SANDIA REPORT

SAND2018-10266
Unlimited Release
Printed September 2018

Next Generation Qualification: Geotech Instruments SMART24B Digitizer Evaluation

George W. Slad
B. John Merchant

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@osti.gov
Online ordering:	http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.gov
Online order:	http://www.ntis.gov/search

SAND2018-10266
Unlimited Release
September 2018

Next Generation Qualification: Geotech Instruments SMART24B Digitizer Evaluation

George Slad
B. John Merchant

Geophysics and
Ground-Based Monