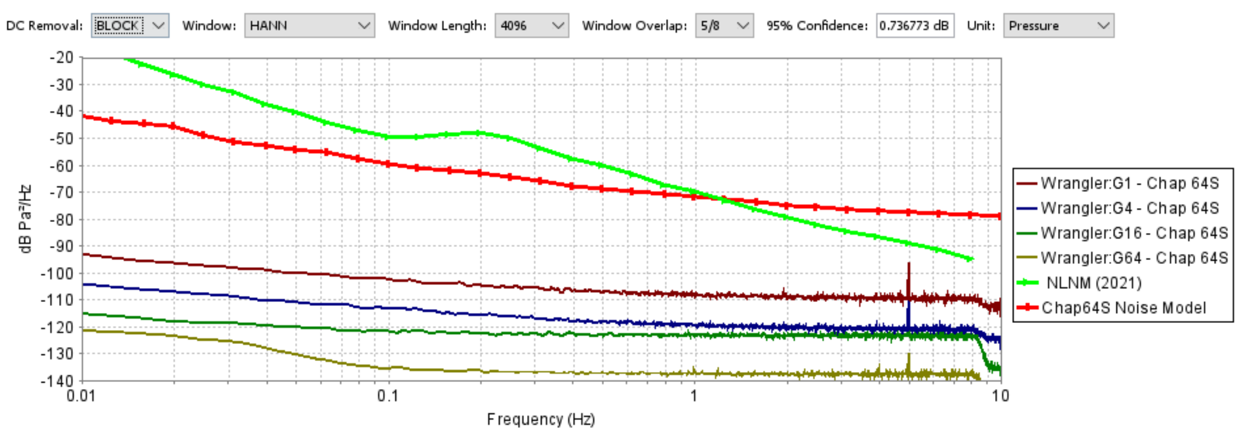

Figure 48 Infrasound System Noise for Chaparral 64S (80 mV/Pa)

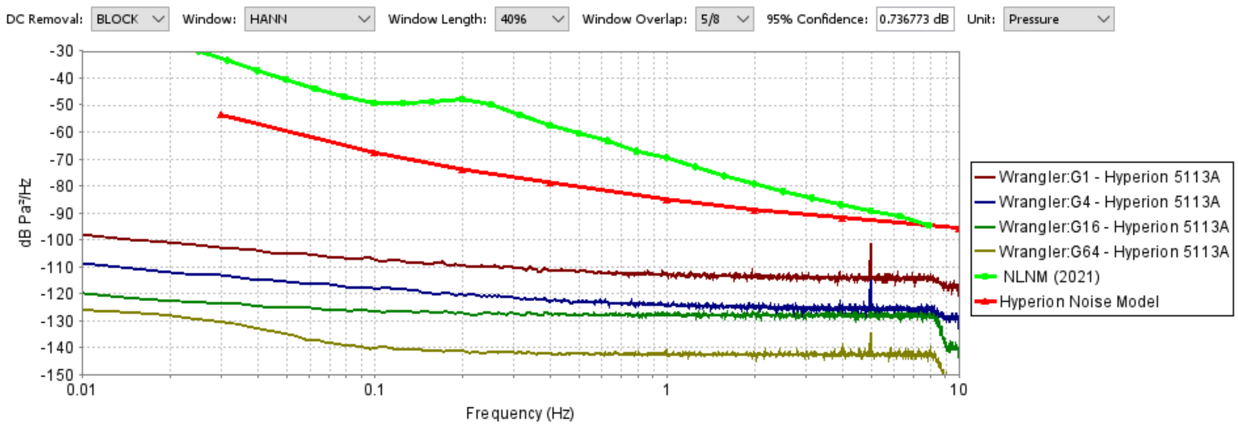

Figure 49 Infrasound System Noise for Hyperion 5113A (140 mV/Pa)

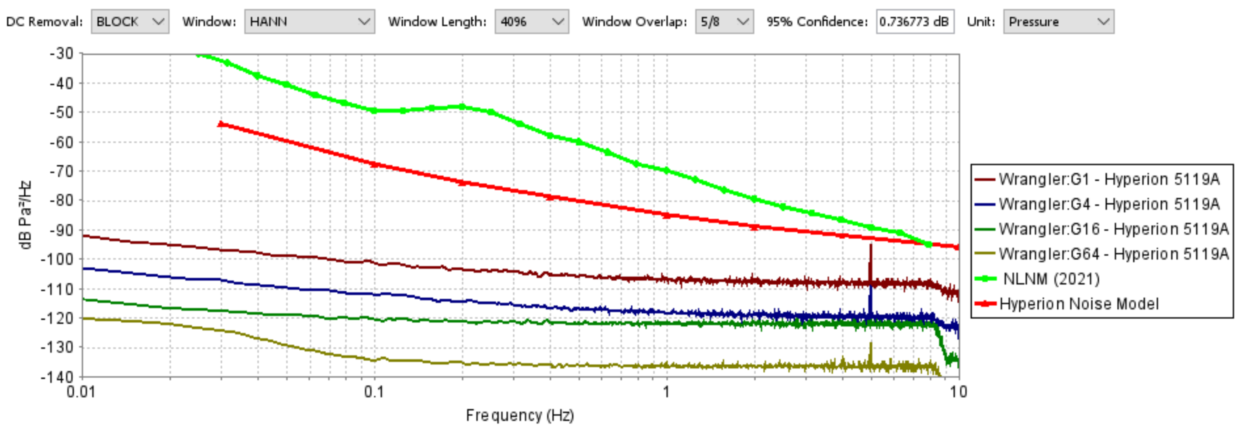

Figure 50 Infrasound System Noise for Hyperion 5119A (70 mV/Pa)

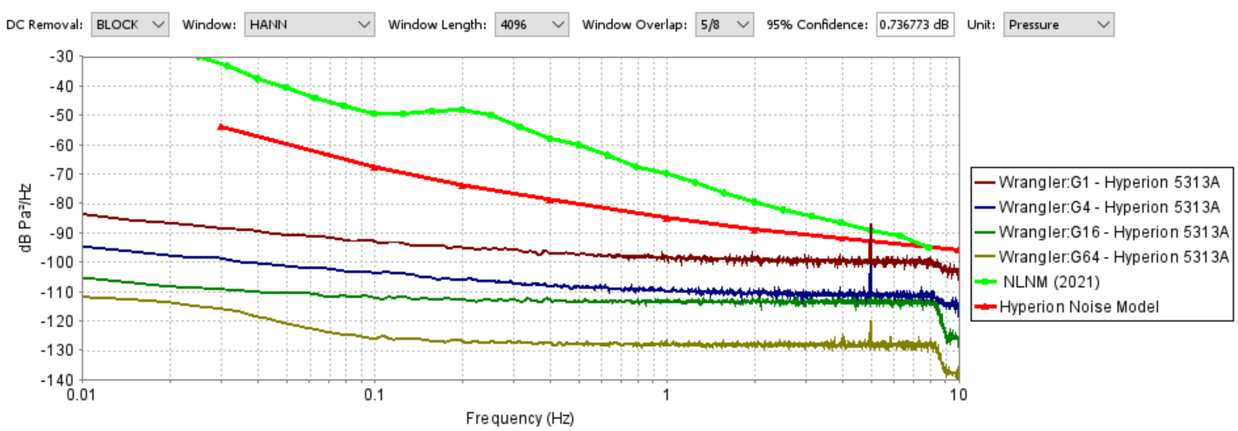

Figure 51 Infrasound System Noise for Hyperion 5313A (26.6 mV/Pa)

3.11 Temperature Self-Noise

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

3.11.1 Measurand

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

3.11.2 Configuration

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

Figure 52 Temperature Self Noise Configuration Diagram

Figure 53 Temperature Self Noise Configuration Picture

Two of the Wrangler digitizers were placed inside of a temperature chamber so that they could be exposed to a range of temperatures. The analog input cables to the digitizers were routed through a cable port in the sidewall of the temperature chamber so that the terminating resistors could be connected to the inputs of the digitizers without exposing the terminating resistors to the thermal conditions within the chamber. The room temperature was kept at 23 C +/- 2 C.

For the temperature test, the digitizer channels were terminated with resistors according to the table below:

Table 54 Digitizer Temperature Self-Noise Terminator Configuration

	Port A				Port B			
	Gain	Channel 1	Channel 2	Channel 3	Gain	Channel 4	Channel 5	Channel 6
Wrangler 3052C	1	50 ohms	100 ohms	200 ohms	1	50 ohms	100 ohms	200 ohms
Wrangler 3052D	1	50 ohms	100 ohms	200 ohms	1	50 ohms	100 ohms	200 ohms

The temperature chamber was programmed to cycle from 20 C, down to -20 C, up to 50 C, and back to 20 C.   The temperature changes in 10 C steps with 4 hrs at each temperature.

Table 55 Self Noise Testbed Equipment

	Manufacturer / Model
Temperature Chamber	ESPEC EPL-2H

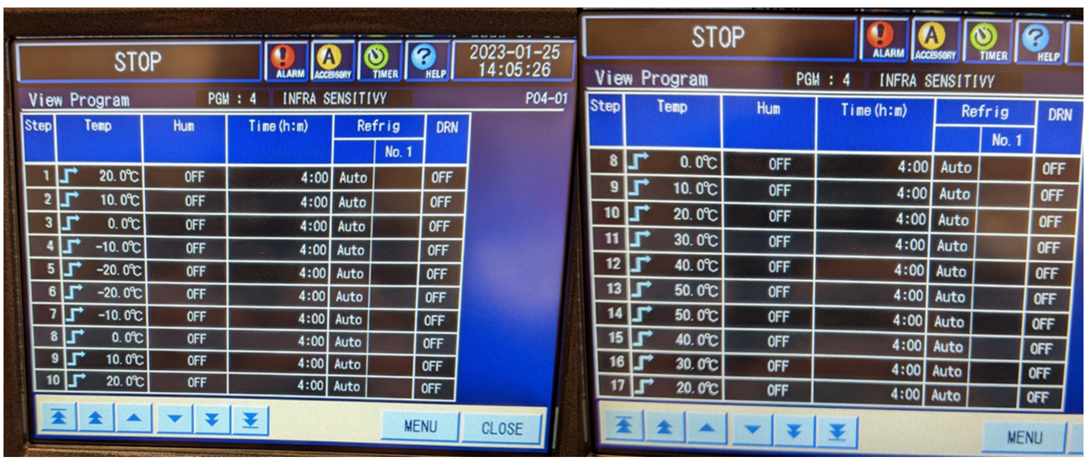

Figure 54 Temperature Chamber Program

3.11.3 Analysis

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

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

The PSD is computed (Merchant, 2011) from the time series using a 16k-sample Hann window for the 100 Hz sample rate data. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation passband of 0.01 Hz and the 90% confidence interval is less than 0.5 dB.

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

Over frequencies (in Hertz):

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

The digitizers were verified to be operating at each of the temperature levels and its noise levels were compared to the ambient 23 C operation.

3.11.4 Result

Representative time series plots from the digitizers are shown below.

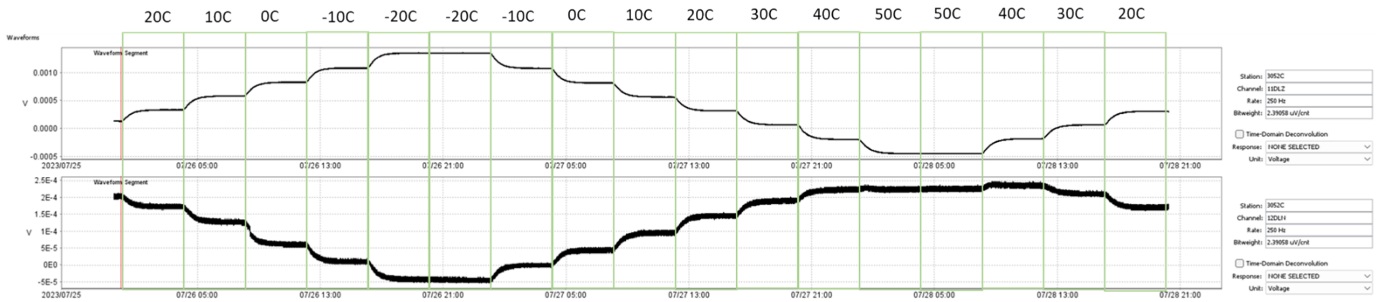

Figure 55 Temperature Self Noise Time Series, 3052C

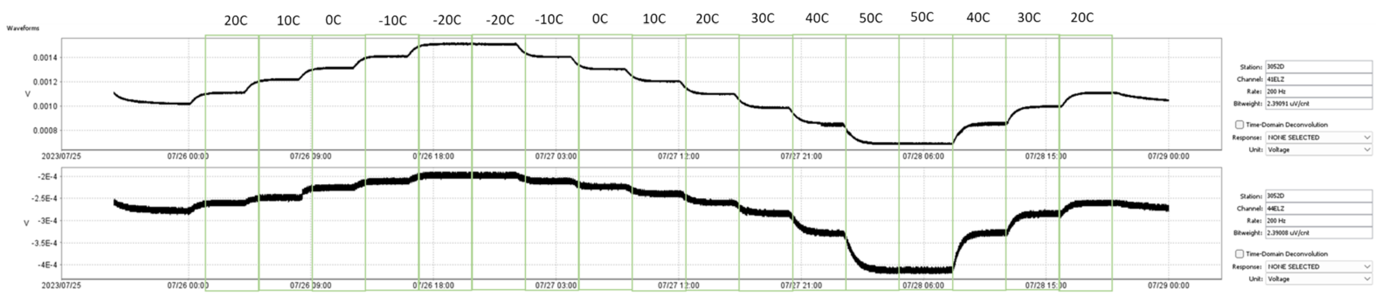

Figure 56 Temperature Self Noise Time Series, 3052D

The two Wranglers showed consistent performance during the temperature test and no operational issues were found when running in environments from -20 C to +50 C.

As expected, small DC offset changes accompany each temperature step. The worst-case DC offset change over the duration of the test was 3.02mV for channel 6 of 3052D. The offset changes for the other channels were less than 3.02mV. With the short duration of the time spent at each, the signals were not sufficiently stable to generate power spectra.

3.12 Relative Transfer Function

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

3.12.1 Measurand

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

3.12.2 Configuration

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

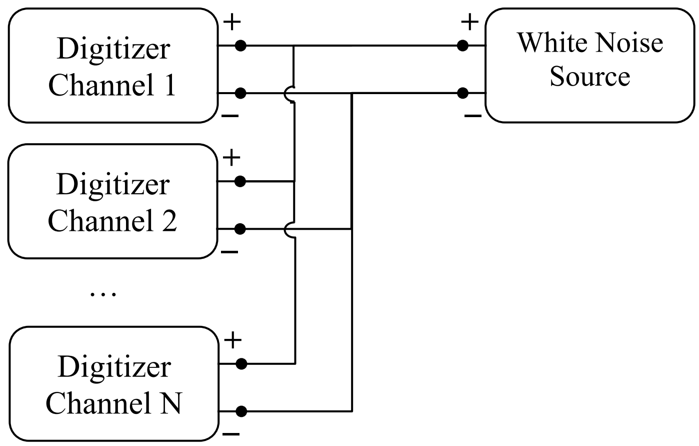

Figure 57 Relative Transfer Function Configuration Diagram

Table 56 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
White Noise Source	SRS DS360	123672	White Noise, 2V amplitude, 400Hz bandwidth	All

The White Noise Source is configured to generate a bandwidth 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.

3.12.3 Analysis

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

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

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

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

The tester defines a frequency range over which to measure the skew where the relative phase is linear, typically from 1 Hz to 80% of the Nyquist rate:

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

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:

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

3.12.4 Result

Select examples of phase delay versus frequency are shown in the figures below. The phase delay plots for other gains and sample rates are not shown as they are similar in appearance. To the extent that delay is a constant time offset, the phase delay is observed to be linear with respect to frequency.

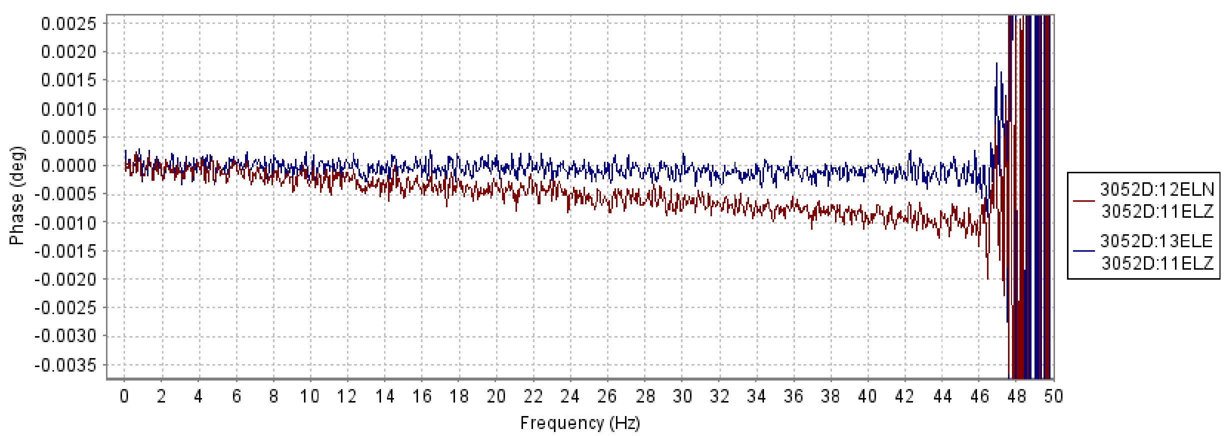

Figure 58 Relative Transfer Function: Wrangler 3052D, Gain 1, 100 sps

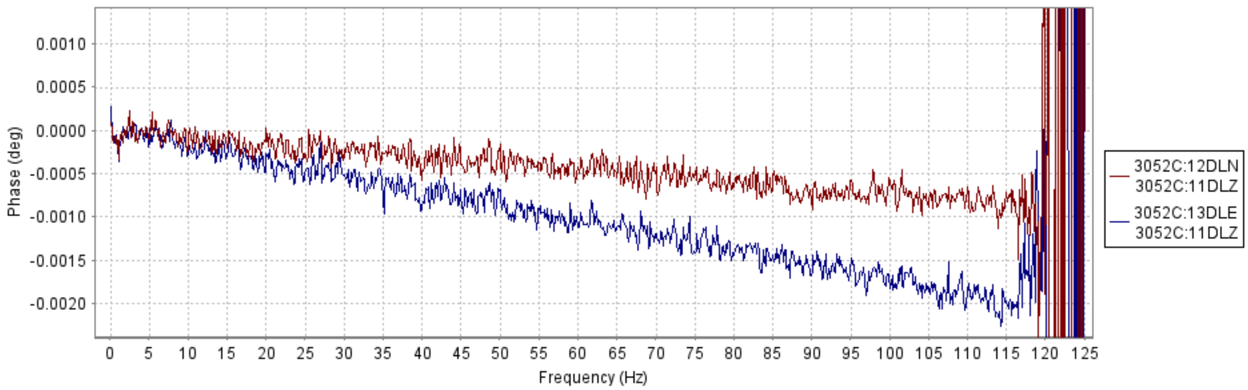

Figure 59 Relative Transfer Function: Wrangler 3052C, Gain 64, 250 sps

All the phase delays are indeed linear with respect to frequency. The constant channel-to-channel timing skew, relative to channels 1 and 4 for ports A and B, respectively, corresponding to these phase delays is shown in the tables below.

Table 57 Relative Transfer Function relative to Channel 1 or 4: Wrangler 3052C

Channel	Gain 1	Gain 4	Gain 16	Gain 64		Channel	Gain 1	Gain 4	Gain 16	Gain 64
1-2 250 sps	-0.013 us	-0.016 us	-0.022 us	-0.023 us		4-5 250 sps	-0.036 us	-0.036 us	-0.029 us	-0.031 us
1-3 250 sps	-0.046 us	-0.050 us	-0.047 us	-0.049 us		4-6 250 sps	-0.009 us	-0.011 us	-0.006 us	-0.003 us

Table 58 Relative Transfer Function relative to Channel 1 or 4: Wrangler 3052D

Channel	Gain 1	Gain 4	Gain 16	Gain 64		Channel	Gain 1	Gain 4	Gain 16	Gain 64
1-2 20 sps	-0.083 us	-0.085 us	-0.132 us	-0.125 us		4-5 20 sps	-0.033 us	-0.014 us	-0.007 us	-0.001 us
1-3 20 sps	-0.020 us	-0.021 us	-0.037 us	-0.047 us		4-6 20 sps	-0.030 us	-0.016 us	0.006 us	-0.010 us
1-2 40 sps	-0.068 us	-0.072 us	-0.093 us	-0.090 us		4-5 40 sps	-0.019 us	-0.010 us	-0.010 us	-0.006 us
1-3 40 sps	-0.014 us	-0.015 us	-0.016 us	-0.021 us		4-6 40 sps	-0.022 us	-0.014 us	-0.004 us	-0.015 us
1-2 100 sps	-0.064 us	-0.064 us	-0.072 us	-0.073 us		4-5 100 sps	-0.011 us	-0.007 us	-0.008 us	-0.008 us
1-3 100 sps	-0.010 us	-0.010 us	-0.007 us	-0.010 us		4-6 100 sps	-0.017 us	-0.012 us	-0.011 us	-0.017 us
1-2 200 sps	-0.062 us	-0.061 us	-0.067 us	-0.068 us		4-5 200 sps	-0.007 us	-0.004 us	-0.010 us	-0.009 us
1-3 200 sps	-0.010 us	-0.010 us	-0.005 us	-0.008 us		4-6 200 sps	-0.014 us	-0.011 us	-0.014 us	-0.017 us

Table 59 Relative Transfer Function relative to Channel 1 or 4: Wrangler 3052E

Channel	Gain 1	Gain 4	Gain 16	Gain 64		Channel	Gain 1	Gain 4	Gain 16	Gain 64
1-2 500 sps	-0.011 us	-0.010 us	-0.011 us	-0.007 us		4-5 500 sps	-0.000 us	0.000 us	-0.048 us	-0.049 us
1-3 500 sps	-0.015 us	-0.015 us	0.043 us	0.044 us		4-6 500 sps	0.003 us	0.003 us	-0.046 us	-0.046 us

All the digitizer channels were observed to have a timing skew that was less than +/- 0.13 microsecond of one another, indicating the channels are consistency sampling synchronously. In general, the relative timing skew between channels did not appear to be significantly impacted by changes in the gain or sample rate of a channel.

3.13 Analog Bandwidth

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

3.13.1 Measurand

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

3.13.2 Configuration

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

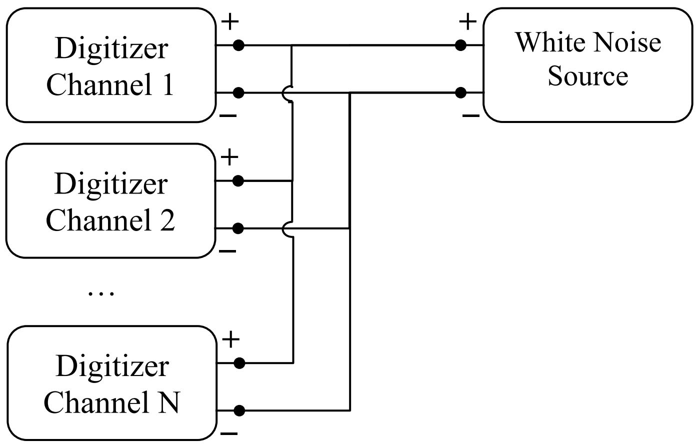

Figure 60 Analog Bandwidth Configuration Diagram

Table 60 Analog Bandwidth Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
White Noise Source	SRS DS360	123672	White Noise, 2V amplitude, 400Hz bandwidth	All

The White Noise Source is configured to generate a bandwidth 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.

3.13.3 Analysis

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

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

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

3.13.4 Result

Select examples of the power spectra of the white noise signal recorded on the digitizer channels are shown in the figures below.

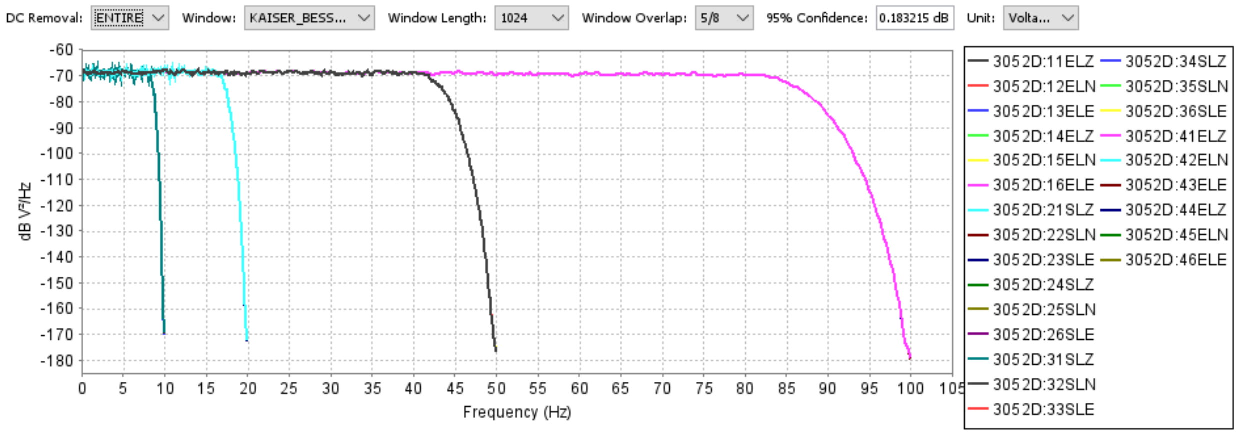

Figure 61 Analog Bandwidth: Wrangler 3052D at Gain 64. 20, 40, 100, 200 sps

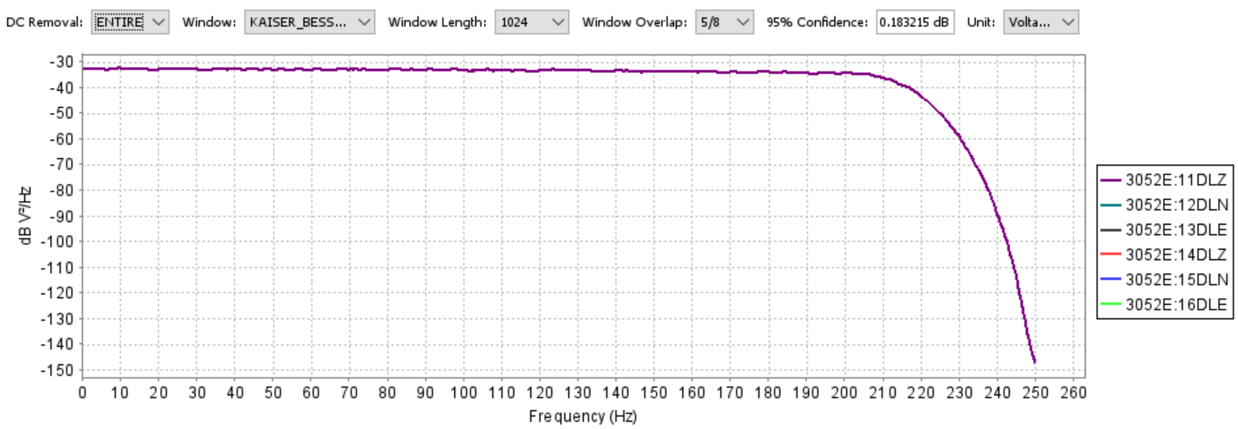

Figure 62 Analog Bandwidth: Wrangler 3052E, Gain 1, 500 sps

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

Table 61 Analog Bandwidth: Wrangler 3052C, 250 sps

Channel	Gain 1	Gain 4	Gain 16	Gain 64
1, 250 sps	105.2 Hz	105.2 Hz	105.2 Hz	105.1 Hz
2, 250 sps	105.2 Hz	105.2 Hz	105.2 Hz	105.1 Hz
3, 250 sps	105.2 Hz	105.2 Hz	105.2 Hz	105.1 Hz
4, 250 sps	105.2 Hz	105.2 Hz	105.2 Hz	105.1 Hz
5, 250 sps	105.2 Hz	105.2 Hz	105.2 Hz	105.1 Hz
6, 250 sps	105.2 Hz	105.2 Hz	105.2 Hz	105.1 Hz

Table 62 Analog Bandwidth: Wrangler 3052D, 20, 40, 100, 200 sps

Channel	Gain 1	Gain 4	Gain 16	Gain 64
1, 100 sps	42.24 Hz	42.17 Hz	42.39 Hz	42.18 Hz
2, 100 sps	42.24 Hz	42.17 Hz	42.39 Hz	42.18 Hz
3, 100 sps	42.24 Hz	42.17 Hz	42.39 Hz	42.18 Hz
4, 100 sps	42.24 Hz	42.17 Hz	42.39 Hz	42.18 Hz
5, 100 sps	42.24 Hz	42.17 Hz	42.39 Hz	42.18 Hz
6, 100 sps	42.24 Hz	42.17 Hz	42.39 Hz	42.18 Hz
1, 40 sps	17.08 Hz	17.08 Hz	17.08 Hz	17.08 Hz
2, 40 sps	17.08 Hz	17.08 Hz	17.08 Hz	17.08 Hz
3, 40 sps	17.08 Hz	17.08 Hz	17.08 Hz	17.08 Hz
4, 40 sps	17.08 Hz	17.08 Hz	17.08 Hz	17.08 Hz
5, 40 sps	17.08 Hz	17.08 Hz	17.08 Hz	17.08 Hz
6, 40 sps	17.08 Hz	17.08 Hz	17.08 Hz	17.08 Hz
1, 20 sps	8.521 Hz	8.524 Hz	8.524 Hz	8.520 Hz
2, 20 sps	8.521 Hz	8.524 Hz	8.524 Hz	8.520 Hz
3, 20 sps	8.521 Hz	8.524 Hz	8.524 Hz	8.520 Hz
4, 20 sps	8.521 Hz	8.524 Hz	8.524 Hz	8.520 Hz
5, 20 sps	8.521 Hz	8.524 Hz	8.524 Hz	8.520 Hz
6, 20 sps	8.521 Hz	8.524 Hz	8.524 Hz	8.520 Hz
1, 200 sps	84.91 Hz	84.78 Hz	84.70 Hz	84.80 Hz
2, 200 sps	84.91 Hz	84.78 Hz	84.70 Hz	84.80 Hz
3, 200 sps	84.91 Hz	84.78 Hz	84.70 Hz	84.80 Hz
4, 200 sps	84.91 Hz	84.78 Hz	84.70 Hz	84.80 Hz
5, 200 sps	84.91 Hz	84.78 Hz	84.70 Hz	84.80 Hz
6, 200 sps	84.91 Hz	84.78 Hz	84.70 Hz	84.80 Hz

Table 63 Analog Bandwidth: Wrangler 3052E, 500 sps

Channel	Gain 1	Gain 4	Gain 16	Gain 64
1, 500 sps	210.3 Hz	210.3 Hz	210.3 Hz	210.3 Hz
2, 500 sps	210.3 Hz	210.3 Hz	210.3 Hz	210.3 Hz
3, 500 sps	210.3 Hz	210.3 Hz	210.3 Hz	210.3 Hz
4, 500 sps	210.3 Hz	210.3 Hz	210.3 Hz	210.3 Hz
5, 500 sps	210.3 Hz	210.3 Hz	210.3 Hz	210.3 Hz
6, 500 sps	210.3 Hz	210.3 Hz	210.3 Hz	210.3 Hz

All the channels were observed to have similar high frequency passband limits for a common sample rate. The table below shows the average value of the passband for each sample rate expressed as a percentage of Nyquist.

Table 64 Passband as percent of Nyquist

Sample Rate	Passband as percent of Nyquist
20 sps	85.22%
40 sps	85.40%
100 sps	84.49%
200 sps	84.80%
250 sps	84.14%
500 sps	84.12%

These results indicate that anti-alias filters used by the Wrangler are compatible with each of the configured sampling rates.

3.14 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.

3.14.1 Measurand

The quantity being measured is the digitizer input channel's linearity expressed in decibels.

3.14.2 Configuration

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

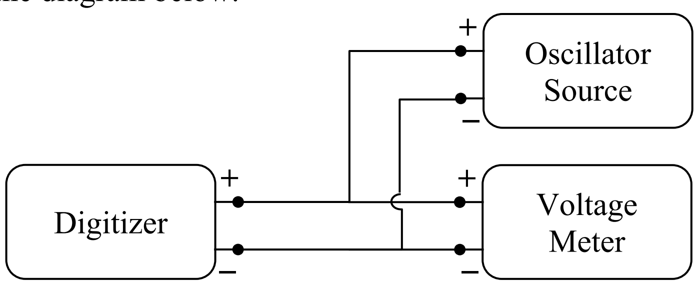

Figure 63 Total Harmonic Distortion Configuration Diagram

Table 65 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
AC Signal Source	Quanterra Supertonal	021202 High Amplitude Output	1.23 Hz, 50% Full Scale 10 V (1x), 5 V (4x)	All for gain 1 and gain 4 tests.
AC Signal Source	Quanterra Supertonal	021202 Low Amplitude Output	1.23 Hz, 50% Full Scale 0.625 V (16x), 0.15625 V (64x)	All for gain 16 and gain 64 tests.
Voltage Meter	Agilent 3458A	MY45048371	100 sps, 10 V full scale	All

The oscillator is configured to generate an AC signal with an amplitude of 50% of the digitizer input channel's full scale and a frequency equal to 1.23 Hz.

Amplitude levels were chosen to maximize the signal to noise ratio on the digitizer channel and the reference meter to better resolve harmonic peaks in the sinusoids PSD. An additional consideration is the Agilent 3458A has a variable peak amplitude and resolution level depending on whether the sinusoidal signal amplitude is within its 100 V, 10 V, 1 V, or 0.1 V ranges.

The test frequency of 1.23Hz was chosen as it is near the calibration frequency of 1 Hz and neither the fundamental frequency nor any of its nearby harmonics coincide with integer valued frequencies which are typically often corrupted with noise from electronics that refresh at a 1 Hz multiple.

Both the high and low outputs from the Quanterra Supertonal were used for the THD tests. When the Wranglers were operated at the x1 and x4 gain levels, the high output of the Supertonal was used. For the x16 and x64 gain tests, where the amplitude of the input signal needed to be smaller, the low output of the Supertonal was used.

The meter and the digitizer channels record the described AC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz, which is sufficiently above the frequency of the signal of interest to reduce the Agilent 3458A Meter's response roll-off at 1 Hz to less than 0.013 %.

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

A minimum of 30 minutes of data is recorded.

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

3.14.3 Analysis

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

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

The PSD is computed (Merchant, 2011) from the time series using a 2k-sample Kaiser-Bessel window. A Kaiser-Bessel window is used to minimize the width of the main lobe and the amplitude of side-lobes. The window length and data duration were chosen to provide sufficient frequency resolution around the primary harmonic.

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

Over frequencies (in Hertz):

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

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

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

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

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

3.14.4 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 1.23 Hz sinusoid that was used to measure harmonic distortion.

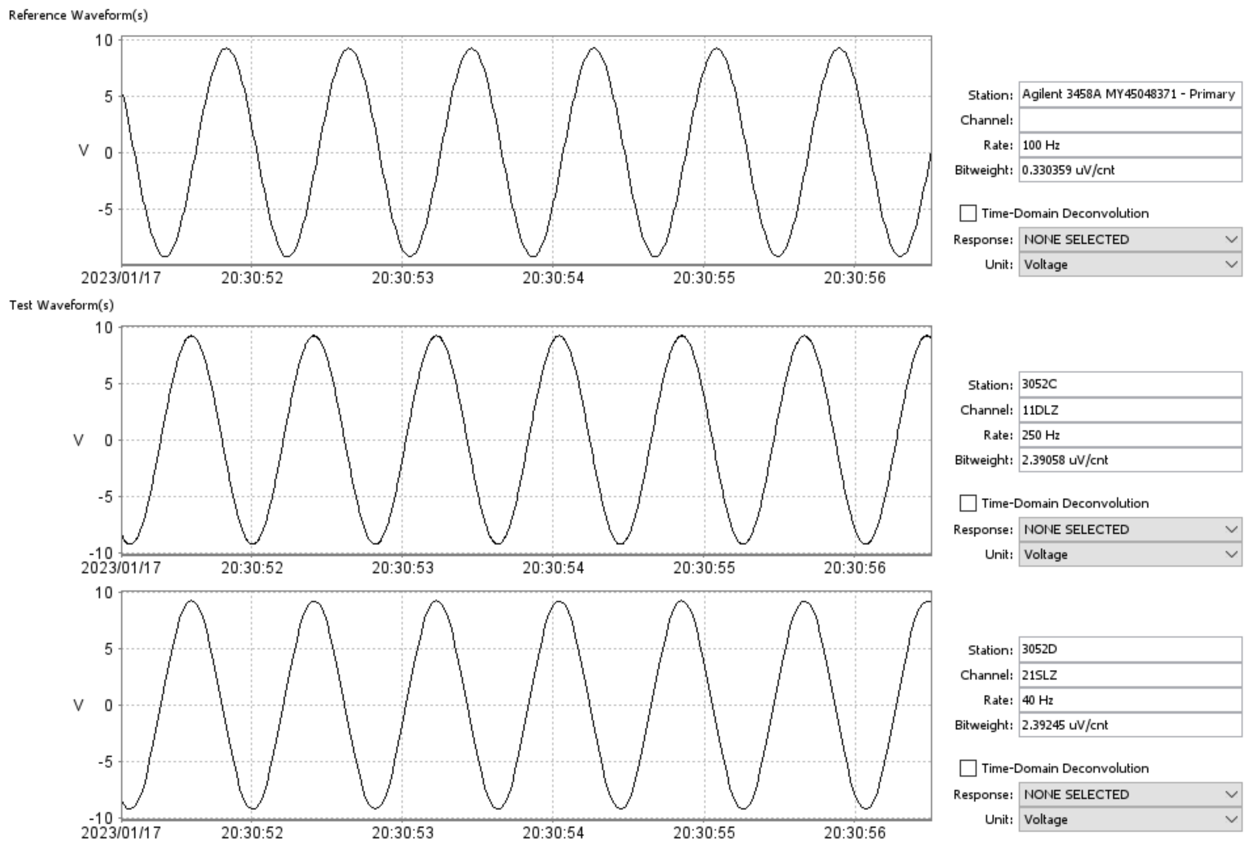

Figure 64 THD Waveform Time Series

The figures below show representative power spectra for the channels evaluated for multiple gain levels and sample rates. Alongside the plots of power spectra are the noise models representing the noise floor of the reference meter in the mode in which it was operated shown in green and the noise floor of the Quanterra Supertonal output that was used to generate the sinusoid shown in red.

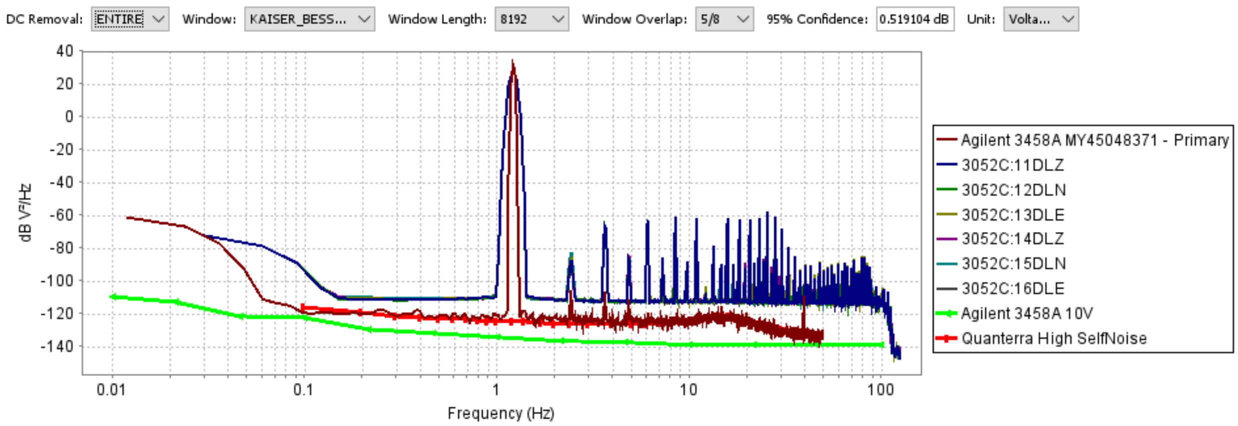

Figure 65 THD Power Spectra, Wrangler 3052C, 250 sps, gain 1x

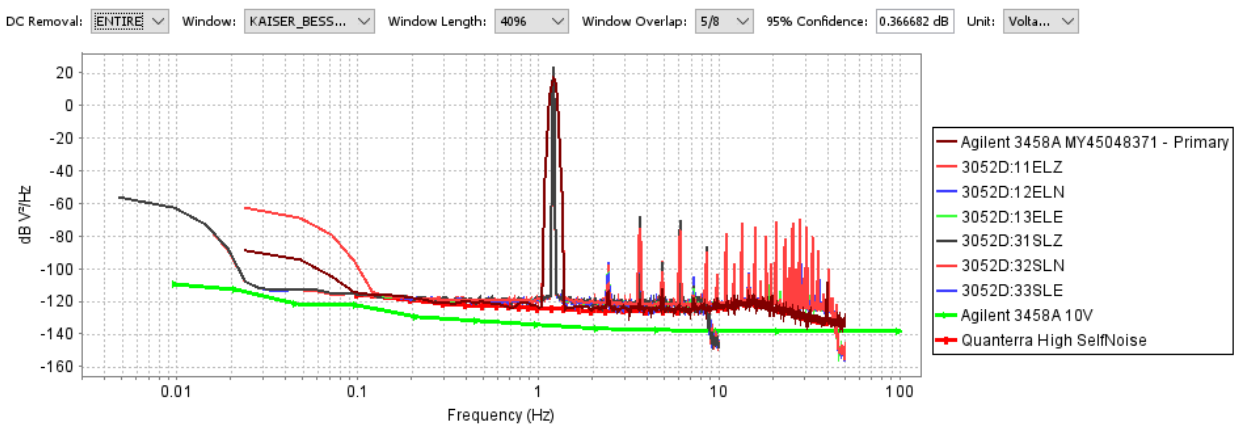

Figure 66 THD Power Spectra, Wrangler 3052D, 100 and 20 sps, gain 4x

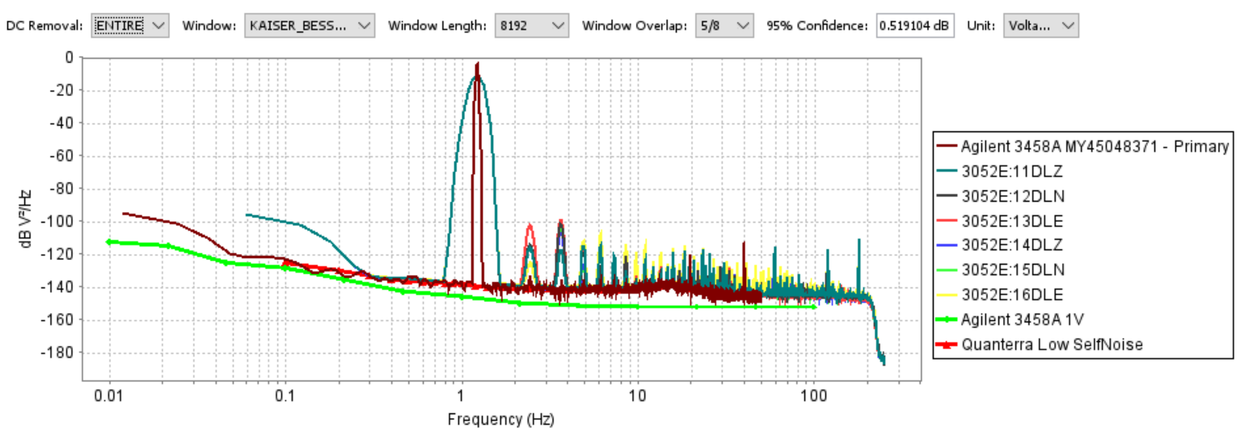

Figure 67 THD Power Spectra, Wrangler 3052E, 500 sps, gain 64x

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

Table 66 Total Harmonic Distortion: Wrangler 3052C, 250 sps

	Gain 1	Gain 4	Gain 16	Gain 64
Peak Amplitude	6.5470 V rms	1.7473 V rms	0.40919 V rms	0.10921 V rms
Reference Meter	-133.83 dB	-124.43 dB	-133.44 dB	-121.03 dB
Ch 1, 250 sps	-83.606 dB	-85.181 dB	-83.482 dB	-85.256 dB
Ch 2, 250 sps	-83.791 dB	-85.395 dB	-83.662 dB	-85.492 dB
Ch 3, 250 sps	-83.664 dB	-85.203 dB	-83.543 dB	-85.284 dB
Ch 4, 250 sps	-83.732 dB	-85.336 dB	-83.592 dB	-85.430 dB
Ch 5, 250 sps	-83.755 dB	-85.454 dB	-83.641 dB	-85.534 dB
Ch 6, 250 sps	-83.822 dB	-85.385 dB	-83.692 dB	-85.471 dB

Table 67 Total Harmonic Distortion: Wrangler 3052D, 20, 40, 100, 200 sps

	Gain 1	Gain 4	Gain 16	Gain 64
Peak Amplitude	6.5470 V rms	1.7473 V rms	0.40919 V rms	0.10921 V rms
Reference Meter	-133.83 dB	-124.43 dB	-133.44 dB	-121.03 dB
Ch 1, 100 sps	-83.702 dB	-85.252 dB	-83.577 dB	-85.339 dB
Ch 2, 100 sps	-83.886 dB	-85.439 dB	-83.778 dB	-85.522 dB
Ch 3, 100 sps	-83.757 dB	-85.369 dB	-83.623 dB	-85.446 dB
Ch 4, 100 sps	-83.780 dB	-85.406 dB	-83.643 dB	-85.493 dB
Ch 5, 100 sps	-83.882 dB	-85.467 dB	-83.733 dB	-85.573 dB
Ch 6, 100 sps	-83.792 dB	-85.357 dB	-83.662 dB	-85.459 dB
Ch 1, 40 sps	-83.701 dB	-85.244 dB	-83.576 dB	-85.332 dB
Ch 2, 40 sps	-83.885 dB	-85.430 dB	-83.777 dB	-85.515 dB
Ch 3, 40 sps	-83.756 dB	-85.360 dB	-83.622 dB	-85.438 dB
Ch 4, 40 sps	-83.781 dB	-85.397 dB	-83.643 dB	-85.484 dB
Ch 5, 40 sps	-83.881 dB	-85.458 dB	-83.733 dB	-85.566 dB
Ch 6, 40 sps	-83.790 dB	-85.348 dB	-83.661 dB	-85.453 dB
Ch 1, 20 sps	-87.012 dB	-89.319 dB	-86.671 dB	-89.742 dB
Ch 2, 20 sps	-87.210 dB	-89.485 dB	-86.868 dB	-89.910 dB
Ch 3, 20 sps	-87.070 dB	-89.520 dB	-86.729 dB	-89.936 dB
Ch 4, 20 sps	-87.111 dB	-89.608 dB	-86.738 dB	-90.059 dB
Ch 5, 20 sps	-87.218 dB	-89.581 dB	-86.799 dB	-90.122 dB
Ch 6, 20 sps	-87.084 dB	-89.465 dB	-86.681 dB	-89.991 dB
Ch 1, 200 sps	-83.698 dB	-85.245 dB	-83.572 dB	-85.328 dB
Ch 2, 200 sps	-83.882 dB	-85.431 dB	-83.773 dB	-85.510 dB
Ch 3, 200 sps	-83.753 dB	-85.361 dB	-83.618 dB	-85.433 dB
Ch 4, 200 sps	-83.777 dB	-85.398 dB	-83.639 dB	-85.480 dB
Ch 5, 200 sps	-83.879 dB	-85.457 dB	-83.729 dB	-85.560 dB
Ch 6, 200 sps	-83.788 dB	-85.349 dB	-83.657 dB	-85.447 dB

Table 68 Total Harmonic Distortion: Wrangler 3052E, 500 sps

	Gain 1	Gain 4	Gain 16	Gain 64
Peak Amplitude	6.5470 V rms	1.7473 V rms	0.40919 V rms	0.10921 V rms
Reference Meter	-133.83 dB	-124.43 dB	-133.44 dB	-121.03 dB
Ch 1, 500 sps	-98.569 dB	-98.292 dB	-98.578 dB	-98.034 dB
Ch 2, 500 sps	-90.748 dB	-90.040 dB	-90.623 dB	-89.936 dB
Ch 3, 500 sps	-86.964 dB	-86.183 dB	-86.902 dB	-86.104 dB
Ch 4, 500 sps	-94.253 dB	-94.801 dB	-94.208 dB	-94.704 dB
Ch 5, 500 sps	-92.172 dB	-92.125 dB	-92.091 dB	-92.045 dB
Ch 6, 500 sps	-87.848 dB	-88.867 dB	-87.927 dB	-89.048 dB

In all cases, the reference measurement of the signal generated by the low distortion oscillator exceeded the measurement made on the digitizer channel by a significant amount, indicating that the distortion observed is due to the digitizer.

The observed harmonic distortion differed between different dataloggers. 3052E, for instance, had consistently lower distortion than the other two Wranglers. It also had substantially more variability in distortion levels between channels. At a gain of 1, the lowest THD level was recorded by Channel 1 of 3052E and was equal to -98.57dB. The highest THD level at a gain of 1 was -83.61dB and was recorded by channel 1 of 3052C.

3052C and 3052D had similar distortion levels when operated at a gain of 1 and 16. When operated at a gain of 4 and 64, distortion levels improved by about 4dB. THD values for 3052E, on the other hand, did not change with gain level.

Note that there is generally less harmonic distortion on the lower sample rate channels simply due to their being fewer harmonic present in the narrower frequency passband.

3.15 Modified Noise Power Ratio

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

3.15.1 Measurand

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

3.15.2 Configuration

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

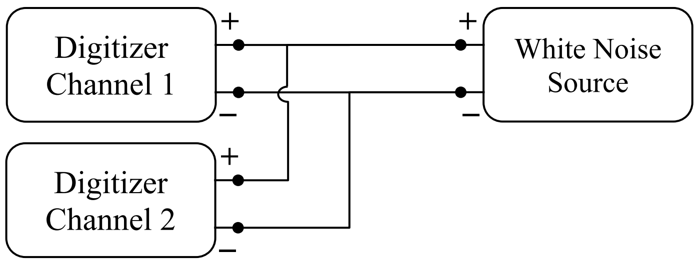

Figure 68 Modified Noise Power Ratio Configuration Diagram

Table 69 Modified Noise Power Ratio Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
White Noise Source	SRS DS360	123672	White Noise, variable amplitude, 100Hz bandwidth	All

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

3.15.3 Analysis

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

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

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

3.15.4 Result

A representative waveform time series plot is shown below for one of the Wrangler digitizers.

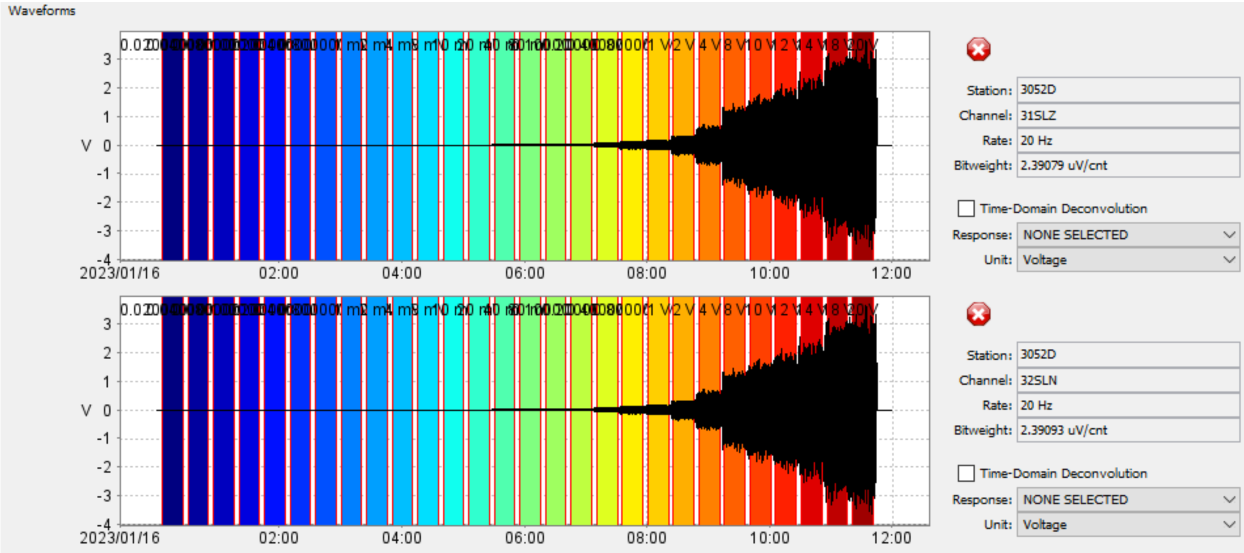

Figure 69 Modified Noise Power Ratio Time Series: Wrangler 3052D, 20sps, gain 1x

To ensure consistent results across the digitizer sample rates, a common frequency passband of 0.01 Hz to 10 Hz was used for all coherence analysis. Higher amplitude results are not shown as the white noise signal generator was producing signal power up to 100 Hz, which is outside of the frequency band limited by the Nyquist rate of some of the digitizer channels and may appear as premature saturation of the channel amplitude range.

The results for each digitizer are only shown for each sample rate it was operated at. Except for Wrangler 3052E, results are only shown between channels 1 and 2 on Port A as the results for the other channel combinations were consistent with one another. For 3052E, results are shown between channels 1 and 3 on port A. Channel 2 is significantly noisier than all other channels and, as a result, was not used in the MNPR analysis.

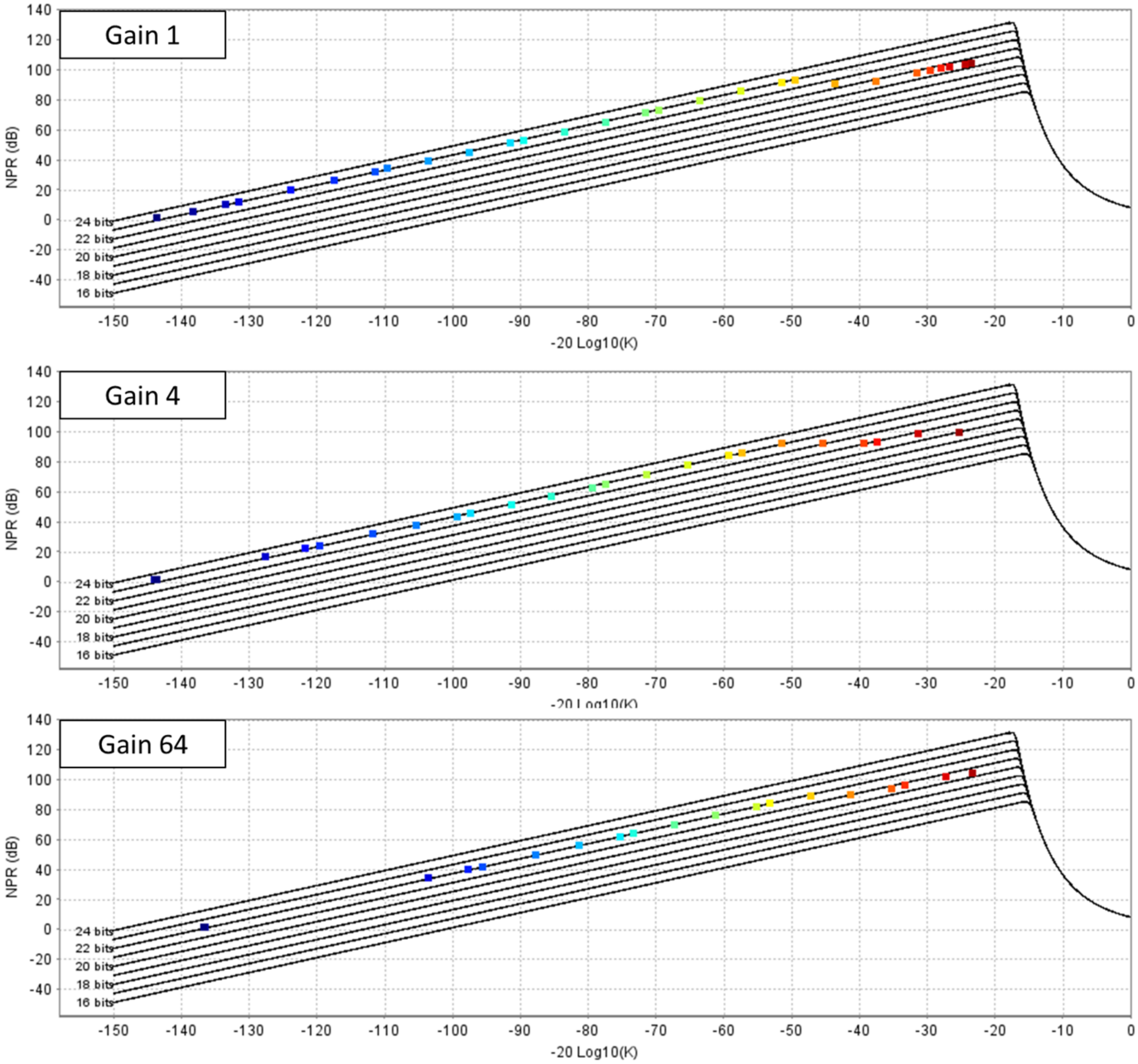

Figure 70 Modified Noise Power Ratio: Wrangler 3052D, 20 sps, gains 1, 4, 64

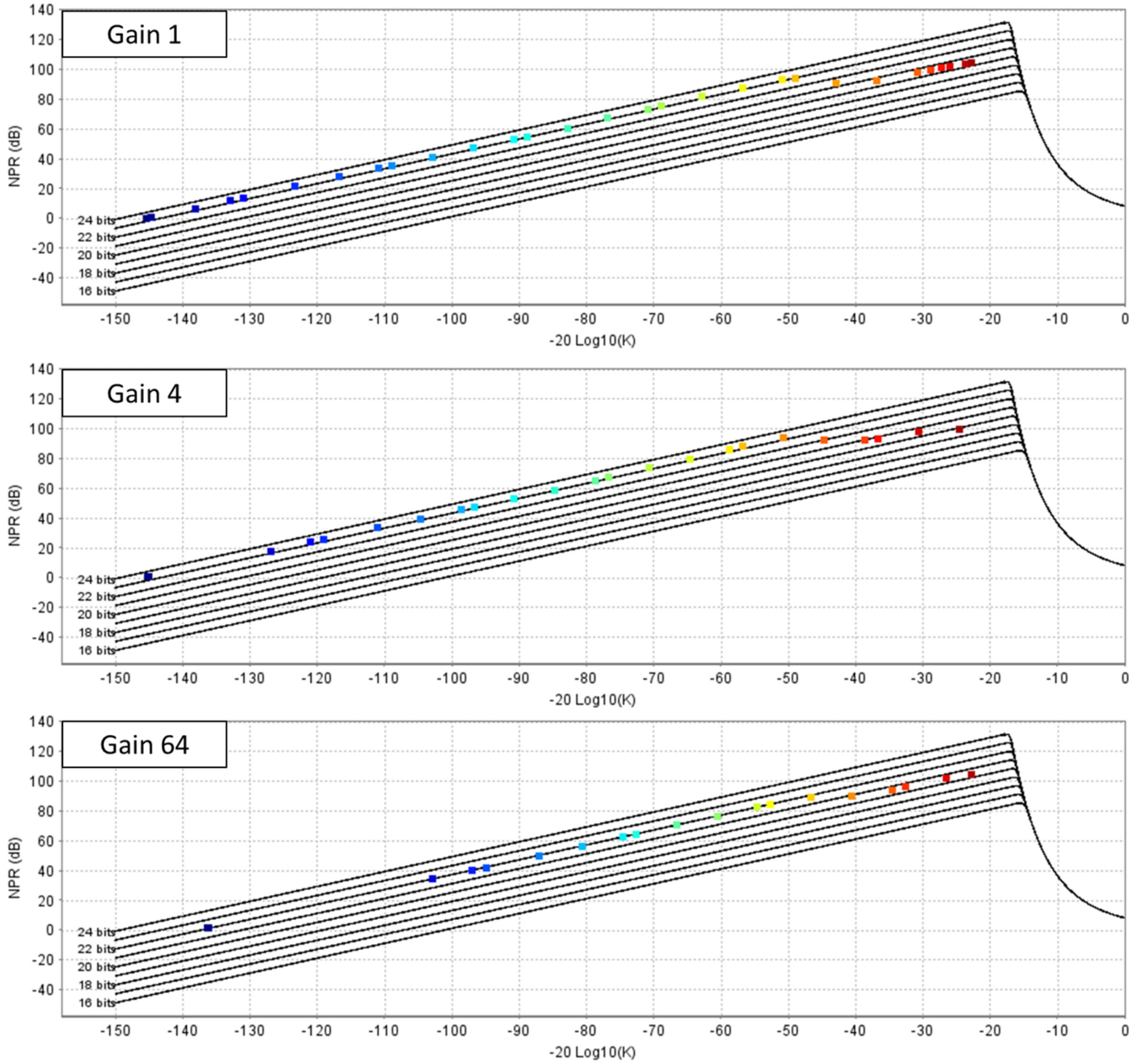

Figure 71 Modified Noise Power Ratio: Wrangler 3052D, 40 sps, gains 1, 4, 64

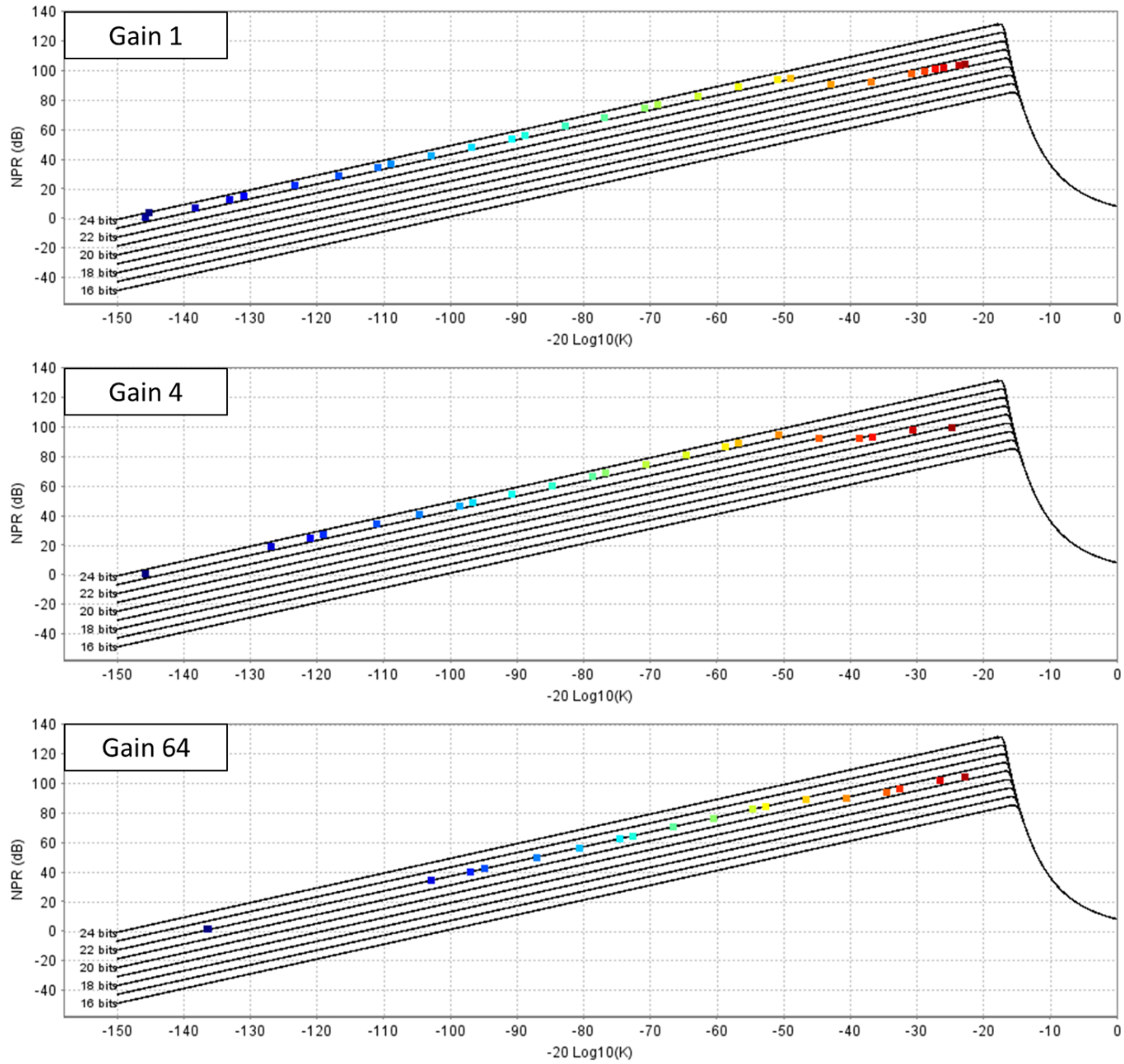

Figure 72 Modified Noise Power Ratio: Wrangler 3052D, 100 sps, gains 1, 4, 64

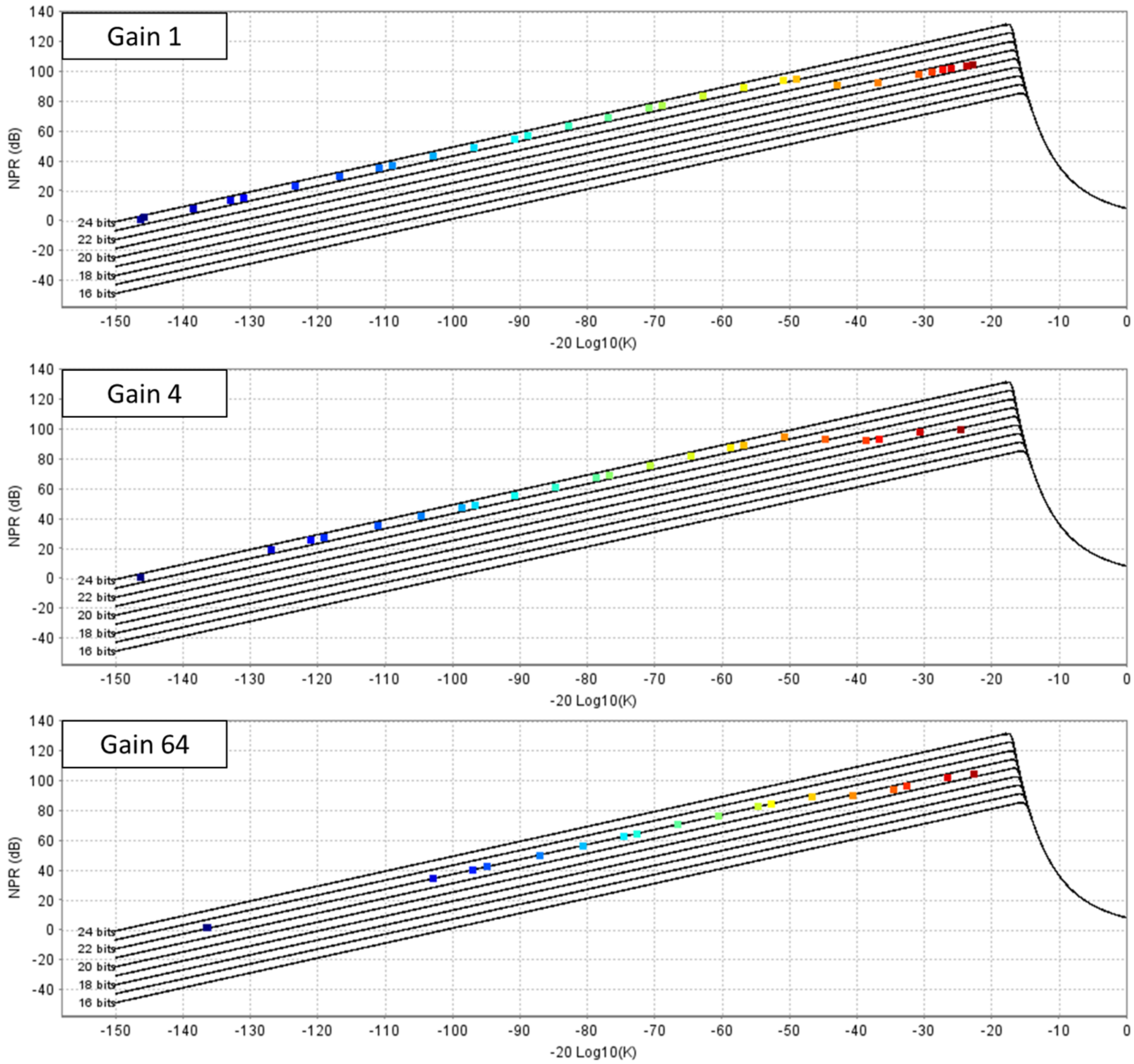

Figure 73 Modified Noise Power Ratio: Wrangler 3052D, 200 sps, gains 1, 4, 64

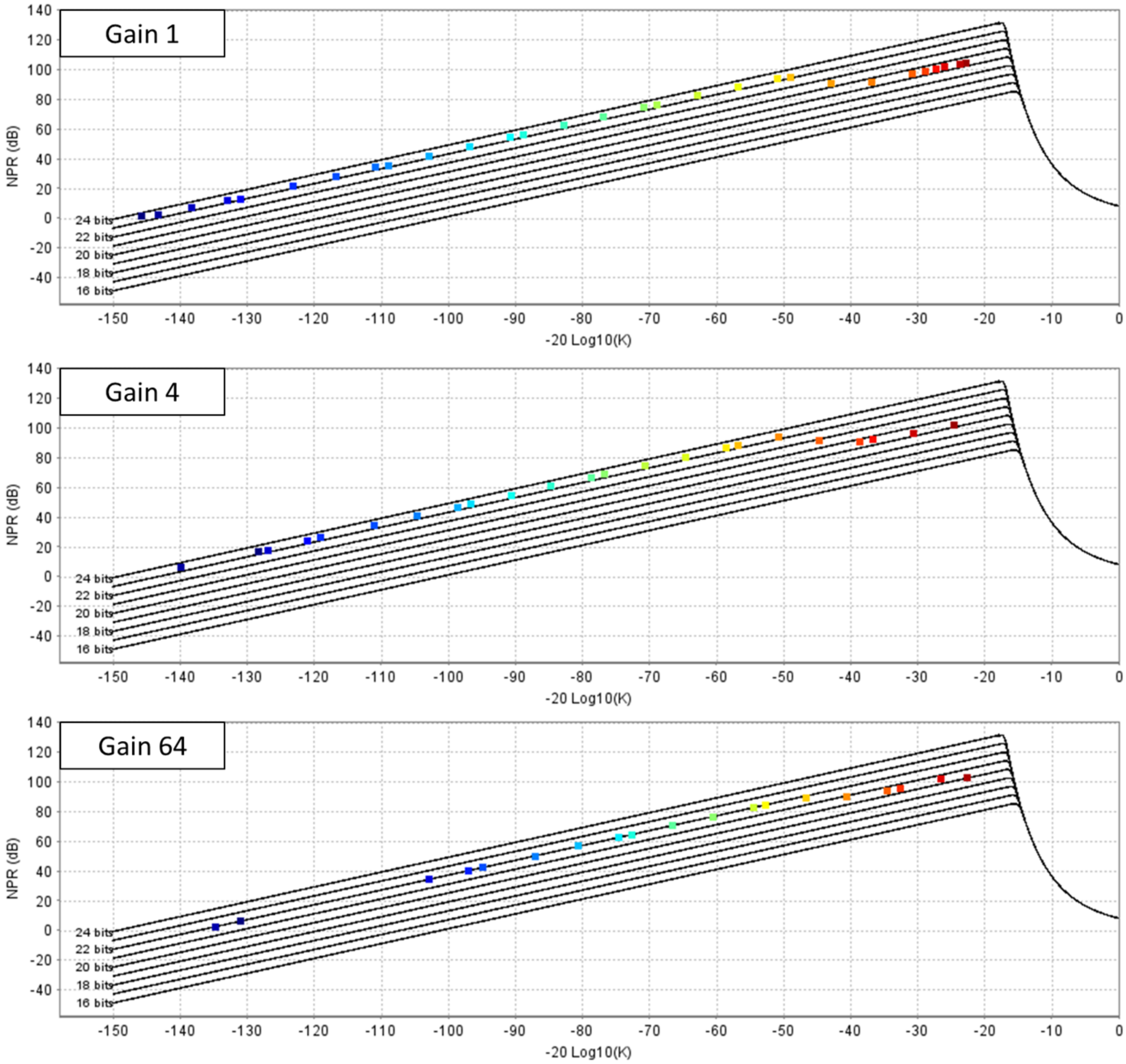

Figure 74 Modified Noise Power Ratio: Wrangler 3052D, 250 sps, gains 1, 4, 64

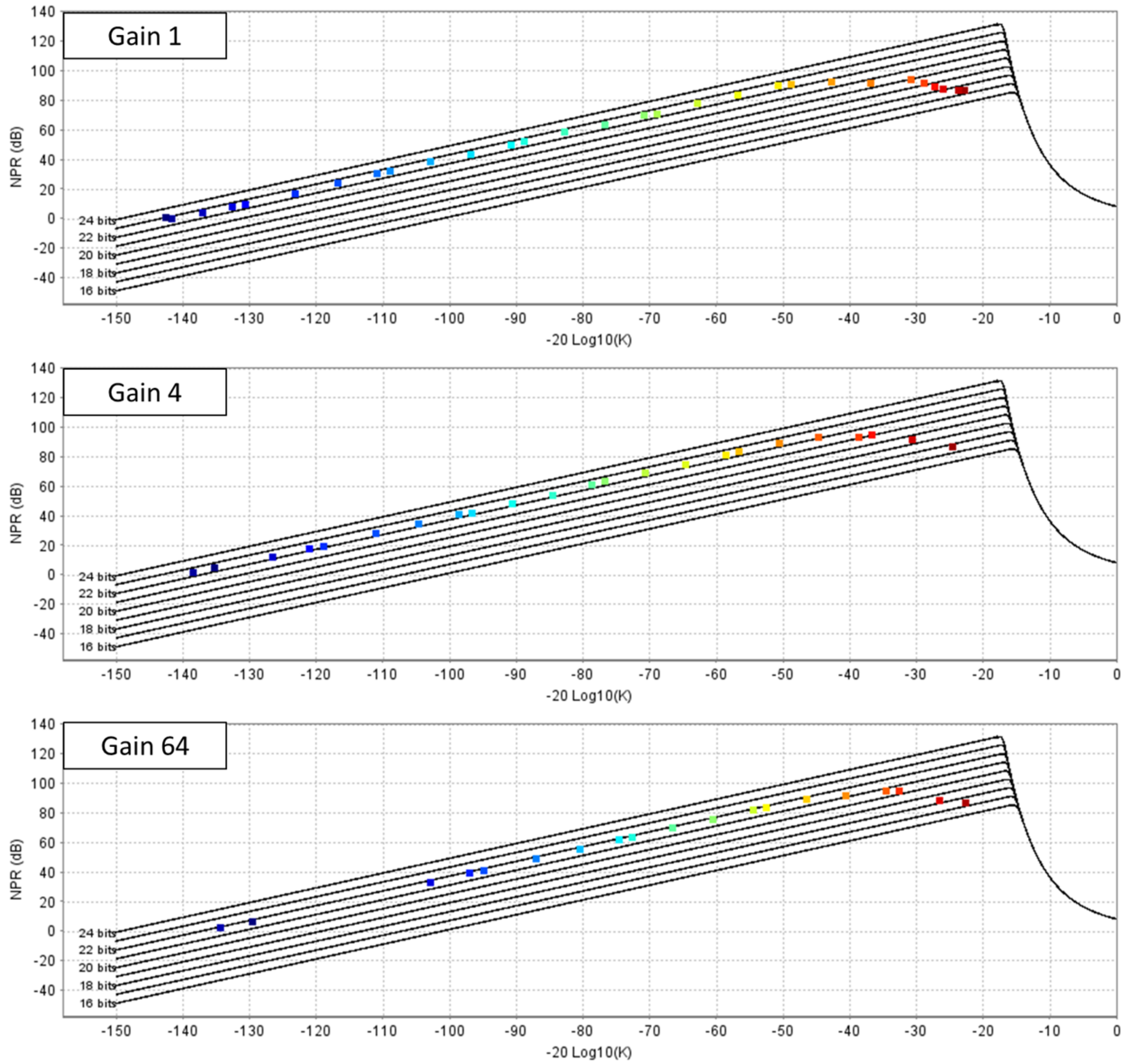

Figure 75 Modified Noise Power Ratio: Wrangler 3052E, 500 sps, gains 1, 4, 64

All three Wranglers displayed a similar pattern of performance. When signal amplitudes are low, performance is higher. This especially true for the x1 and x4 gain stages. Wranglers 3052C and 3052D, in the x1 gain test, had consistent 23-bit performance when the input signal amplitude is small. For larger input signals, however, performance drops off to about 20.5 bits. 3052E follows a similar pattern but with overall poorer performance, likely due to its higher sample rate. For the x4 gain test, 3052C and 3052D achieve approximately 23 bit performance when the input signal amplitude is low and approximately 21 bit performance for larger input signals. 3052E has a similar pattern but with a more substantial degradation in performance for larger input signals.

For the x64 gain test, performance is more consistent across the entire amplitude range. At lower amplitudes performance is about 22 bits and at higher amplitudes it is closer to 20.5 bits.

The following tables contain the MNPR values represented in the above figures.

Table 70 Modified Noise Power Ratio: Wrangler 3052D, 20 sps

Gain 1		Gain 4		Gain 64	
-20 log K	NPR	-20 log K	NPR	-20 log K	NPR
-143.63	1.12	-143.52	1.12	-136.70	1.70
-138.32	5.52	-143.95	1.53	-136.53	1.80
-133.47	10.41	-127.52	16.46	-103.53	34.13
-131.54	12.33	-121.72	22.22	-97.66	39.93
-123.90	20.07	-119.65	24.27	-95.55	41.86
-117.48	26.42	-111.76	32.03	-87.67	49.65
-111.47	32.36	-105.29	38.02	-81.24	55.89
-109.54	34.15	-99.30	43.57	-75.22	62.02
-103.50	39.53	-97.35	45.51	-73.27	64.00
-97.50	45.33	-91.35	51.44	-67.26	70.11
-91.50	51.23	-85.33	56.67	-61.22	76.25
-89.51	53.09	-79.31	62.74	-55.22	82.26
-83.49	58.34	-77.35	64.95	-53.28	84.21
-77.48	64.70	-71.31	71.53	-47.24	89.24
-71.49	71.30	-65.32	78.00	-41.23	89.96
-69.54	73.36	-59.32	84.17	-35.22	94.22
-63.54	79.86	-57.37	86.30	-33.24	96.26
-57.49	86.02	-51.36	92.11	-27.24	101.89
-51.50	91.74	-45.33	92.46	-23.37	104.28
-49.55	92.85	-39.29	92.13		
-43.51	90.99	-37.32	93.27		
-37.49	92.27	-31.28	98.53		
-31.48	97.98	-25.31	99.40		
-29.54	99.88				
-27.95	101.30				
-26.60	102.31				
-24.39	103.85				
-23.50	104.33				

Table 71 Modified Noise Power Ratio: Wrangler 3052D, 40 sps

Gain 1		Gain 4		Gain 64	
-20 log K	NPR	-20 log K	NPR	-20 log K	NPR
-145.34	0.00	-144.96	0.63	-136.30	1.48
-144.67	0.73	-145.22	0.76	-136.09	1.62
-138.08	6.70	-126.91	17.92	-102.88	34.21
-132.93	11.89	-121.07	23.89	-97.00	40.01
-130.99	13.85	-118.99	25.90	-94.90	42.07
-123.25	21.62	-111.09	33.58	-87.02	49.86
-116.82	28.00	-104.62	39.61	-80.57	56.26
-110.81	33.80	-98.64	45.47	-74.57	62.40
-108.88	35.58	-96.68	47.40	-72.62	64.37
-102.85	41.29	-90.69	53.23	-66.61	70.37
-96.83	47.23	-84.67	58.84	-60.57	76.44
-90.83	52.94	-78.64	65.13	-54.56	82.40
-88.86	54.83	-76.69	67.20	-52.62	84.31
-82.83	60.63	-70.64	73.67	-46.58	89.27
-76.82	67.09	-64.65	79.90	-40.56	89.93
-70.82	73.48	-58.66	85.90	-34.54	94.15
-68.89	75.49	-56.71	88.01	-32.59	96.16
-62.86	81.70	-50.69	93.64	-26.58	101.77
-56.84	87.74	-44.66	92.68	-22.70	104.23
-50.84	93.21	-38.63	92.06		
-48.89	94.07	-36.67	93.22		
-42.84	91.02	-30.62	98.42		
-36.84	92.20	-24.64	99.66		
-30.83	97.91				
-28.89	99.78				
-27.29	101.20				
-25.93	102.27				
-23.74	103.80				
-22.85	104.28				

Table 72 Modified Noise Power Ratio: Wrangler 3052D, 100 sps

Gain 1		Gain 4		Gain 64	
-20 log K	NPR	-20 log K	NPR	-20 log K	NPR
-145.16	4.02	-144.96	0.63	-136.43	1.21
-145.78	0.47	-145.22	0.76	-136.27	1.32
-138.30	7.41	-126.91	17.92	-102.87	34.30
-133.02	12.75	-121.07	23.89	-97.00	40.13
-131.02	14.80	-118.99	25.90	-94.90	42.23
-123.25	22.57	-111.09	33.58	-87.02	50.03
-116.82	28.99	-104.62	39.61	-80.57	56.50
-110.81	34.62	-98.64	45.47	-74.57	62.55
-108.89	36.53	-96.68	47.40	-72.62	64.57
-102.85	42.51	-90.69	53.23	-66.60	70.52
-96.83	48.44	-84.67	58.84	-60.57	76.52
-90.83	54.16	-78.64	65.13	-54.56	82.50
-88.87	56.18	-76.69	67.20	-52.63	84.41
-82.83	62.31	-70.64	73.67	-46.59	89.31
-76.83	68.65	-64.65	79.90	-40.57	89.89
-70.82	74.76	-58.66	85.90	-34.53	94.11
-68.88	76.77	-56.71	88.01	-32.59	96.12
-62.86	82.85	-50.69	93.64	-26.58	101.73
-56.84	88.82	-44.66	92.68	-22.70	104.19
-50.85	94.07	-38.63	92.06		
-48.89	94.72	-36.67	93.22		
-42.84	91.04	-30.62	98.42		
-36.83	92.18	-24.64	99.66		
-30.83	97.88				
-28.88	99.76				
-27.29	101.16				
-25.93	102.23				
-23.75	103.76				
-22.84	104.24				

Table 73 Modified Noise Power Ratio: Wrangler 3052D, 200 sps

Gain 1		Gain 4		Gain 64	
-20 log K	NPR	-20 log K	NPR	-20 log K	NPR
-145.83	1.88	-146.22	0.36	-136.46	1.10
-146.18	0.31	-146.29	0.30	-136.31	1.20
-138.35	7.77	-126.91	19.37	-102.86	34.32
-133.01	13.17	-121.07	25.27	-96.98	40.18
-131.01	15.19	-118.99	27.28	-94.88	42.27
-123.24	22.95	-111.07	34.96	-87.00	50.10
-116.80	29.38	-104.61	41.47	-80.54	56.57
-110.79	35.16	-98.61	47.44	-74.56	62.61
-108.87	37.03	-96.68	49.32	-72.61	64.62
-102.83	43.14	-90.68	55.15	-66.58	70.56
-96.81	48.98	-84.65	61.29	-60.55	76.57
-90.81	54.87	-78.62	67.48	-54.55	82.50
-88.85	57.03	-76.68	69.40	-52.61	84.41
-82.82	63.06	-70.62	75.61	-46.57	89.32
-76.81	69.23	-64.63	81.62	-40.55	89.88
-70.80	75.30	-58.65	87.45	-34.52	94.10
-68.86	77.26	-56.71	89.46	-32.57	96.11
-62.85	83.29	-50.66	94.96	-26.56	101.71
-56.82	89.27	-44.65	92.83	-22.68	104.17
-50.83	94.40	-38.62	92.04		
-48.88	94.94	-36.66	93.15		
-42.83	91.04	-30.61	98.37		
-36.81	92.16	-24.63	99.72		
-30.81	97.87				
-28.87	99.75				
-27.27	101.14				
-25.92	102.21				
-23.73	103.76				
-22.82	104.23				

Table 74 Modified Noise Power Ratio: Wrangler 3052C, 250 sps

Gain 1		Gain 4		Gain 64	
-20 log K	NPR	-20 log K	NPR	-20 log K	NPR
-145.65	1.28	-128.22	16.69	-131.04	6.06
-143.30	2.50	-139.82	5.95	-134.77	2.56
-138.26	7.25	-126.85	17.44	-102.84	34.25
-132.88	11.62	-121.04	24.00	-96.97	40.06
-130.91	13.02	-118.96	26.62	-94.87	42.14
-123.21	21.55	-111.06	34.24	-86.98	50.08
-116.77	27.73	-104.61	41.01	-80.52	56.67
-110.78	34.09	-98.60	46.76	-74.54	62.66
-108.87	35.56	-96.66	48.82	-72.58	64.54
-102.83	41.95	-90.66	54.83	-66.56	70.62
-96.80	48.29	-84.63	60.65	-60.53	76.58
-90.79	54.43	-78.60	66.71	-54.52	82.66
-88.83	56.35	-76.66	68.81	-52.59	84.53
-82.79	62.34	-70.60	74.76	-46.55	89.47
-76.79	68.51	-64.61	80.38	-40.53	90.04
-70.78	74.52	-58.63	86.60	-34.49	94.05
-68.84	76.42	-56.68	88.53	-32.55	96.00
-62.82	82.46	-50.64	94.00	-26.54	101.70
-56.80	88.15	-44.63	91.89	-22.66	103.13
-50.81	93.83	-38.59	90.71		
-48.85	94.99	-36.64	92.08		
-42.80	90.97	-30.59	96.74		
-36.79	91.36	-24.61	102.01		
-30.78	97.55				
-28.84	98.93				
-27.25	100.88				
-25.89	102.28				
-23.71	104.03				
-22.80	104.73				

Table 75 Modified Noise Power Ratio: Wrangler 3052E, 500 sps

Gain 1		Gain 4		Gain 64	
-20 log K	NPR	-20 log K	NPR	-20 log K	NPR
-142.55	0.71	-135.16	4.74	-129.63	6.46
-141.57	0.18	-138.39	1.10	-134.29	1.99
-136.94	4.11	-126.51	12.09	-102.82	33.14
-132.55	7.99	-120.94	17.22	-96.94	39.08
-130.68	9.47	-118.89	19.48	-94.84	40.57
-123.15	17.04	-111.05	27.99	-86.96	49.03
-116.77	24.06	-104.58	34.09	-80.50	55.45
-110.77	30.68	-98.58	40.62	-74.51	61.49
-108.85	31.98	-96.63	42.07	-72.56	63.33
-102.80	38.32	-90.63	48.27	-66.53	69.54
-96.77	43.54	-84.61	54.14	-60.51	75.63
-90.77	49.44	-78.57	60.82	-54.50	81.65
-88.81	52.19	-76.64	63.40	-52.56	83.63
-82.77	58.25	-70.57	68.99	-46.52	89.04
-76.77	63.42	-64.59	74.69	-40.52	91.38
-70.75	69.88	-58.61	81.42	-34.49	94.98
-68.81	71.10	-56.66	83.38	-32.54	95.24
-62.80	78.12	-50.62	88.99	-26.54	88.48
-56.77	83.96	-44.61	93.28	-22.65	86.44
-50.79	89.97	-38.59	93.47		
-48.83	91.07	-36.64	94.46		
-42.79	92.62	-30.59	91.79		
-36.78	91.40	-24.60	87.13		
-30.78	94.26				
-28.85	91.56				
-27.25	89.50				
-25.89	87.94				
-23.70	86.62				
-22.80	86.42				

3.16 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.

3.16.1 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.

3.16.2 Configuration

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

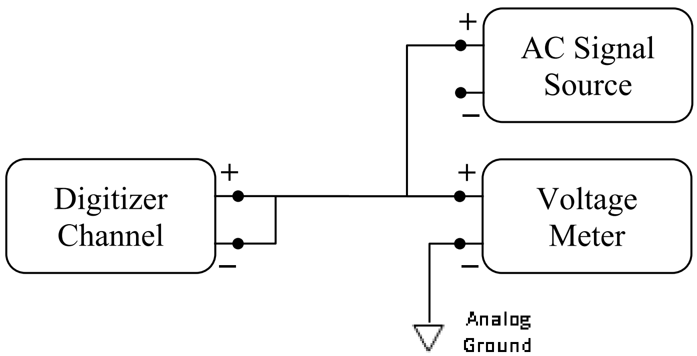

Figure 76 Common Mode Rejection Configuration Diagram

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

Table 76 Common Mode Rejection Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
AC Signal Source	SRS DS360	123672	1 Hz AC, 1% Full Scale	All
Voltage Meter	Agilent 3458A	MY45048371	200 sps, 1 V full scale	All

The AC Signal Source is configured to generate an AC voltage with an amplitude of 1% 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 used to measure the voltage time series has an active calibration from the Primary Standard Laboratory at Sandia.

3.16.3 Analysis

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

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

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

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

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

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

3.16.4 Result

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

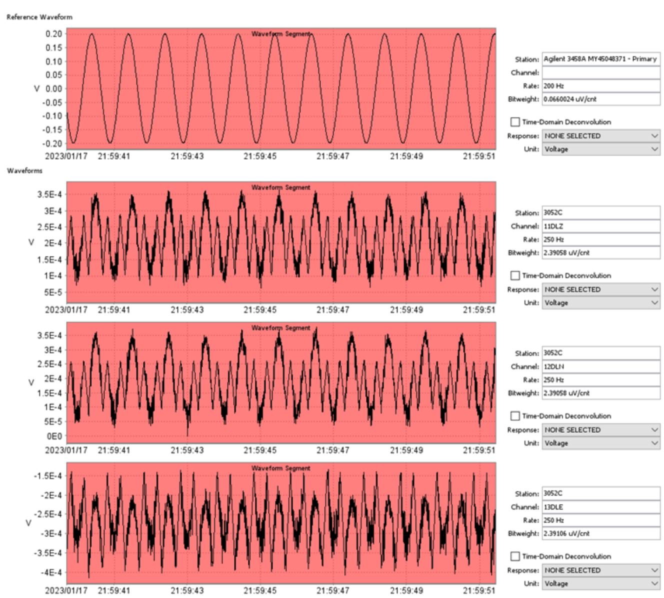

Figure 77 Common Mode Rejection Time Series, Wrangler 3052C 250sps, gain 1

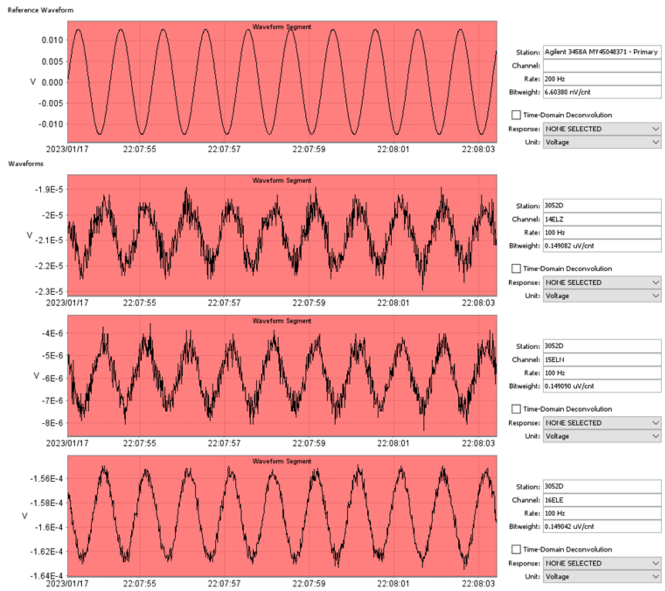

Figure 78 Common Mode Rejection Time Series, Wrangler 3052D 100sps, gain 16

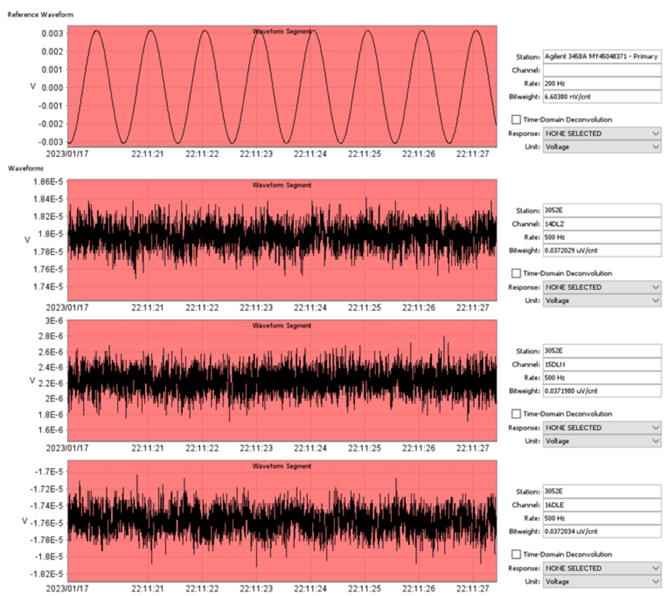

Figure 79 Common Mode Rejection Time Series, Wrangler 3052E 500sps, gain 64

The observed common mode rejection ranged between 50 dB and 114 dB, as compared to the Wrangler datasheet specification of > 90 dB. In cases where the common mode rejection exceeded 90, the observed common mode noise amplitude was very low, on the order of the channel self-noise, making an estimate of amplitude problematic. This may be seen in Figure 78. The common mode rejection ratio generally increased as gain increased (and input signal amplitude decreased), although this relationship did not hold true for all channels. The following tables contain the measured common mode noise rejection ratio values.

Table 77 Common Mode Rejection: Wrangler 3052C, 250 sps

Channel	Gain 1	Gain 4	Gain 16	Gain 64
Reference	0.199791 V	49.8910 mV	12.4820 mV	3.11637 mV
1, 250 sps	70.699 dB	70.813 dB	82.420 dB	103.44 dB
2, 250 sps	68.149 dB	70.937 dB	83.939 dB	99.476 dB
3, 250 sps	90.689 dB	68.215 dB	79.499 dB	95.087 dB
4, 250 sps	53.284 dB	73.850 dB	84.981 dB	96.329 dB
5, 250 sps	55.361 dB	62.103 dB	73.196 dB	86.709 dB
6, 250 sps	94.147 dB	69.238 dB	80.546 dB	95.347 dB

Table 78 Common Mode Rejection: Wrangler 3052D, 20, 40, 100 and 200 sps

Channel	Gain 1	Gain 4	Gain 16	Gain 64
Reference	0.199791 V	49.8910 mV	12.4820 mV	3.11637 mV
1, 100 sps	58.225 dB	83.846 dB	94.723 dB	108.77 dB
2, 100 sps	71.961 dB	69.909 dB	82.567 dB	96.278 dB
3, 100 sps	55.567 dB	62.209 dB	74.290 dB	86.516 dB
4, 100 sps	74.515 dB	68.667 dB	81.227 dB	93.120 dB
5, 100 sps	74.685 dB	68.945 dB	79.439 dB	92.956 dB
6, 100 sps	49.999 dB	58.964 dB	70.985 dB	83.047 dB
1, 40 sps	58.225 dB	83.861 dB	94.692 dB	108.77 dB
2, 40 sps	71.956 dB	69.907 dB	82.528 dB	96.271 dB
3, 40 sps	55.568 dB	62.209 dB	74.292 dB	86.494 dB
4, 40 sps	74.520 dB	68.666 dB	81.230 dB	93.243 dB
5, 40 sps	74.687 dB	68.950 dB	79.426 dB	92.992 dB
6, 40 sps	49.999 dB	58.963 dB	70.983 dB	83.029 dB
1, 20 sps	58.226 dB	83.857 dB	94.776 dB	108.79 dB
2, 20 sps	71.961 dB	69.906 dB	82.507 dB	96.108 dB
3, 20 sps	55.567 dB	62.209 dB	74.292 dB	86.560 dB
4, 20 sps	74.515 dB	68.668 dB	81.211 dB	93.169 dB
5, 20 sps	74.676 dB	68.950 dB	79.443 dB	92.923 dB
6, 20 sps	49.999 dB	58.964 dB	70.981 dB	83.074 dB
1, 200 sps	58.224 dB	83.835 dB	94.713 dB	108.42 dB
2, 200 sps	71.955 dB	69.908 dB	82.600 dB	96.213 dB
3, 200 sps	55.567 dB	62.210 dB	74.287 dB	86.518 dB
4, 200 sps	74.516 dB	68.664 dB	81.220 dB	93.119 dB
5, 200 sps	74.689 dB	68.948 dB	79.441 dB	92.937 dB
6, 200 sps	49.999 dB	58.963 dB	70.984 dB	83.059 dB

Table 79 Common Mode Rejection: Wrangler 3052E, 500 sps

Channel	Gain 1	Gain 4	Gain 16	Gain 64
Reference	0.199791 V	49.8910 mV	12.4820 mV	3.11637 mV
1, 500 sps	85.297 dB	80.225 dB	96.438 dB	103.48 dB
2, 500 sps	83.224 dB	69.791 dB	81.483 dB	93.800 dB
3, 500 sps	55.646 dB	69.511 dB	81.840 dB	92.466 dB
4, 500 sps	62.171 dB	76.482 dB	87.879 dB	100.75 dB
5, 500 sps	68.009 dB	91.129 dB	114.20 dB	111.96 dB
6, 500 sps	57.687 dB	72.724 dB	85.671 dB	96.936 dB

3.17 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.

3.17.1 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.

3.17.2 Configuration

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

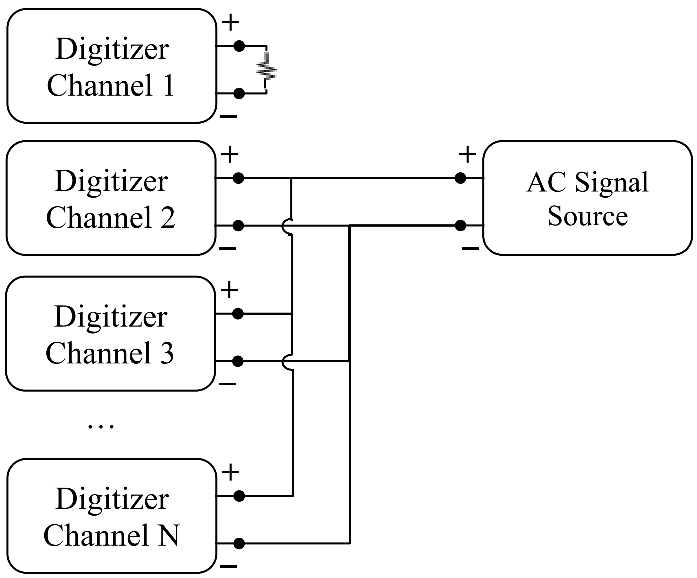

Figure 80 Crosstalk Configuration Diagram

Table 80 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizers
AC Signal Source	SRS DS360	123672	1.23 Hz AC, 50% Full Scale	All

The AC Signal Source is configured to generate an AC voltage with an amplitude of 50% of the digitizer input channel's full scale and a frequency equal to the 1.23 Hz. Approximately 10 minutes of data is recorded.

3.17.3 Analysis

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

$$x[n]$$

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

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

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

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

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

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

3.17.4 Result

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

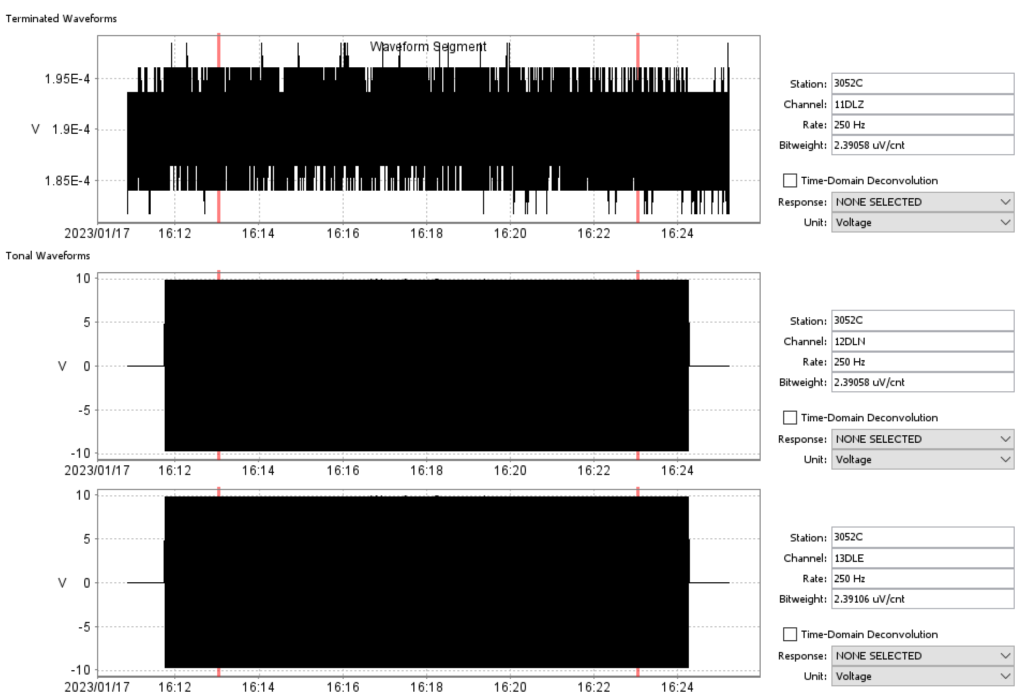

Figure 81 Crosstalk Representative Waveform Time Series

The figures below show representative power spectra of the terminated and tonal channels.

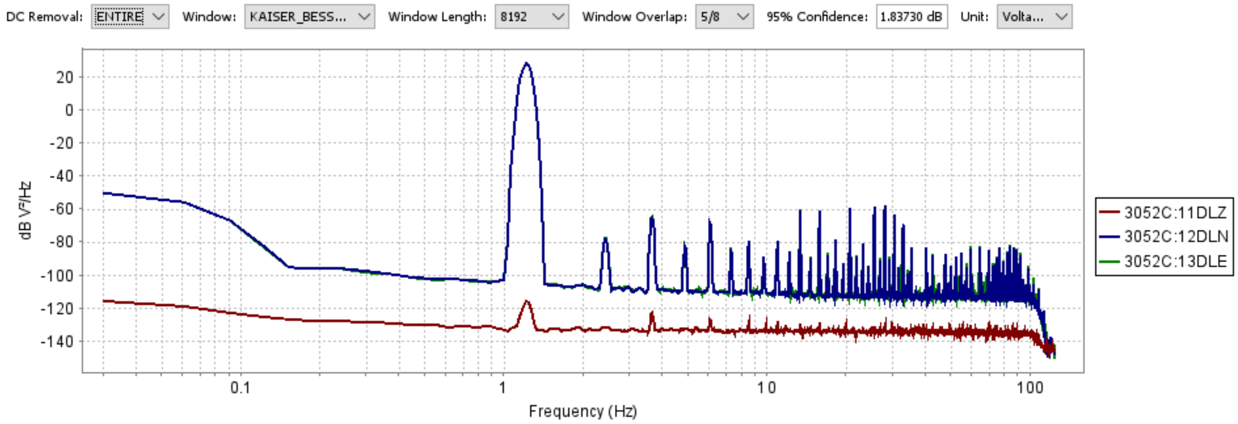

Figure 82 Crosstalk Power Spectra, Wrangler 3052, gain 1, 250 sps

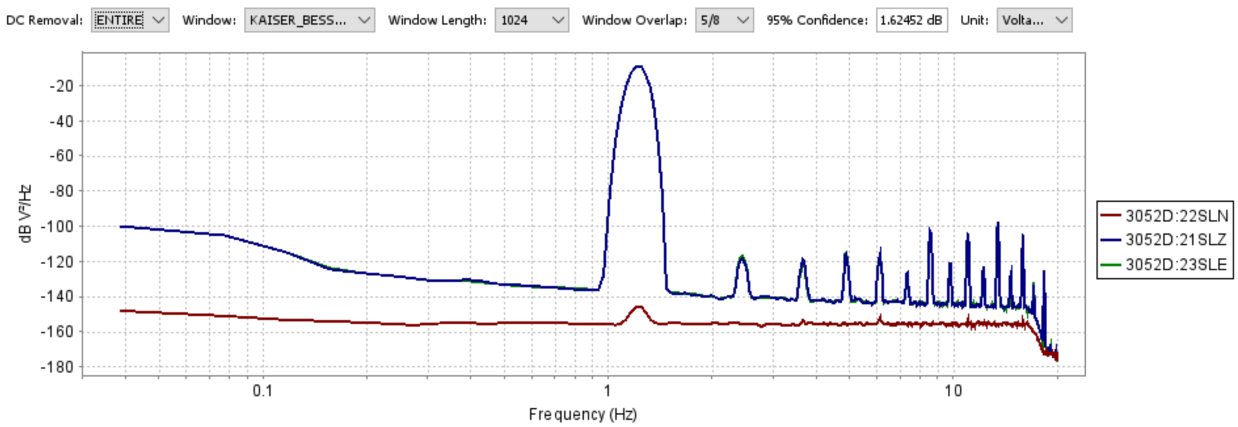

Figure 83 Crosstalk Power Spectra, Wrangler 3052D, gain 64, 40 sps

The tables below contain the computed levels of crosstalk. Crosstalk values were all between -131.14 dB and -154.27 dB. Crosstalk levels were consistent between the sample rates, which is to be expected as crosstalk is primarily affected by the physical circuitry layout. The slight difference between the sample rates is due to the difference in frequency resolution in the estimates of power spectra.

Table 81 Crosstalk for Wrangler 3052C, 250 sps

Terminated Channel	Gain 1	Gain 4	Gain 16	Gain 64
Ch 1, 250 sps	-143.49 dB	-144.17 dB	-138.01 dB	-138.72 dB
Ch 2, 250 sps	-138.69 dB	-139.47 dB	-137.32 dB	-135.51 dB
Ch 3, 250 sps	-144.06 dB	-144.20 dB	-139.96 dB	-137.12 dB
Ch 4, 250 sps	-143.08 dB	-143.89 dB	-140.05 dB	-138.00 dB
Ch 5, 250 sps	-137.53 dB	-138.52 dB	-136.09 dB	-136.62 dB
Ch 6, 250 sps	-142.68 dB	-143.64 dB	-137.78 dB	-138.21 dB

Table 82 Crosstalk for Wrangler 3052D, 20, 40, 100, 200 sps

Terminated Channel	Gain 1	Gain 4	Gain 16	Gain 64
1, 100 sps	-143.58 dB	-144.81 dB	-140.94 dB	-139.19 dB
2, 100 sps	-138.04 dB	-139.15 dB	-137.48 dB	-135.32 dB
3, 100 sps	-144.22 dB	-144.84 dB	-138.72 dB	-139.78 dB
4, 100 sps	-144.10 dB	-144.27 dB	-140.29 dB	-137.04 dB
5, 100 sps	-138.11 dB	-139.06 dB	-135.93 dB	-134.98 dB
6, 100 sps	-142.74 dB	-143.98 dB	-139.88 dB	-139.39 dB
1, 40 sps	-143.66 dB	-144.94 dB	-140.29 dB	-139.22 dB
2, 40 sps	-137.98 dB	-139.02 dB	-137.48 dB	-135.43 dB
3, 40 sps	-144.48 dB	-145.09 dB	-140.42 dB	-139.71 dB
4, 40 sps	-143.36 dB	-144.64 dB	-140.40 dB	-138.71 dB
5, 40 sps	-137.95 dB	-138.80 dB	-136.48 dB	-136.08 dB
6, 40 sps	-143.45 dB	-144.47 dB	-140.93 dB	-139.41 dB
1, 20 sps	-143.06 dB	-143.47 dB	-141.44 dB	-139.78 dB
2, 20 sps	-137.96 dB	-139.04 dB	-137.00 dB	-135.39 dB
3, 20 sps	-143.09 dB	-143.66 dB	-139.98 dB	-139.72 dB
4, 20 sps	-143.04 dB	-143.11 dB	-140.49 dB	-138.64 dB
5, 20 sps	-137.87 dB	-138.94 dB	-136.34 dB	-136.11 dB
6, 20 sps	-143.04 dB	-145.24 dB	-140.46 dB	-139.86 dB
1, 200 sps	-143.69 dB	-145.01 dB	-140.16 dB	-139.14 dB
2, 200 sps	-138.03 dB	-139.18 dB	-137.58 dB	-135.30 dB
3, 200 sps	-144.36 dB	-144.71 dB	-138.78 dB	-139.81 dB
4, 200 sps	-144.16 dB	-144.28 dB	-140.70 dB	-137.11 dB
5, 200 sps	-138.12 dB	-138.93 dB	-136.07 dB	-134.96 dB
6, 200 sps	-142.92 dB	-143.70 dB	-139.95 dB	-139.28 dB

Table 83 Crosstalk for Wrangler 3052E, 250 sps

Terminated Channel	Gain 1	Gain 4	Gain 16	Gain 64
1, 500 sps	-151.16 dB	-150.76 dB	-144.08 dB	-141.80 dB
2, 500 sps	-134.22 dB	-136.06 dB	-131.55 dB	-131.14 dB
3, 500 sps	-148.30 dB	-149.68 dB	-143.12 dB	-140.68 dB
4, 500 sps	-152.59 dB	-152.37 dB	-143.75 dB	-140.93 dB
5, 500 sps	-145.84 dB	-150.97 dB	-143.38 dB	-139.83 dB
6, 500 sps	-154.05 dB	-154.27 dB	-143.73 dB	-141.64 dB

3.18 Time Tag Accuracy

The Time Tag Accuracy test measures the digitizer's timing accuracy under stable conditions in which the digitizer is clock is locked and stable with a timing source, either GNSS or PTP.

3.18.1 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 timestamp minus the expected timestamp.

3.18.2 Configuration

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

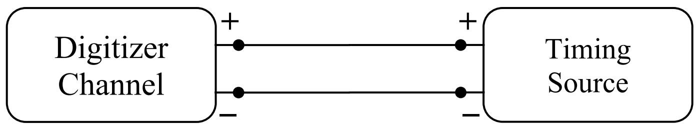

Figure 84 Time Tag Accuracy Configuration Diagram

Figure 85 Time Tag Accuracy PPM Source

Table 84 Time Tag Accuracy Testbed Equipment

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

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

In this test, all Wrangler digitizers were configured to receive their continuous timing signal from the GNSS satellite network.

3.18.3 Analysis

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

3.18.4 Result

The figures below show a representative waveform time series of a Pulse-Per-Minute (PPM) for the recording made on a digitizer channel under test.

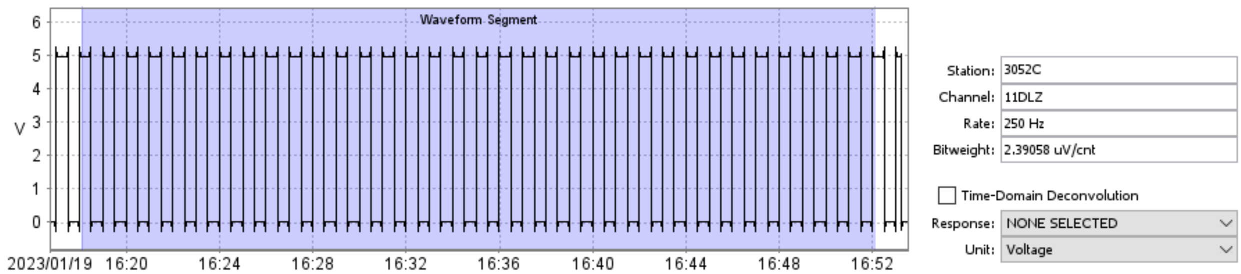

Figure 86 Time Tag Accuracy PPM Time Series

The following table contains the computed timing accuracy results for the test. As may be seen, the three Wranglers have very accurate time stamping of the recorded data. All units were within 4.53 us of the timing reference for the duration of the test. Additionally, the standard deviation of the timing accuracy was less than 1us for all unit, indicating their time stamping accuracy is very stable when they are operated in the continuous GNSS timing mode.

Table 85 Time Tag Accuracy, GNSS

Digitizer	Configuration	Channel	Sample Rate	Mean	Min	Max	Stddev
3052C	GNSS	1	250 sps	2.7839 us	2.3842 us	3.3379 us	0.25 us rms
3052D	GNSS	1	20 sps	4.3196 us	4.0531 us	4.5300 us	0.14 us rms
3052D	GNSS	1	40 sps	3.8498 us	3.5763 us	4.0531 us	0.10 us rms
3052D	GNSS	1	100 sps	3.3589 us	3.0994 us	3.5763 us	0.09 us rms
3052D	GNSS	1	200 sps	3.4360 us	2.8610 us	4.0531 us	0.38 us rms
3052E	GNSS	1	500 sps	2.8610 us	1.6689 us	3.5763 us	0.62 us rms

The measured absolute timing accuracy of within 4.53 us was better than the Wrangler specification of +/- 10 us. It was also better than the timing accuracy minimum requirements for IMS Seismic, IMS Infrasound, and OSI of 10 ms, 1 ms, and 100 us, respectively.

3.19 Timing Drift

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

3.19.1 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 timestamp minus the expected timestamp.

3.19.2 Configuration

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

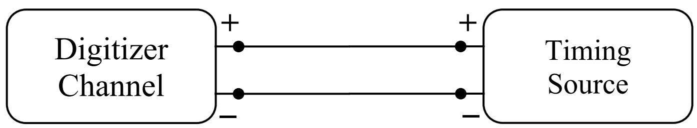

Figure 87 Timing Drift Configuration Diagram

Figure 88 Timing Drift PPM Source

Figure 89 Timing Drift GNSS Antennas Shielded

Table 86 Timing Drift Testbed Equipment

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

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

The digitizer clock is allowed to stabilize before the GNSS antenna is covered resulting in the digitizer to lose timing lock. The digitizer is allowed to drift over-night for a minimum of 12 hours before the GNSS antenna is uncovered and allowed to regain its timing lock.

In order for the digitizer GNSS receiver to lose reception, it was necessary to wrap the GNSS antennas in metal foil and placed in a metal cabinet in a separate room, as shown in Figure 89.

3.19.3 Analysis

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

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

3.19.4 Result

The figures below show the timing offsets over time as the digitizer channels drift and recover. Only a single sample rate is included, as the previous time tag accuracy analysis showed that multiple sample rates perform equivalently.

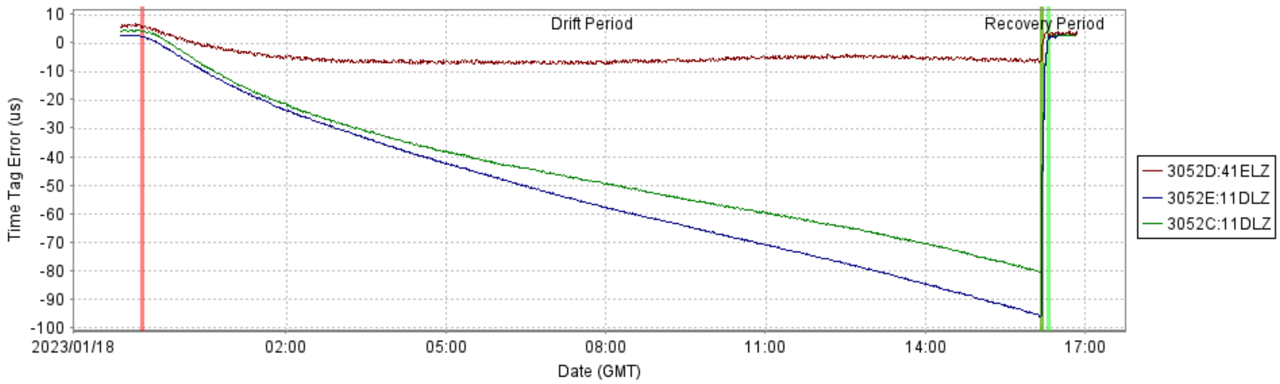

Figure 90 Time Tag Drift and Recovery

The following table contains the computed timing offsets when locked, drifting, and recovering and the estimated rate at which the digitizer was observed to drift and recover.

Table 87 Time Tag Drift and Recovery

Digitizer	Configuration	Channel	Sample Rate	Lock Level	Drift Rate	Recovery Time	Recovery Level
3052C	GNSS	1	250 sps	6 us	-4.37 us/h	< 8 min	3.0 us
3052D	GNSS	1	200 sps	4 us	-0.203 us/h	< 8 min	3.2 us
3052E	GNSS	1	500 sps	2.5 us	-5.33 us/h	< 8 min	3.2 us

The three Wranglers had very low timing drift during the 17 hours when their GNSS antennas were covered and unable to receive timing information. 3052E had the largest drift rate of -5.33us/h. After 17 hours this unit had a timing error of about 95us. 3052D only drifted at a rate of -0.203 us/h and, as a result, had minimal time stamping error at the end of the test. This test indicates that the Wranglers have highly stable internal clocks that can maintain accurate timing in the absence of GNSS signal reception.

The largest observed timing drift of 5.33 us/h is equivalent to approximately 0.0015 PPM, far less than the Wrangler datasheet Free-Running Accuracy of 0.1 PPM over 0 C to 70 C. It should be acknowledged that the timing drift testing was performed at a very stable 23 C ambient temperature, which should contribute to the stability of the timing drift rate.

3.20 Calibrator

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

3.20.1 Measurand

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

3.20.2 Configuration

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

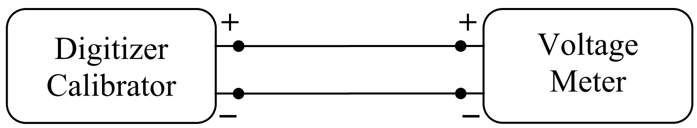

Figure 91 Calibrator Configuration Diagram

Table 88 Calibrator Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration	Digitizer
Voltage Meter	Agilent 3458A	MY45048371	DC Voltage	3052D
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage	3052E

The calibrator is configured to generate sinusoids across a range of amplitudes and frequencies.

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

3.20.3 Analysis

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

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

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

The measured signal characteristics are then compared against what was programmed into the digitizer's calibrator.

3.20.4 Result

The Reftek Wrangler digitizers provide a calibration system where the signal parameters such as amplitude, frequency and duration as well as the signal type such as sinusoid, step, and random binary can be configured by the user. The user may also load their own arbitrary signal into the Wrangler for use in calibrations. The Wrangler has a dedicated analog to digital converter for recording the generated calibration signal. The recorded calibration signal can be saved to internal memory or streamed from the Wrangler using its available protocols. In the case of this testing, the calibration signal was saved as a miniseed file and pulled from the Wrangler using the seedlink protocol.

3.20.4.1 Sine Amplitude

The calibrator performance was demonstrated on the 3052D and 3052E Wranglers using sinusoids at 1 Hz over a range of amplitudes. The figures and tables below show the reference meter recording of the calibrator output (top plot) along with the Wrangler's interal recording of the calibration signal (bottom plot).

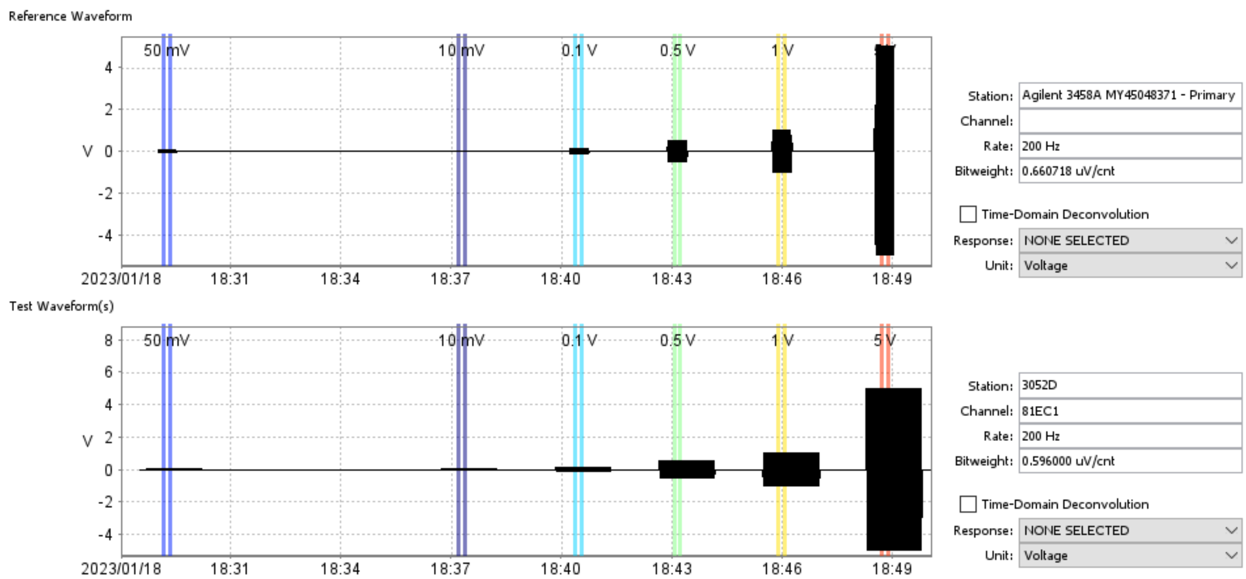

Figure 92 Calibrator Sine Amplitude at 1 Hz, Wrangler 3052D

Table 89 Calibrator Sine Amplitude at 1 Hz, Wrangler 3052D

Programmed Amplitude	Measured Amplitude	Internally Recorded Amplitude	Percent Deviation
0.01 V	0.00993 V	0.00988 V	-0.74%
0.05 V	0.04986 V	0.04965 V	-0.28%
0.10 V	0.09985 V	0.09942 V	-0.15%
0.50 V	0.49940 V	0.49810 V	-0.12%
1.00 V	0.99890 V	0.99600 V	-0.11%
5.00 V	4.99500 V	4.98000 V	-0.10%

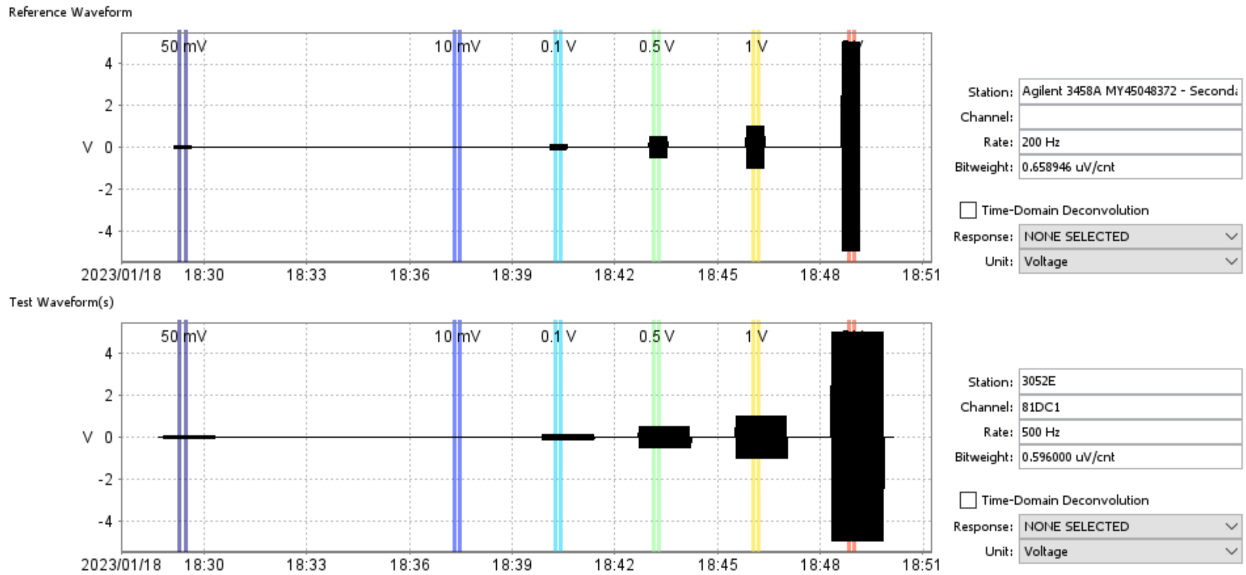

Figure 93 Calibrator Sine Amplitude at 1 Hz, Wrangler 3052E

Table 90 Calibrator Sine Amplitude at 1 Hz, Wrangler 3052E

Programmed Amplitude	Measured Amplitude	Internally Recorded Amplitude	Percent Deviation
0.01 V	0.00990 V	0.00987 V	-1.02%
0.05 V	0.04984 V	0.04971 V	-0.32%
0.10 V	0.09983 V	0.09958 V	-0.17%
0.50 V	0.49940 V	0.49800 V	-0.12%
1.00 V	0.99890 V	0.99630 V	-0.11%
5.00 V	4.99500 V	4.98200 V	-0.10%

The calibrator sinusoid amplitudes were measured to be between -1.02 % and -0.1% of the values programmed into the digitizer.

3.20.4.2 Sine Frequency

The calibrator performance was demonstrated on the 3052D and 3052E Wranglers using sinusoids at 1 V over a range of frequencies. The figures and tables below show the reference meter recording of the calibrator output.

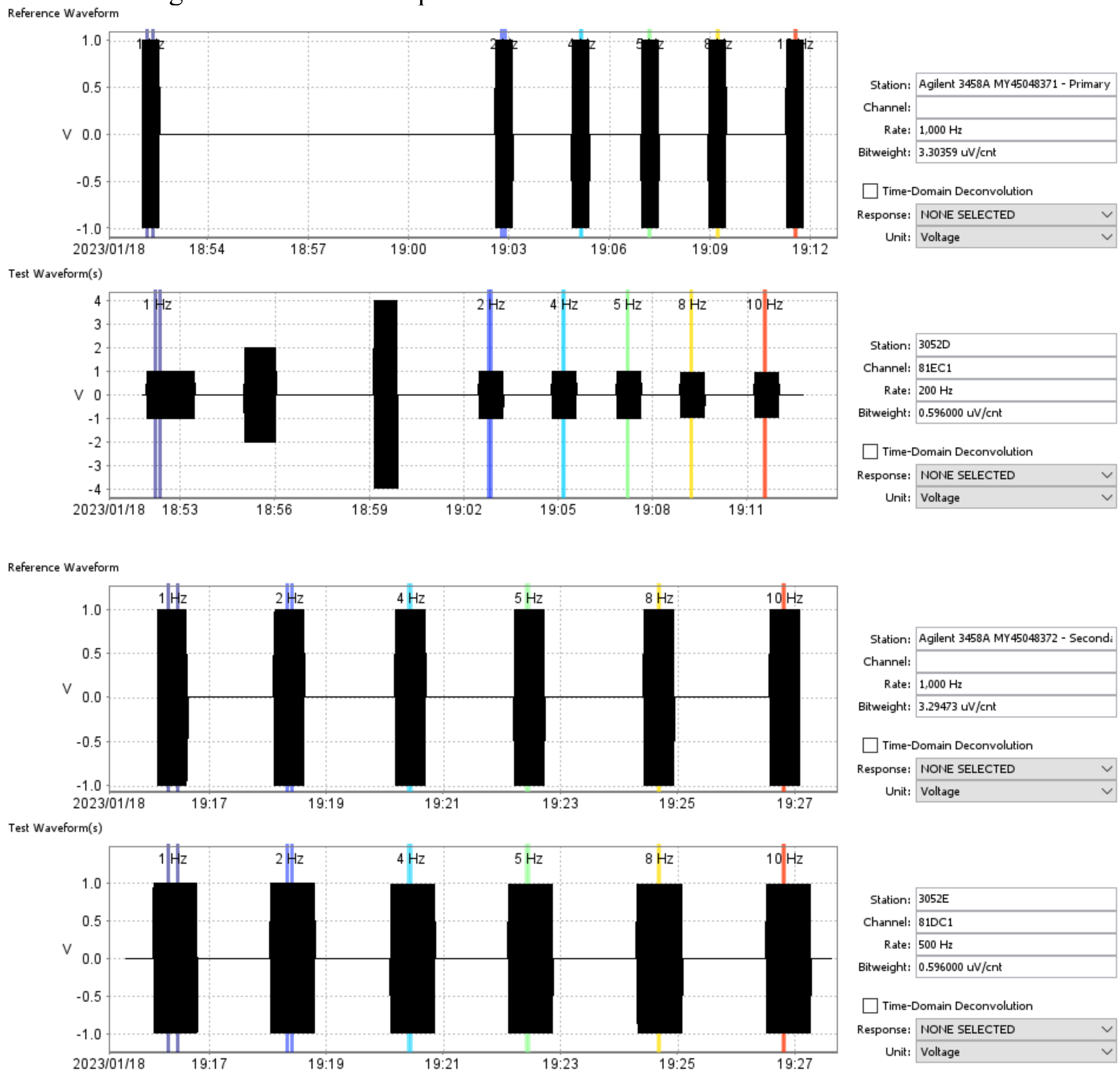

Figure 94 Calibrator Sine Frequency at 1 V for 3052D and 3052E

Table 91 Calibrator Sine Frequency at 1 V, Wrangler 3052D

Programmed Frequency	Measured Frequency
1 Hz	0.999 Hz
2 Hz	1.998 Hz
4 Hz	3.996 Hz
5 Hz	4.996 Hz
8 Hz	7.992 Hz
10 Hz	9.992 Hz

Table 92 Calibrator Sine Frequency at 1 V, Wrangler 3052E

Programmed Frequency	Measured Frequency
1 Hz	0.999 Hz
2 Hz	1.998 Hz
4 Hz	3.996 Hz
5 Hz	4.996 Hz
8 Hz	7.992 Hz
10 Hz	9.992 Hz

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

3.21 Sensor Compatibility Verification

The Wrangler digitizers were connected to several example sensors to demonstrate compatibility and functionality. Each sensor was operated sufficiently to determine that it was performing properly.

3.21.1 Seismometers: GS13, STS-2, Trillium Horizon, and Colt-120s

Multiple seismometers were connected to the Wrangler data recording channels, as shown in the table below.

Table 93 Seismometer Compatibility Configuration

Digitizer	Channel	Gain	Sensor Model	Sensor Serial #
Wrangler 3052C	1, 2, 3	1	STS-2	120651
Wrangler 3052C	4	4	GS-13	881
Wrangler 3052D	1, 2, 3	1	Colt (120 sec)	213012
Wrangler 3052D	4, 5, 6	1	STS-2	19026
Wrangler 3052E	1, 2, 3	1	Colt (120 sec)	213011
Wrangler 3052E	4, 5, 6	1	T120 Horizon v1	0769

Figure 95 Seismometer Compatibility

The seismometers were allowed to operate over-night to collect data and observe their measurements of background noise.

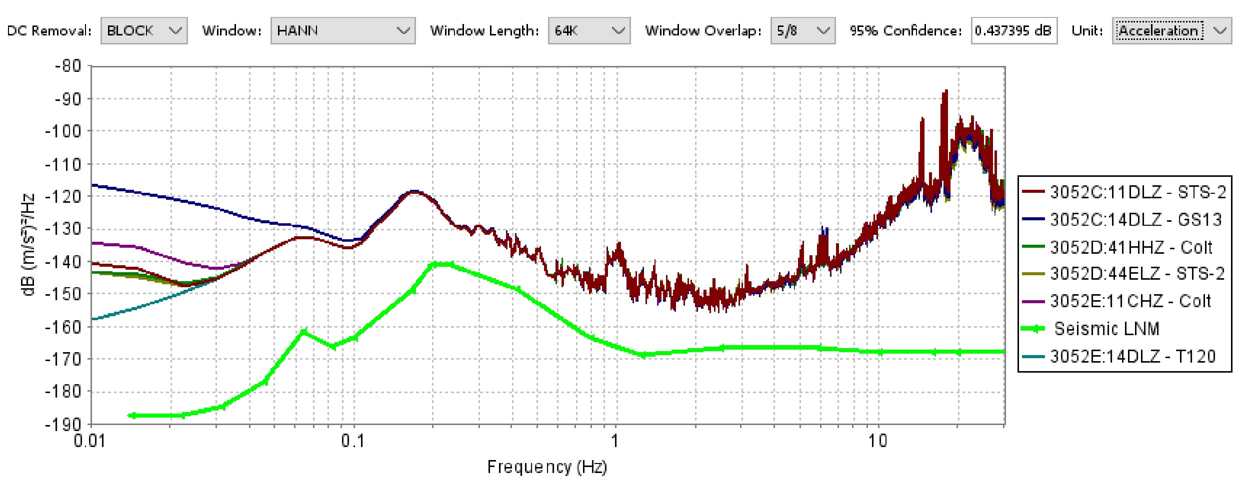

Figure 96 Seismometer Power Spectra Comparison, Vertical

The vertical channels from each seismometer are overlaid in Figure 96 (PSD) and Figure 97 (coherence). Where the sensors have a common passband, their amplitudes agree well with one another, and the signals are highly coherent. Below 0.1 Hz, the response roll off and self-noise of the Geotech GS13 seismometer limits its ability to resolve the long-period background. The T120 Horizon is noticeably quieter at long periods that the other broadband sensors. This is likely because the T120 Horizon was installed in an insulated box and had been powered and operating in the bunker for several weeks prior to the Wrangler testing. The other broadbands were installed the afternoon of the test and were not covered with additional insulation.

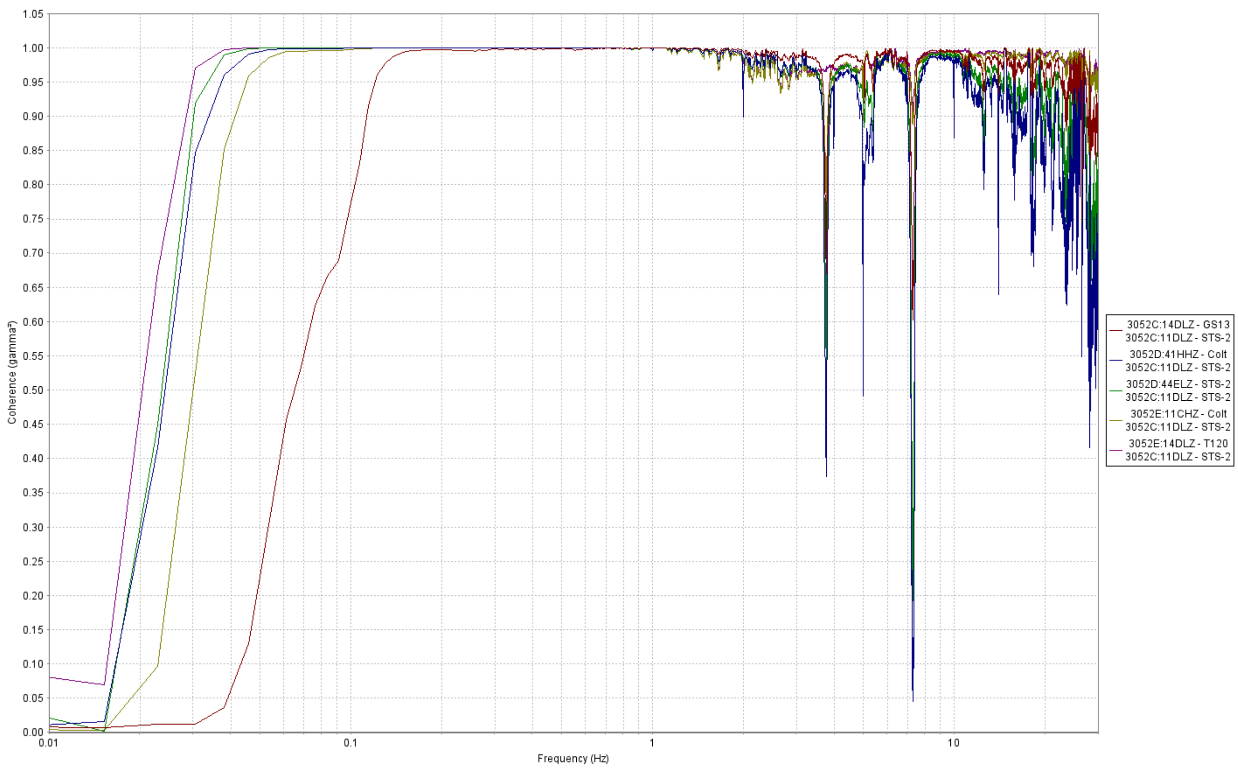

Figure 97 Seismometer Coherence, Vertical

The coherence between the vertical channels of the seismometers is excellent between 0.15 to 2 Hz where there is good SNR. Note that in Figure 97 STS-2 120651 is being used as the reference and the coherency measurements are between it and the other sensors.

Similarly, comparisons of the horizontal North and East seismometer channels are shown in the figures below.

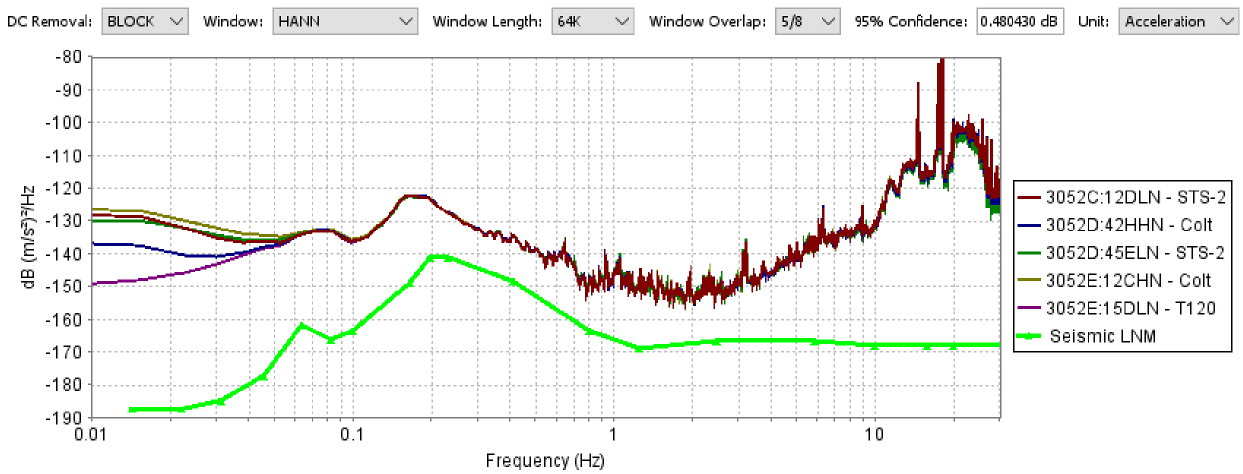

Figure 98 Seismometer Power Spectra Comparison, North

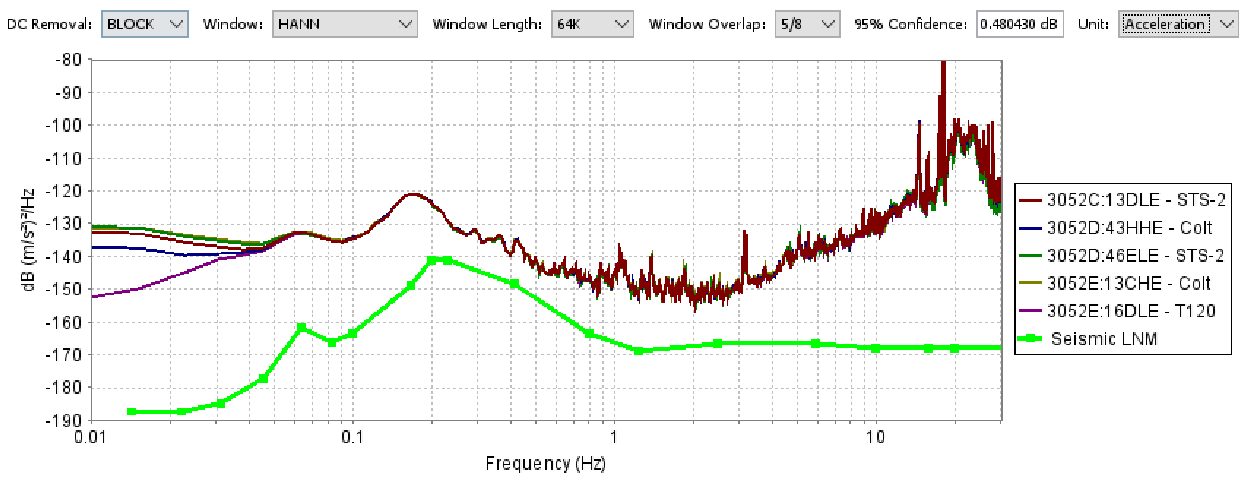

Figure 99 Seismometer Power Spectra Comparison, East

The horizontal seismometer channels show similar agreement in the signal amplitudes for both the North/South and East/West channels. Elevated noise at low frequencies, below 0.05 Hz, makes comparing the seismometers difficult in the horizontal axes.

3.21.1.1 Seismometer Electrical Calibrations

The Wrangler dataloggers were used to carry out several electrical calibrations of seismometers. The Wranglers were configured to record the calibration signal they generated and sent to the seismometers as well as the output from the sensors. In this way the recorded data could be used to verify the electrical calibration performance of the seismometers. The tests performed are summarized in the table below.

Table 94 Seismometer Electrical Calibrations

Digitizer	Channel	Gain	Sensor	Calibration Type
Wrangler 3052C	1, 2, 3	1	STS-2 120651	0.1V, 1Hz, Sinusoid
Wrangler 3052D	1, 2, 3	1	Colt 213012	0.1V, 1Hz, Sinusoid
Wrangler 3052E	1, 2, 3	1	Colt 213011	0.1V, 1Hz, Sinusoid
Wrangler 3052C	4	1	GS-13 881	0.1V, 5Hz, Sinusoid 0.5V, 5Hz, Sinusoid
Wrangler 3052C	1, 2, 3	1	STS-2 120651	0.1V, RandomLP, 300s
Wrangler 3052D	1, 2, 3	1	Colt 213012	0.1V, RandomLP, 300s
Wrangler 3052E	1, 2, 3	1	Colt 213011	0.1V, RandomLP, 300s
Wrangler 3052C	4	1	GS-13 881	0.5V, RandomSP, 60s
Wrangler 3052D	4, 5, 6	1	STS-2 19026	0.1V, 1Hz, Sinusoid
Wrangler 3052D	4, 5, 6	1	STS-2 19026	0.1V, RandomLP, 300s

The Wranglers performed all electrical calibrations correctly and appropriately recorded both the input signal sent to the seismometers as well as the seismometers' output signals. The Wranglers appear to default to using 24 bit resolution and the x4 gain bit-weight when recording the generated calibration signals. Thus, the calibration signals are recorded with a 0.596 uv/cnt bitweight. Representative examples of the calibration signals are shown in the figures below.

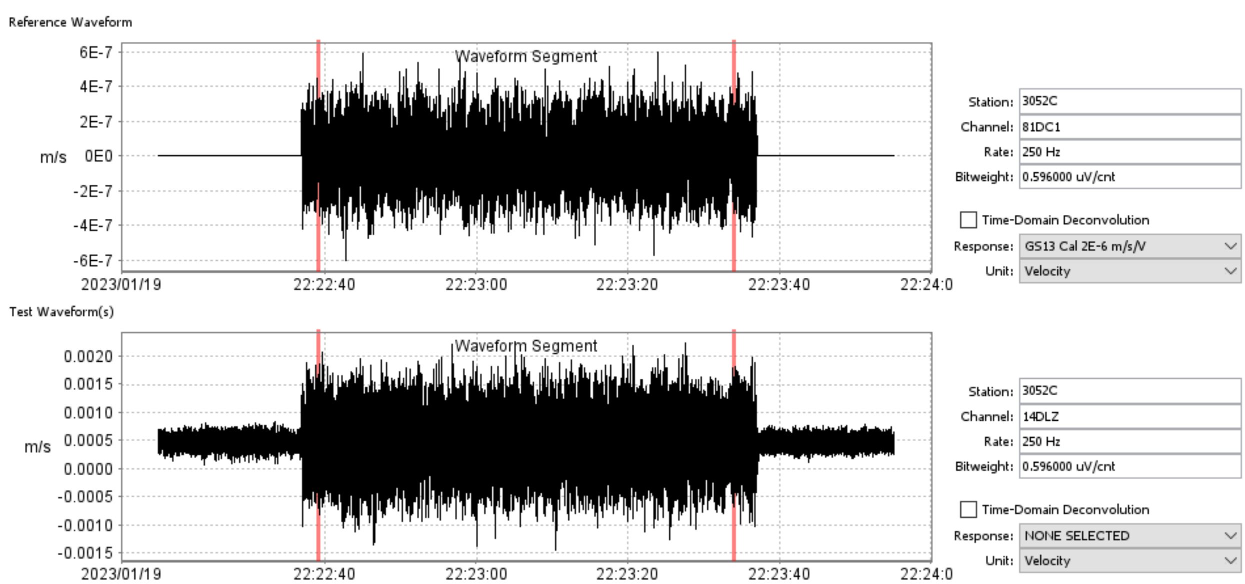

Figure 100 Time series of 0.5V, RandomSP calibration of GS-13 881

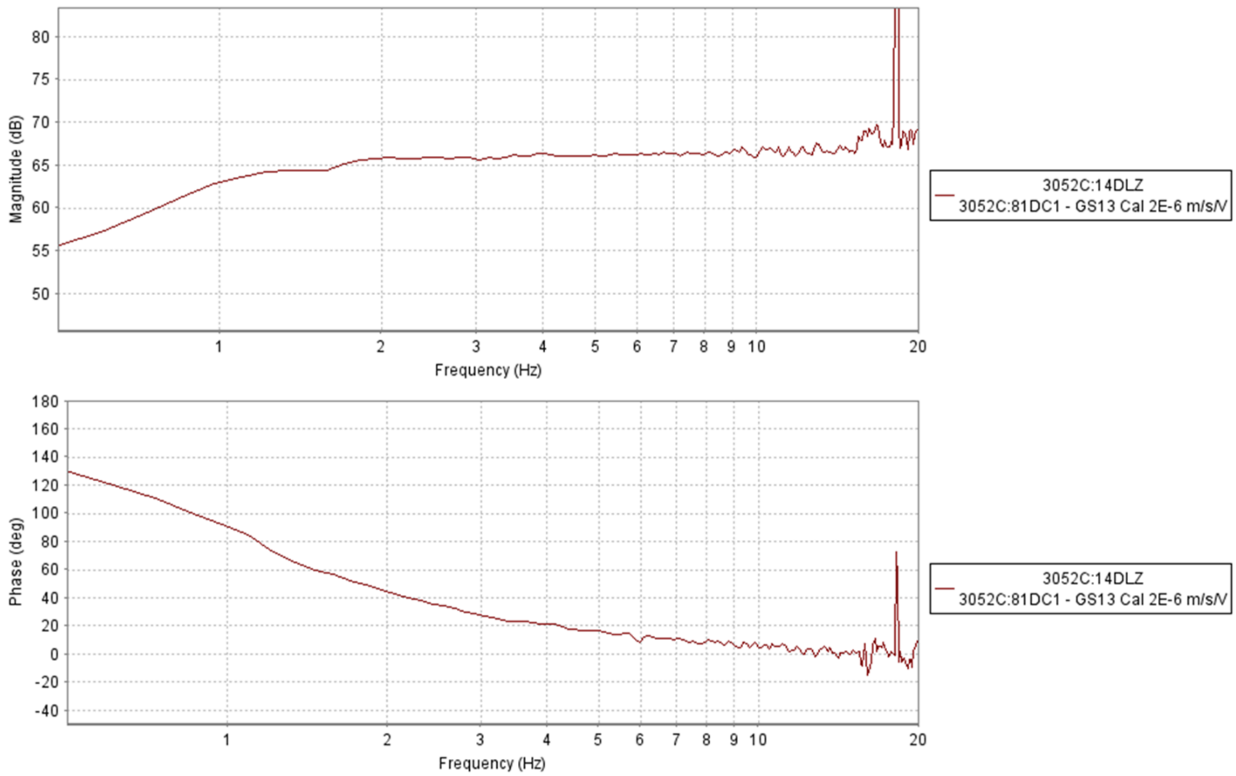

Figure 101 Calculated amplitude and phase response of the GS-13 using the Random LP calibration data.

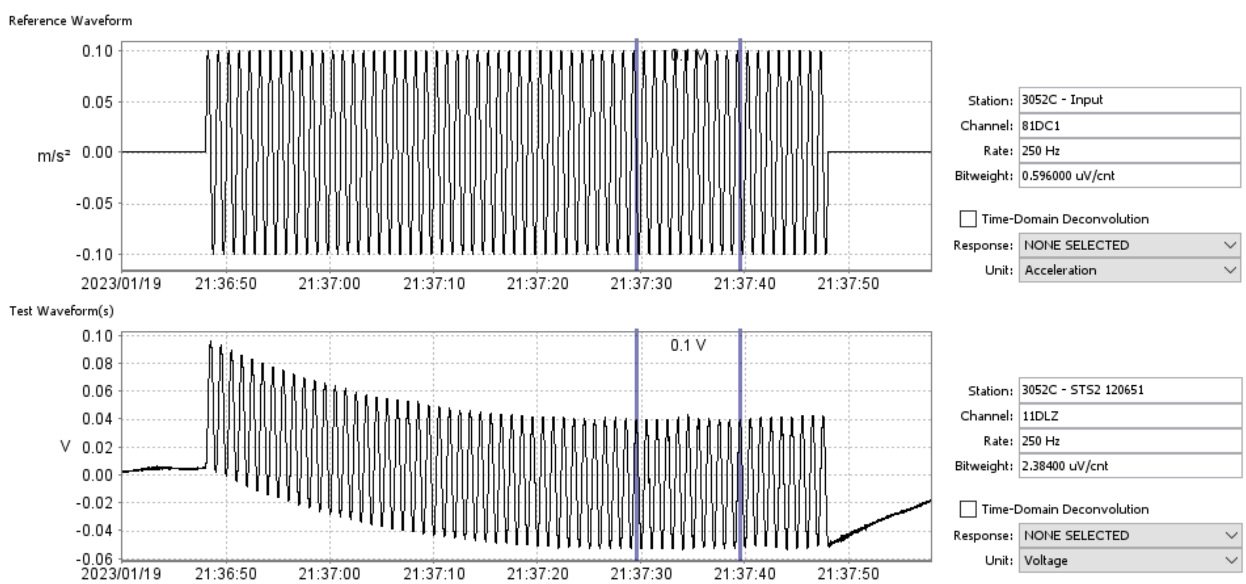

Figure 102 0.1V, 1Hz Sinusoidal calibration of STS-2 120651.

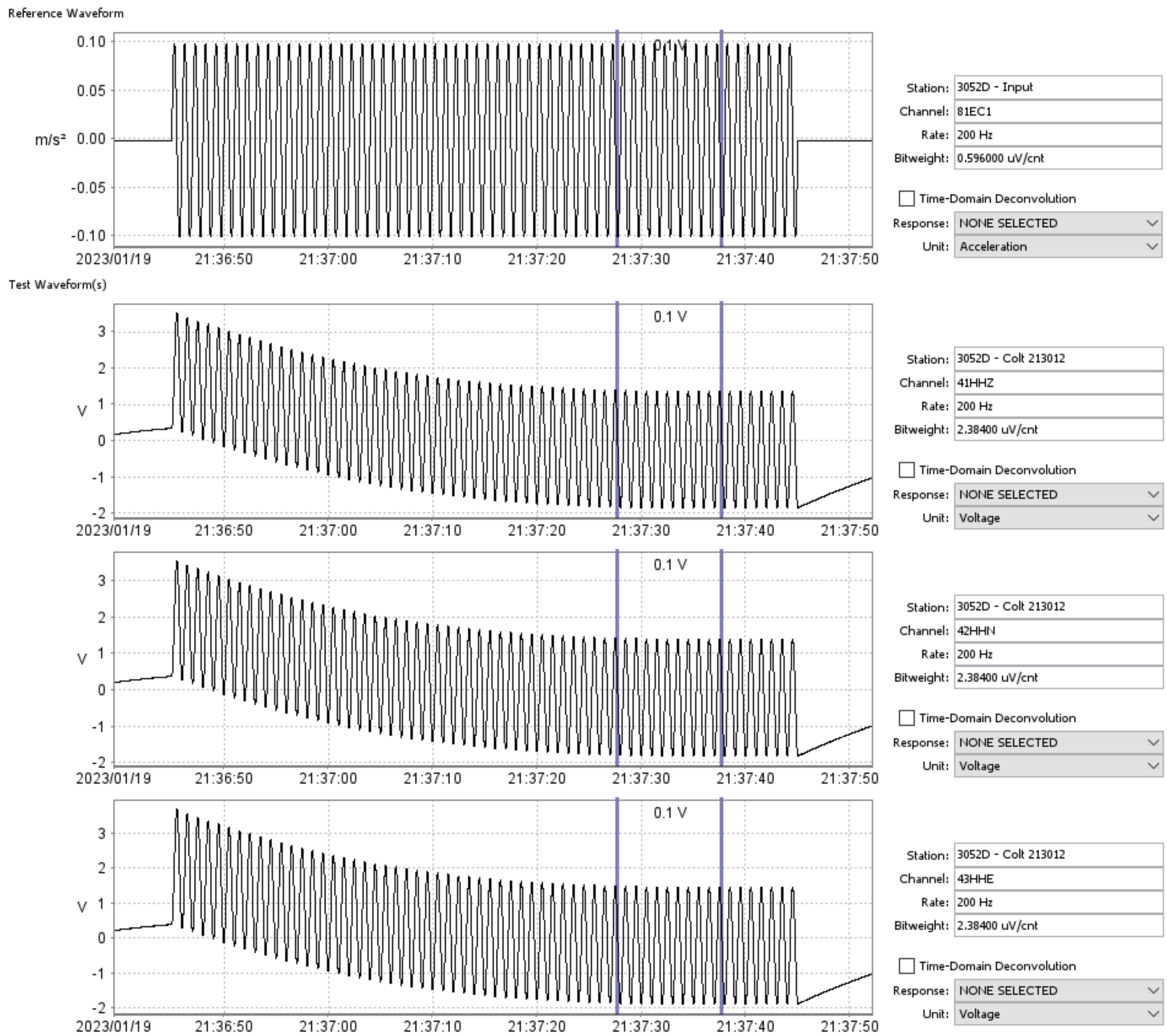

Figure 103 0.1V, 1Hz Sinusoidal Calibration of Colt 213012

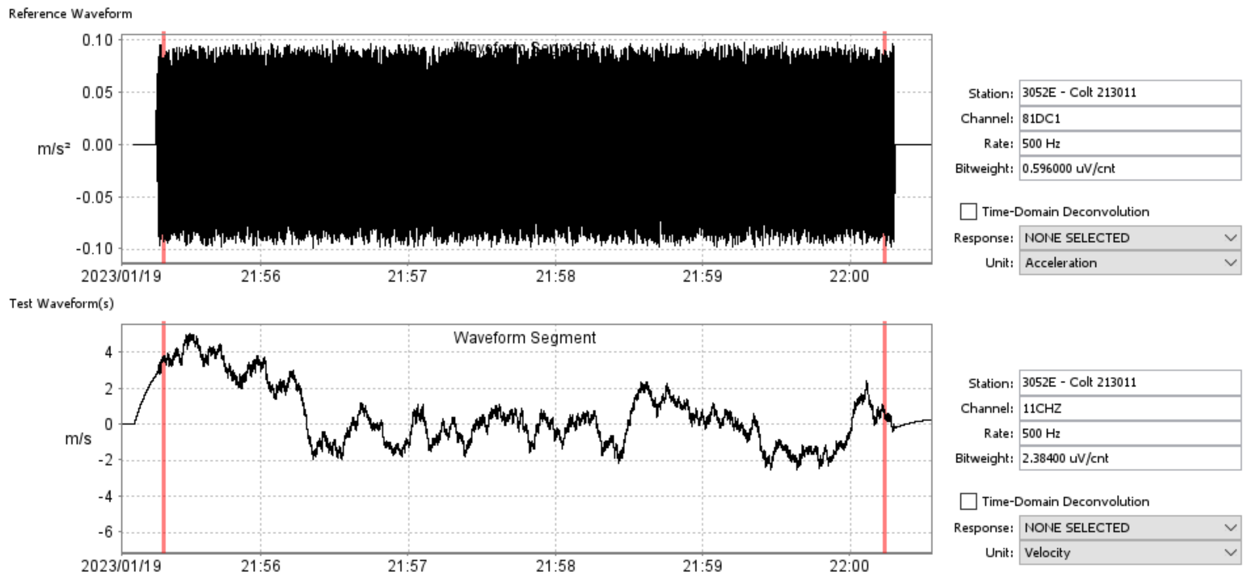

Figure 104 0.1V, RandomLP, 300s Calibration of Colt 213011

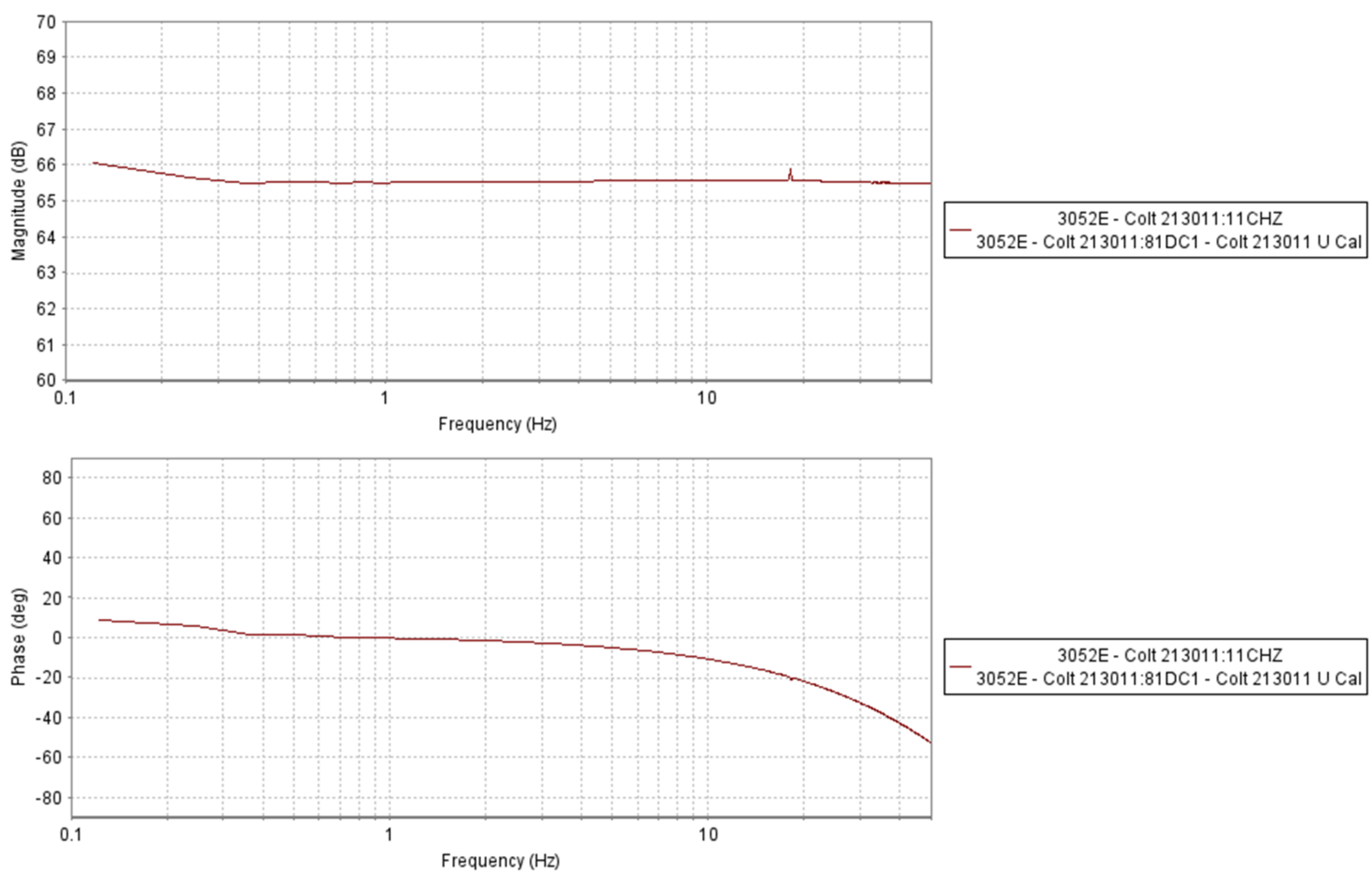

Figure 105 Calculated magnitude and phase response for Colt 213011 using Random LP calibration data

3.21.2 Infrasound Sensors: MB3a, MB2000, Hyperion 5113A

Multiple infrasound sensors were connected to the Wrangler data recording channels, as shown in the table below.

Table 95 Infrasound Sensor Compatibility Configuration

Digitizer	Channel	Gain	Sensor Model	Sensor Serial #
Wrangler 3052D	1	1	MB2000	#1380
Wrangler 3052D	2	1	Hyperion IFS-5113A	#20150306.003
Wrangler 3052D	3	1	MB3a	#25/0715

The infrasound sensors were left with an inlet open to record ambient background noise.

Figure 106 Infrasound Sensor Compatibility

Note that this test was performed in a relatively noisy environment with no attempt to temperature stabilize the sensors or couple their inlets to improve consistent signal amplitudes or coherence. It was simply meant as a demonstration of compatibility between the sensors and the digitizers.

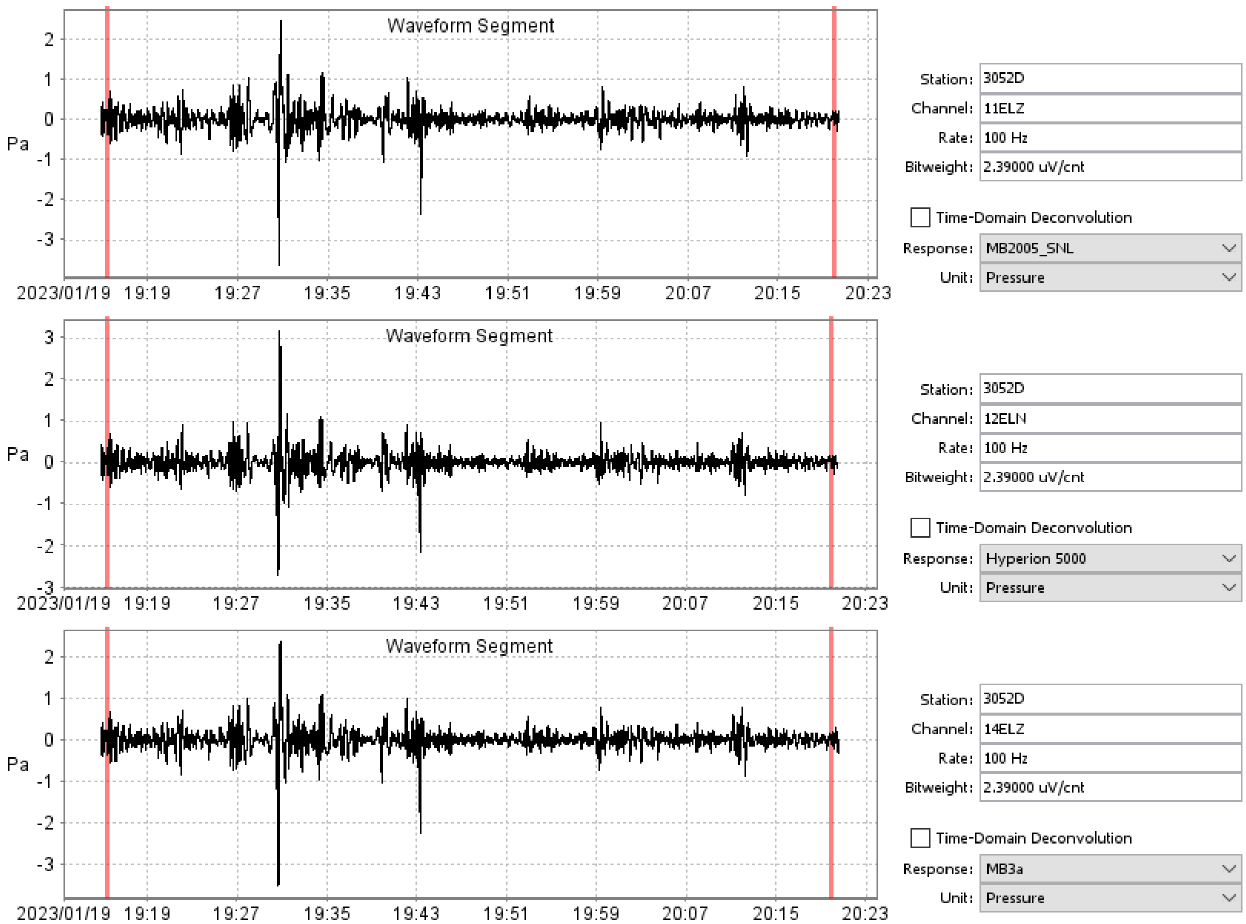

Figure 107 Infrasound Sensor Compatibility Time Series, filtered from 0.02 to 4 Hz

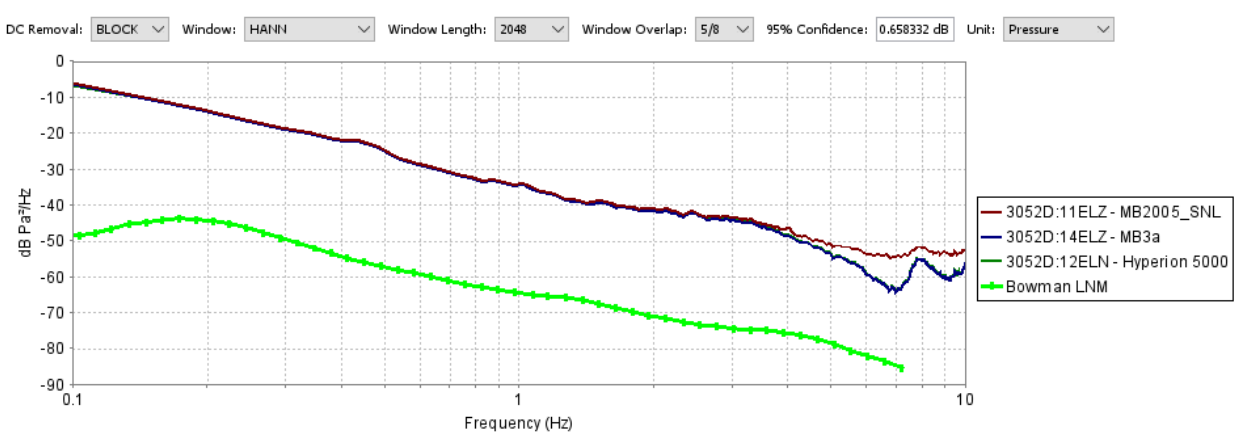

Figure 108 Infrasound Sensor Compatibility Power Spectra

The recording of the sensors, scaled by their nominal frequency responses, all shows consistent time-series and power spectra for this short duration comparison. Note that the MB2000 recorded higher signal levels above approximately 5 Hz, where the sensor's self-noise levels become apparent.

Applying coherence analysis, we were able to extract the incoherent portions of the infrasound recordings, equivalent to various sensors self-noise levels.

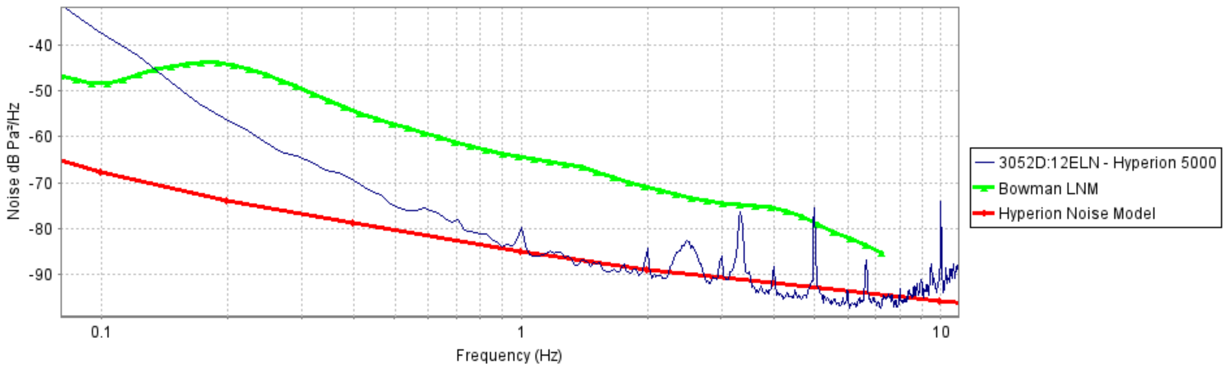

Figure 109 Hyperion Self-Noise

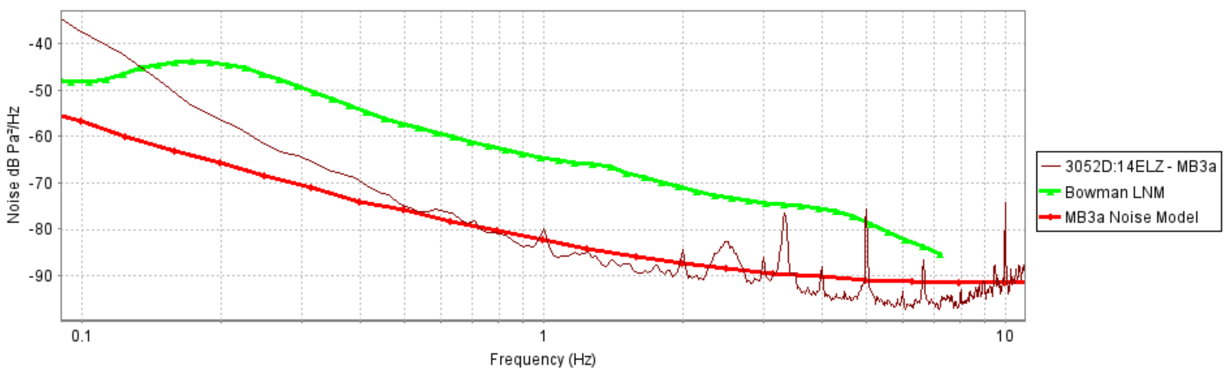

Figure 110 MB3a Self-Noise

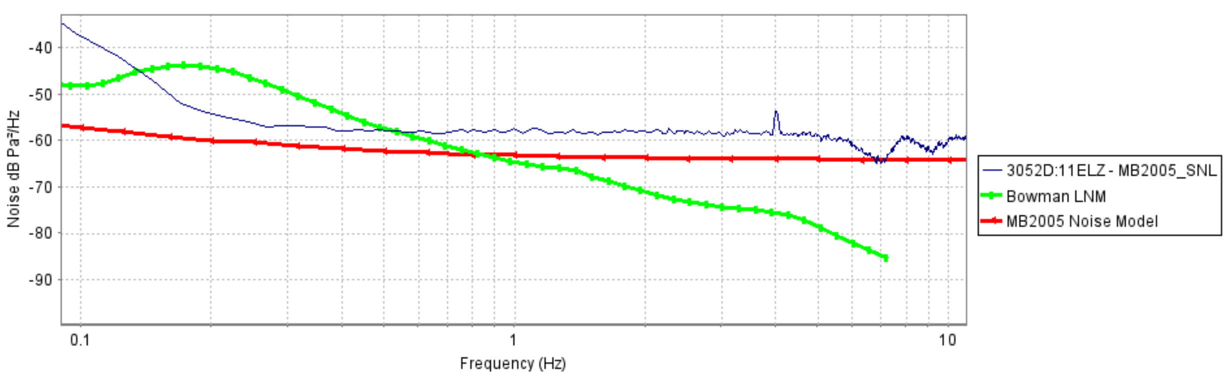

Figure 111 MB2000 Self-Noise

3.21.2.1 Infrasound Electrical Calibrations

The 3052D Wrangler was used to carry out several electrical calibrations of the MB3A infrasound sensor. The Wrangler was configured to record the generated calibration signal sent to the sensor as well as the output from the sensor. In this way the recorded data could be used to verify the electrical calibration performance of the MB3A. The tests performed are summarized in the table below.

Table 96 Infrasound Electrical Calibrations

Digitizer	Channel	Gain	Sensor	Calibration Type
Wrangler 3052D	4	1	MB3A 25/0715	1.0V, 1Hz, Sinusoid
Wrangler 3052D	4	1	MB3A 25/0715	1.0V, Random LP, 300s duration

The Wrangler performed both electrical calibrations correctly and appropriately recorded the input signal sent to the MB3A as well as the unit's output signal. The figures below show time series plots of both the input calibration signal and the MB3A's output.

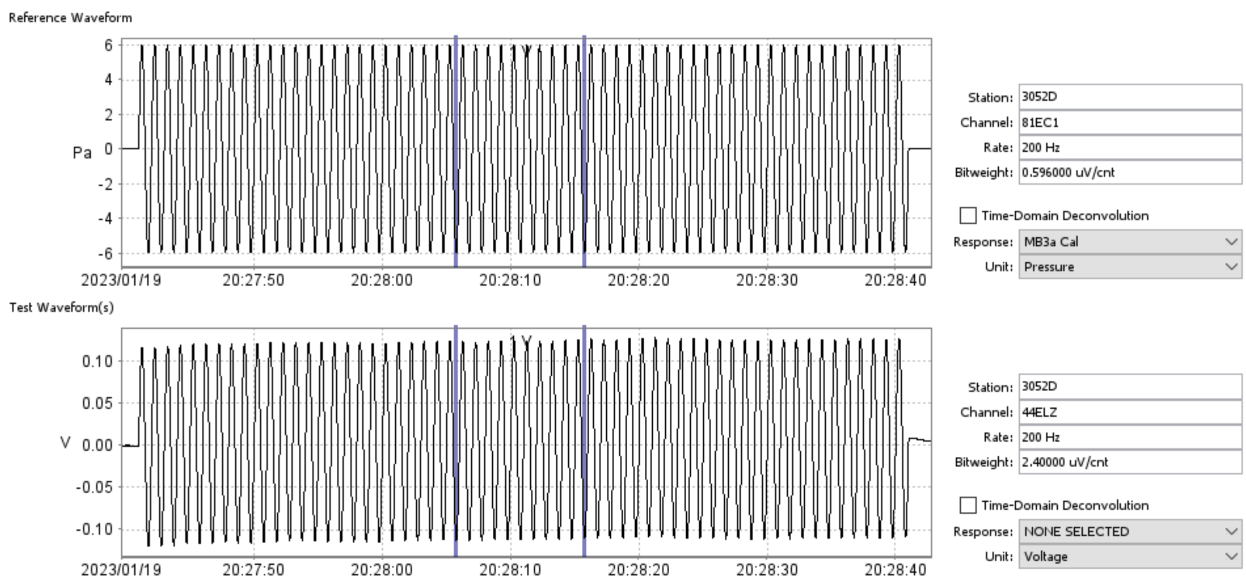

Figure 112 1V, 1Hz Sinusoidal Calibration of MB3A

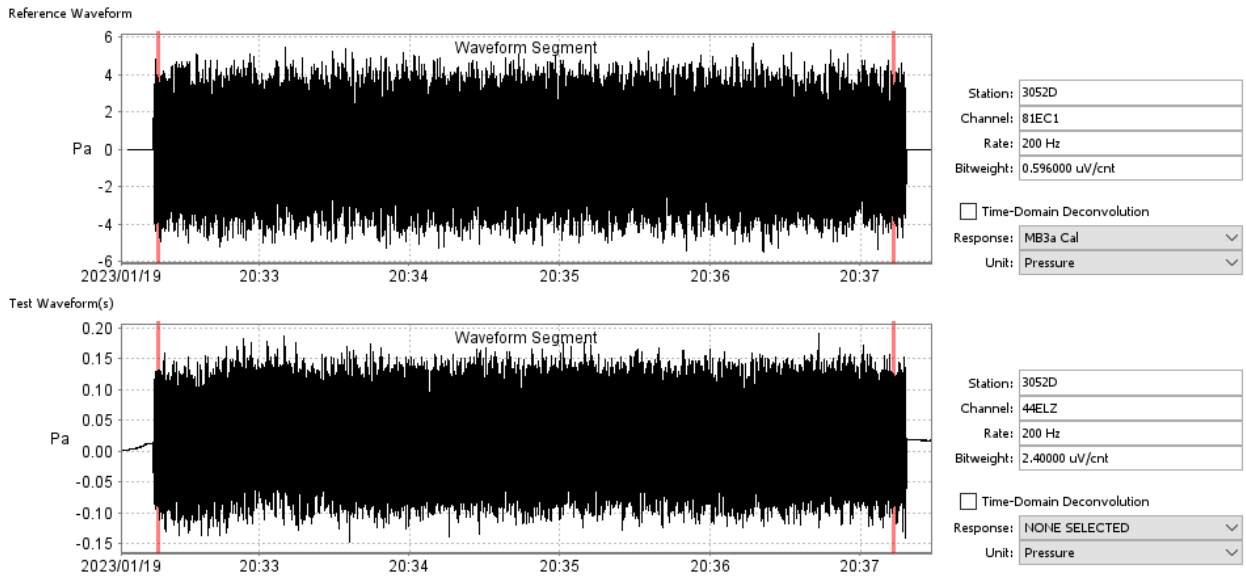

Figure 113 1.0V, RandomLP, 300s duration electrical calibration of the MB3A

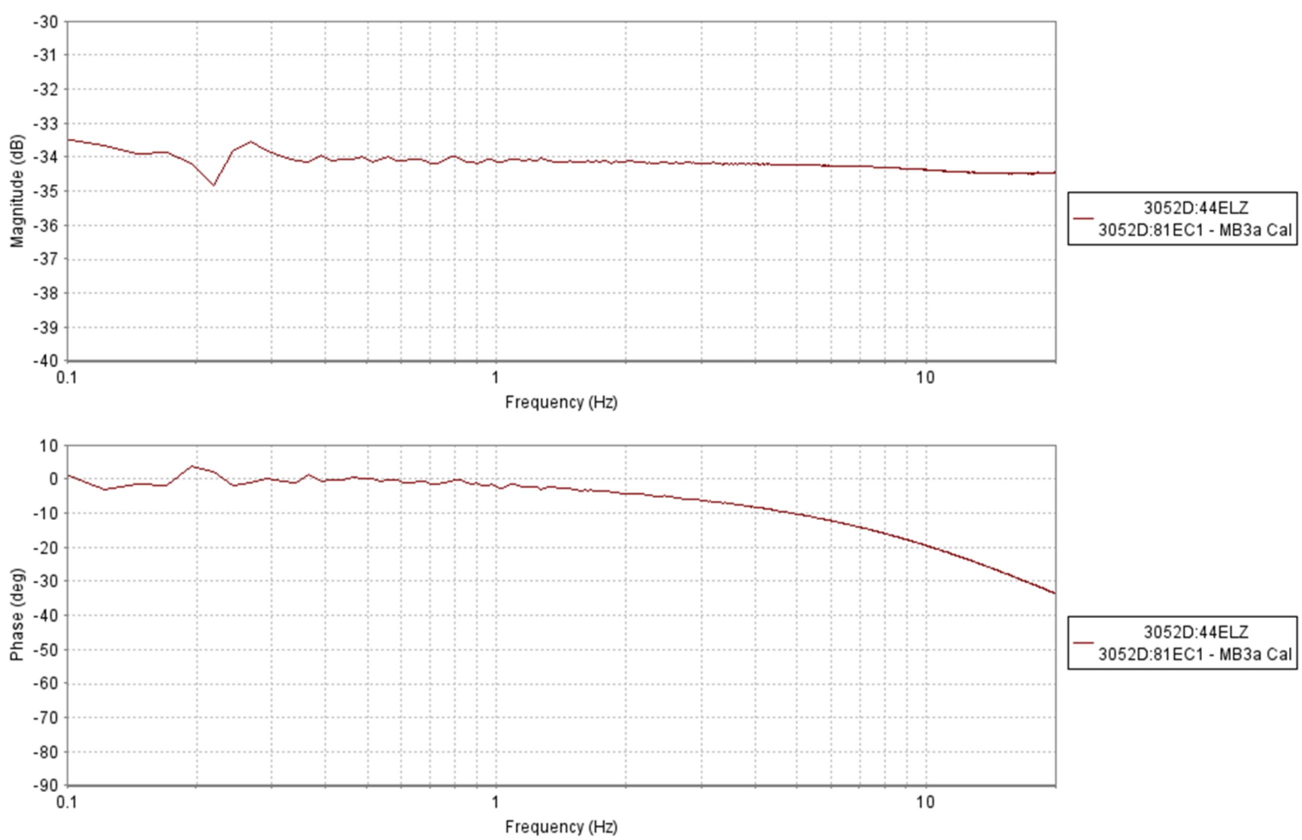

Figure 114 Derived magnitude and phase response of the MB3A using the Random LP data

4 SUMMARY

Power Consumption
The Wrangler digitizers were found to consume between 2.55 W and 2.91 W of power in general operation. Power consumption was not observed to change with gain levels. Power consumption levels dropped to between 2.28 W and 2.33 W when the units were not connected to an ethernet switch and were unable to stream data. In addition to the measurement of power consumption, the Wrangler digitizers were operated at power supply voltage levels ranging from 10.5 to 30.5 V and confirmed to function. Power consumption levels were slightly elevated above the datasheet specification of 2.3 W, likely due to the configuration of continuous GNSS timing. Measured power consumption levels were less than the OSI requirements of 5 W.

Input Impedance
The Wrangler digitizer channels were found to have an input impedance that was within 1.35% of the nominal 26 kohm value when they were operated at the x1 and x16 gain levels. When operated at the x4 and x64 gain levels, the input impedance was within 2.89% of the nominal 2.0 Mohm value.

DC Accuracy
The Wrangler digitizer channels were found to have bit-weights that were consistent with the nominal values to within 0.33%, when measured using constant DC voltages, of 2.384 uV/cnt, 0.596 uV/cnt, 0.149 uV/cnt, and 0.0373 uV/cnt at gain of x1, x4, x16, and x64, respectively.

AC Accuracy
The Wrangler digitizer channels were found to have bit-weights that were consistent with the nominal values to within 0.36%, when measured using 1 Hz sinusoids, of 2.384 uV/cnt, 0.596 uV/cnt, 0.149 uV/cnt, and 0.0373 uV/cnt at gain of x1, x4, x16, and x64, respectively.

AC Full Scale
The Wrangler digitizer channels could fully resolve peak-to-peak amplitudes at their full-scale level without any apparent signs of distortion across the 20 Hz, 40 Hz, 100 Hz, 200 Hz, 250 Hz, and 500 Hz sample rates and gains of x1, x4, x16, and x64.

AC Over Scale
The Wrangler digitizer channels all were determined to have a full-scale amplitude that was nearly identical to their specified full-scale level. When operated at the x1, x4 and x16 gain levels the measured full-scale amplitude was slightly higher than the specified full-scale level of 40 Vpp, 10 Vpp, and 2.5 Vpp, respectively. For the x64 gain level the measured full-scale amplitude was 0.176% less than the specified full-scale amplitude of 0.625 Vpp. The full-scale clipping levels measured all exceeded the minimum OSI requirements of 20 Vpp at gain x1 and 0.6 Vpp at gain x32, although the Wrangler does not support a gain of x32.

Input Shorted Offset
The Wrangler digitizer channels were found to have a DC offset that in all cases was less than 3 mV. In general, offsets were unique to each channel and were approximately constant in units of counts, thus the offset in volts scaled inversely with the gain setting.

Self-Noise

The Wrangler digitizers were observed to have self-noise levels that are typically less than 1 count of noise when operated at the x1 and x4 gain levels. Noise levels were typically higher when the units operated at the x16 and x64 gain levels. Self-noise generally scaled with gain level with the exception being the x16 gain level which had the same noise floor and the x4 gain level for frequencies above about 5 Hz.

Dynamic Range

Dynamic range values varied with the application passband, sample rate, gain setting, and the termination resistor. However, dynamic ranges were generally between 138 dB and 148 dB for the x1 and x4 gain levels. The worst-case Dynamic Range values occurred when the units were operated in the x16 gain stage, generally in the range of 120 dB and 135 dB. The Dynamic Range values for the x64 gain stage were better than the x16 gain stage but lower than the values achieved in with the x1 and x4 gain levels.

The Dynamic Range exceeded the IMS Seismic and Infrasound requirements of 120 dB and 108 dB, respectively, for the appropriate sample rates and frequency passbands at level of between 132 dB and 148 dB. For OSI application requirement of at least 135 dB at 100 sps, the Dynamic range was better than that at approximately 140 dB at gains of x1 and x4, but lower at between 126 dB and 131 dB at gains of x16 and x64.

System Noise

System noise plots are provided to demonstrate the impact of the digitizer self-noise for a variety of seismometer and infrasound sensor applications.

Temperature Self-Noise

The Wrangler digitizers were exposed to temperatures ranging from -20 C to +50 C without any operational issues. With the digitizer inputs terminated, the only observable change in performance as a function of temperature was a small, less than 3 mV, change in the DC offset.

Relative Transfer Function

The Wrangler digitizer channels exhibited less than 0.13 microseconds of timing skew from channel to channel, indicating that the channels are sampling synchronously.

Analog Bandwidth

The Wrangler digitizer channels exhibited a bandwidth of between 84.12% and 85.4% of the Nyquist rate at sample rates of 20 Hz, 40 Hz, 100 Hz, 200 Hz, 250 Hz and 500 Hz. Bandwidth was not observed to vary with gain level. This indicates that the anti-alias filter in use was compatible with the configured sampling rate.

Total Harmonic Distortion

The Wrangler digitizer channels exhibited harmonic distortion ranging between -98.6 dB and -83.6 dB at a gain of 1x, -98.3 dB and -85.2 dB at a gain of 4x, -98.6 dB and -83.5 dB at a gain of 16x, and –98.0 dB and -85.3 dB at a gain of 64x. This distortion was measurable against the reference signal which contained between -121 dB and -134 dB of distortion.

Modified Noise Power Ratio

The Wrangler digitizer channels exhibited a modified noise power ratio at gains of 1x and 4x with a performance of approximately 23 bits at low amplitudes and between 20 and 21 bits at high amplitudes. At 64x gain, the modified noise power ratio indicated a performance of about 22 bits at low amplitudes and 20.5 bits at high amplitudes.

Common Mode Rejection

The Wrangler digitizer channels exhibited common mode rejection ratios of between 50 and 114 dB, as compared to the datasheet specification of > 90 dB. At values above 90 dB, little to no common mode noise was observable.

Crosstalk

The Wrangler digitizer channels exhibited crosstalk that was measured to be better than between -131 dB and -154 dB.

Time Tag Accuracy

The Wrangler digitizers were measured to have timing accuracy values with a mean level of 4.53 us or better when using GNSS continuously. This measured value is better than the datasheet specification of +/- 10 us and also better than the timing accuracy minimum requirements for IMS Seismic, IMS Infrasound, and OSI of 10 ms, 1 ms, and 100 us, respectively.

Time Tag Drift

The Wrangler digitizer timing accuracy drifted by between 0.2 and 5.3 us/hr. The digitizers recovered back to their original time tag accuracy within 8 minutes of regaining GNSS lock. This timing drift is far lower than the datasheet specification 0.1 PPM, although the measurement was only made under stable 23 C conditions.

Calibrator

The Wrangler digitizers demonstrated the ability to accurately generate sinusoids at amplitudes of between 0.01 V and 5 V and frequencies between 1 Hz and 10 Hz.

Sensor Compatibility Verification

The Wrangler digitizer was able to demonstrate the proper operation and calibration of a Trillium Horizon 120 seismometer, a STS2 seismometer, multiple Colt seismometers, a GS-13 seismometer, an MB2005 infrasound sensor, an MB3a infrasound sensor, and a Hyperion infrasound sensor.

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

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

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

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

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

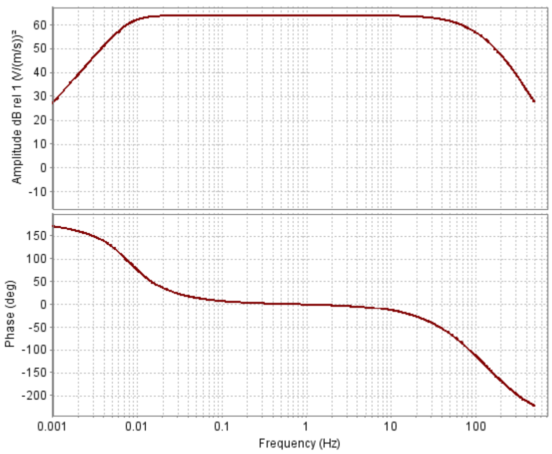
6. Merchant, B. John, and Darren M. Hart (2011), *Component Evaluation Testing and Analysis Algorithms*, SAND2011-8265.

7. Merchant, B. John, and George Slad (2018), *2018 Nanometrics Centaur Digitizer Evaluation*, SAND2018-11442.

8. 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.

APPENDEX A: RESPONSE MODELS

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



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

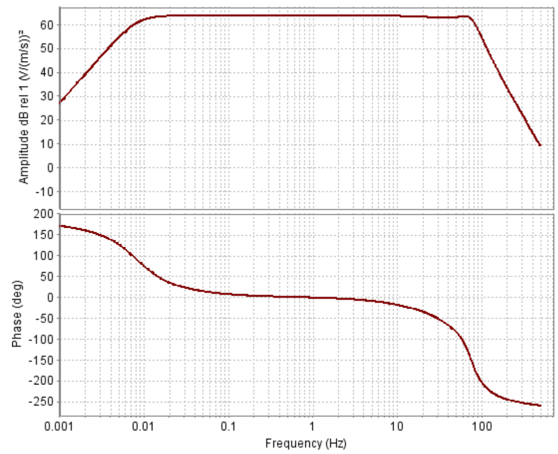
-1130.0	0.0
-1010.0	0.0
-503.0	0.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
861,208.00814 MV·s/m

Kinemetrics STS-2 Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

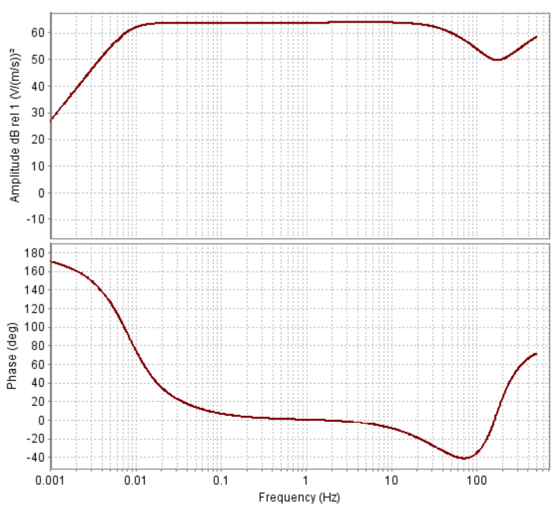
-251.0	0.0
-131.0	467.0
-131.0	-467.0
-0.037	0.037
-0.037	-0.037

Zeros:

0.0	0.0
0.0	0.0

A:
88,586.67303 MV·s/m

Kinemetrics STS-5A Seismometer



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

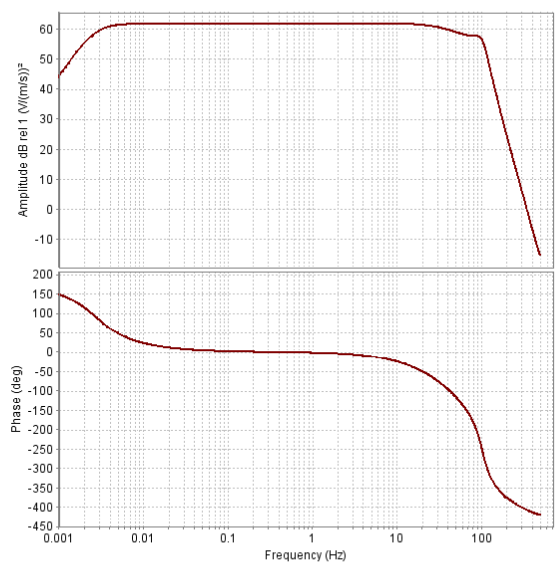
-961.0	0.0
-339.0	116.0
-339.0	-116.0
-16.0	0.0
-16.0	0.0
-0.037	-0.037
-0.037	0.037

Zeros:

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

A:
0.27503 V·s/m

Kinemetrics STS-6A Seismometer



Sensitivity:
1,200 V·s/m at 1.0 Hz

Poles:

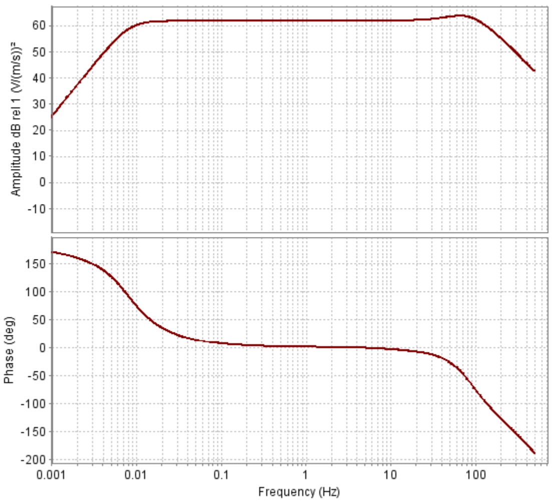
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-501.105	0.0
-351.858	0.0
-121.58	647.231
-121.58	-647.231
-22.3068	0.0
-22.3068	0.0
-0.01231	0.01206
-0.01231	-0.01206

Zeros:

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

A:
51.422261E9 MV·s/m

Nanometrics Trillium 120 Seismometer



Sensitivity:
1,200 V·s/m at 1.0 Hz

Poles:

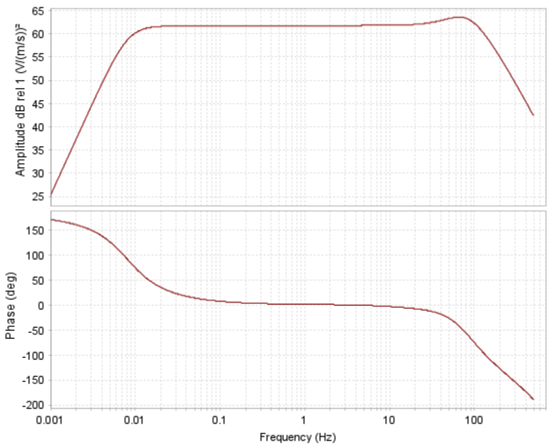
-7100.0	1700.0
-7100.0	-1700.0
-4900.0	5204.0
-4900.0	-5204.0
-1260.0	0.0
-364.0	404.0
-364.0	-404.0
-142.0	0.0
-32.55	0.0
-0.036614	0.037059
-0.036614	-0.037059

Zeros:

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

A:
999.05912E12 MV·s/m

Nanometrics Horizon 120 v1 Seismometer



Sensitivity:
1,202.50 V·s/m at 1.0 Hz

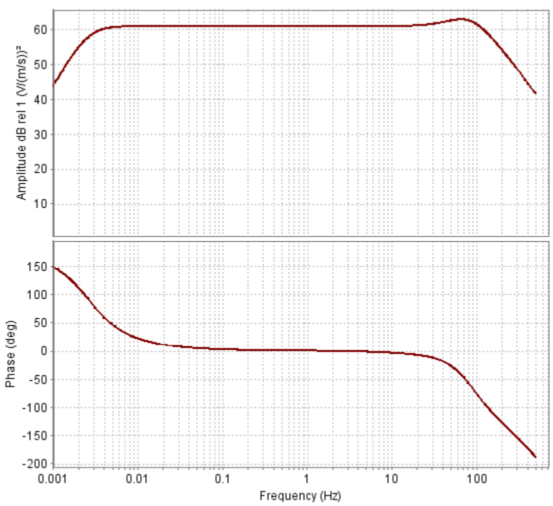
Poles:

-7100.0	1700.0
-7100.0	-1700.0
-4900.0	5200.0
-4900.0	-5200.0
-1260.0	0.0
-364.0	404.0
-364.0	-404.0
-142.0	0.0
-32.55	0.0
-0.036614	0.037059
-0.036614	-0.037059

Zeros:

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

Nanometrics Trillium 360 Seismometer



Sensitivity:
1,100 V·s/m at 1.0 Hz

Poles:

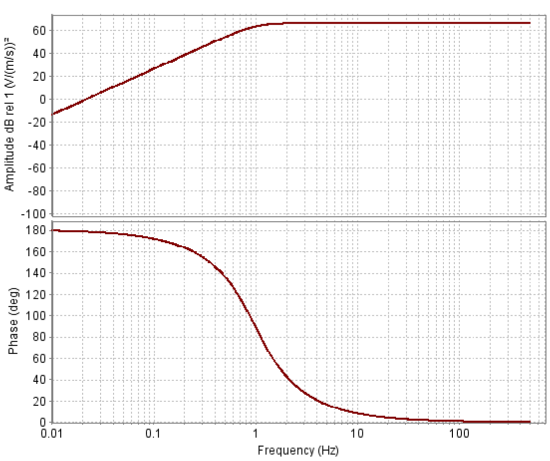
-7200.0	1700.0
-7200.0	-1700.0
-4900.0	5200.0
-4900.0	-5200.0
-1234.0	0.0
-360.0	405.0
-360.0	-405.0
-146.0	0.0
-0.01189	0.01189
-0.01189	-0.01189

Zeros:

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

A:
942.91505E12 MV·s/m

Geotech GS13 Seismometer



Sensitivity:
2,000 V·s/m at 5.0 Hz

Poles:

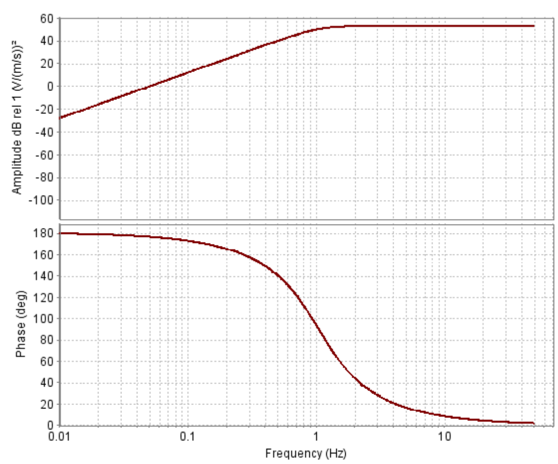
-4.443	4.443
-4.443	-4.443

Zeros:

0.0	0.0
0.0	0.0

A:
2,001.59953 V·s/m

Geotech GS21 Seismometer



Sensitivity:
418 V·s/m at 5.0 Hz

Poles:

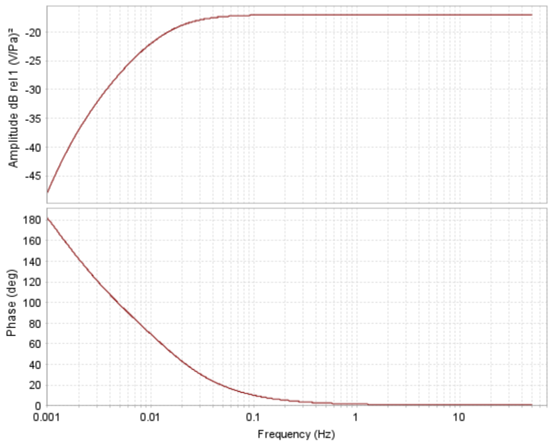
-4.4138	4.9251
-4.4138	-4.9251

Zeros:

0.0	0.0
0.0	0.0

A:
416.38503 V·s/m

Hyperion 5113A Infrasound Sensor



Sensitivity:
0.140000 V/Pa at 1.0 Hz

Poles:

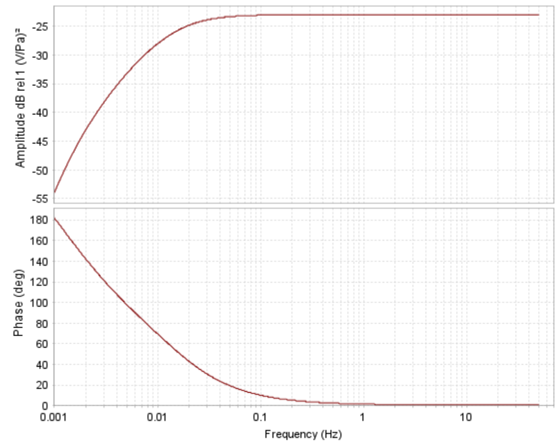
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
0.140015 V/Pa

Hyperion 5119A Infrasound Sensor



Sensitivity:
70 mV/Pa at 1.0 Hz

Poles:

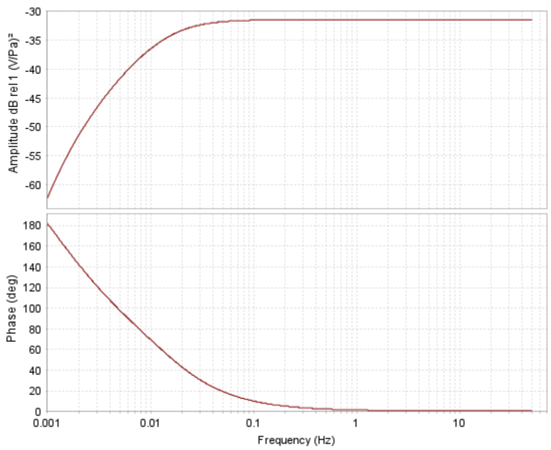
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
70.0077 mV/Pa

Hyperion 5313A Infrasound Sensor



Sensitivity:
26.6000 mV/Pa at 1.0 Hz

Poles:

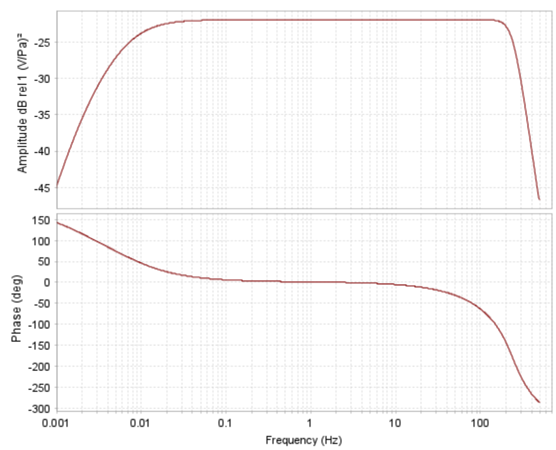
-0.09264	0.0
-0.01064	0.0
-0.004668	0.0

Zeros:

0.0	0.0
0.0	0.0
0.0	0.0

A:
26.6029 mV/Pa

Chaparral 64S Infrasound Sensor



Sensitivity:
80 mV/Pa at 1.0 Hz

Poles:

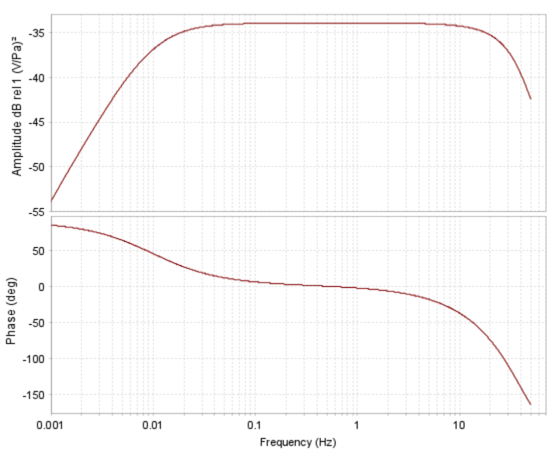
-62830.0	0.0
-1422.23	589.12
-1422.23	-589.12
-589.121	1422.23
-589.121	-1422.23
-0.045	0.0
-0.011	0.0

Zeros:

0.0	0.0
0.0	0.0

A:
28.228816E9 MV/Pa

MB2005 Infrasound Sensor



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

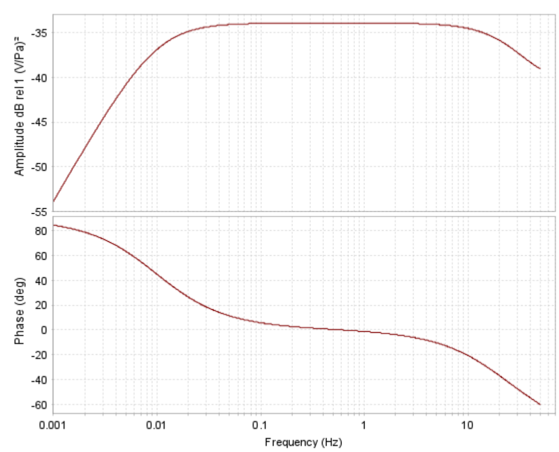
-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.06283	0.0

Zeros:

-468820.0	0.0
0.0	0.0

A:
466,950 MV/Pa

MB3a Infrasound Sensor



Sensitivity:
20 mV/Pa at 1.0 Hz

Poles:

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

Zeros:

-1156.25	0.0
0.0	0.0

A:
1,403.53 V/Pa

APPENDEX B: TESTBED CALIBRATIONS

Agilent 3458A # MY45048371

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

Calibration Certificate
Document #: 6652541_11864604

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	Geophysical Detection Programs 06752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1044
Date of Receipt	January 21, 2022
Dates Tested (Start – End)	May 03, 2022 - May 03, 2022
Date Approved	May 10, 2022
Calibration Expiration Date	May 03, 2023

Calibration Description

Calibration Lab	PSL-DC
Calibration Procedure, rev.	DC 3458 NEXT GEN, 1
Temperature	23 ± 1 °C
Humidity	40 ± 5 %RH
Barometric Pressure	NA mmHg
As Found Condition	NONCONFORM
As Left Condition	PASS-ADJ
Software Used	MET/CAL 10.1.0
Tamper Seal	None

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6652541_11864604

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

Calibration Results

This 3458A digital multimeter has been calibrated over a range of test points for resistance, DC voltage, DC current, AC voltage, AC current, and frequency. The measured values for each test point were observed to be within the manufacturer's stated 1-year specifications. In addition, the expanded measurement uncertainty intervals about the measured values were calculated to be within specification. All expanded uncertainties are given at *k (Coverage factor)* = 2.

Resistance

Range	Expanded Uncertainty
10 ohm	± (15 μΩ/Ω of reading + 5 μΩ/Ω of range)
100 ohm	± (12 μΩ/Ω of reading + 5 μΩ/Ω of range)
1k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
10k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
100k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
1M ohm	± (15 μΩ/Ω of reading + 2 μΩ/Ω of range)
10M ohm	± (50 μΩ/Ω of reading + 10 μΩ/Ω of range)
100M ohm	± (500 μΩ/Ω of reading + 10 μΩ/Ω of range)
1G ohm	± (0.5% of reading + 10 μΩ/Ω of range)

DC Voltage

Range	Expanded Uncertainty
100 mV	± (9(5) μV/V of reading + 3 μV/V of range)
1 V	± (8(4) μV/V of reading + 0.3 μV/V of range)
10 V	± (8(4) μV/V of reading + 0.05 μV/V of range)
100 V	± (10(6) μV/V of reading + 0.3 μV/V of range)
1000 V	± (10(6) μV/V of reading + 0.1 μV/V of range)
	Add 12 μV/V × $(Vin/1000)^2$ additional error for inputs > 100V

Note: (Expanded Uncertainty for Option 002).

DC Current

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Agilent 3458A # MY45048372

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

Calibration Certificate
Document #: 6652539_11870592

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	Geophysical Detection Programs 06752
Custodian	Merchant, Bion J.
Location	SNLNM/TA1/758/1042
Date of Receipt	April 27, 2022
Dates Tested (Start – End)	July 22, 2022 - July 22, 2022
Date Approved	July 28, 2022
Calibration Expiration Date	July 22, 2023

Calibration Description

Calibration Lab	PSL-DC
Calibration Procedure, rev.	EXTCAL, Commercial Calibration Lab (CCL)
Temperature	23 ± 1 °C
Humidity	40 ± 5 %RH
Barometric Pressure	NA mmHg
As Found Condition	NONCONFORM
As Left Condition	PASS-ADJ
Software Used	SEE CCL CERT
Tamper Seal	None

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

Calibration Results

This asset was calibrated by Keysight Technologies, Roseville, CA. Keysight is a PSL-approved Commercial Calibration Laboratory (CCL). The attached Certificate certifies that this unit has been calibrated using applicable Keysight Technologies procedures in compliance with ISO/IEC 17025:2017 and ANSI/NCSL Z540.1-1994 (2002). The Quality Management System is registered to ISO 9001:2015.

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HP 3458A # 2823A10915

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

Calibration Certificate
Document #: 41628_11874631

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	Geophysical Detection Programs 06752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1029
Date of Receipt	June 01, 2022
Dates Tested (Start – End)	August 01, 2022 - August 01, 2022
Date Approved	August 04, 2022
Calibration Expiration Date	August 01, 2023

Calibration Description

Calibration Lab	PSL-DC
Calibration Procedure, rev.	DC LAB 3458 NEXT GEN V2, 2
Temperature	23 ± 1 °C
Humidity	40 ± 5 %RH
Barometric Pressure	NA mmHg
As Found Condition	PASS
As Left Condition	PASS
Software Used	MET/CAL 10.1.0
Tamper Seal	None

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

Calibration Results

This 3458A Option 002 digital multimeter has been calibrated over a range of test points for resistance, DC voltage, DC current, AC voltage, AC current, and frequency. The measured values for each test point were observed to be within the manufacturer's stated 1-year specifications. In addition, the expanded measurement uncertainty intervals about the measured values were calculated to be within specification. All expanded uncertainties are given at *k(Coverage factor)* = 2.

Resistance

Range	Expanded Uncertainty
10 ohm	± (15 μΩ/Ω of reading + 5 μΩ/Ω of range)
100 ohm	± (12 μΩ/Ω of reading + 5 μΩ/Ω of range)
1k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
10k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
100k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
1M ohm	± (15 μΩ/Ω of reading + 2 μΩ/Ω of range)
10M ohm	± (50 μΩ/Ω of reading + 10 μΩ/Ω of range)
100M ohm	± (500 μΩ/Ω of reading + 10 μΩ/Ω of range)
1G ohm	± (0.5% of reading + 10 μΩ/Ω of range)

DC Voltage

Range	Expanded Uncertainty
100 mV	± (5 μV/V of reading + 3 μV/V of range)
1 V	± (4 μV/V of reading + 0.3 μV/V of range)
10 V	± (4 μV/V of reading + 0.05 μV/V of range)
100 V	± (6 μV/V of reading + 0.3 μV/V of range)
1000 V	± (6 μV/V of reading + 0.1 μV/V of range)
	Add 12 μV/V × $(Vin/1000)^2$ additional error for inputs > 100V

DC Current

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HP 3458A # 2823A06443

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

Calibration Certificate
Document #: 10992_11870575

Item Identification

Asset Number	10992
Description	Meter,Multifunction
Model	3458A
Serial #	2823A06443
Manufacturer	Hewlett Packard Co
Customer Asset Id	N/A
Purchase Order	N/A
Customer	Geophysical Detection Programs 06752
Custodian	Merchant, Bion J.
Location	SNLNM/TA1/758/1044
Date of Receipt	April 27, 2022
Dates Tested (Start – End)	May 04, 2022 - May 04, 2022
Date Approved	May 10, 2022
Calibration Expiration Date	May 10, 2023

Calibration Description

Calibration Lab	PSL-DC
Calibration Procedure, rev.	DC 3458 NEXT GEN, 1
Temperature	23 ± 1 °C
Humidity	40 ± 5 %RH
Barometric Pressure	NA mmHg
As Found Condition	PASS
As Left Condition	PASS
Software Used	MET/CAL 10.1.0
Tamper Seal	None

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

Calibration Results

This 3458A digital multimeter has been calibrated over a range of test points for resistance, DC voltage, DC current, AC voltage, AC current, and frequency. The measured values for each test point were observed to be within the manufacturer's stated 1-year specifications. In addition, the expanded measurement uncertainty intervals about the measured values were calculated to be within specification. All expanded uncertainties are given at *k (Coverage factor)* = 2.

Resistance

Range	Expanded Uncertainty
10 ohm	± (15 μΩ/Ω of reading + 5 μΩ/Ω of range)
100 ohm	± (12 μΩ/Ω of reading + 5 μΩ/Ω of range)
1k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
10k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
100k ohm	± (10 μΩ/Ω of reading + 0.5 μΩ/Ω of range)
1M ohm	± (15 μΩ/Ω of reading + 2 μΩ/Ω of range)
10M ohm	± (50 μΩ/Ω of reading + 10 μΩ/Ω of range)
100M ohm	± (500 μΩ/Ω of reading + 10 μΩ/Ω of range)
1G ohm	± (0.5% of reading + 10 μΩ/Ω of range)

DC Voltage

Range	Expanded Uncertainty
100 mV	± (9(5) μV/V of reading + 3 μV/V of range)
1 V	± (8(4) μV/V of reading + 0.3 μV/V of range)
10 V	± (8(4) μV/V of reading + 0.05 μV/V of range)
100 V	± (10(6) μV/V of reading + 0.3 μV/V of range)
1000 V	± (10(6) μV/V of reading + 0.1 μV/V of range)
	Add 12 μV/V × $(Vin/1000)^2$ additional error for inputs > 100V

Note: (Expanded Uncertainty for Option 002).

DC Current

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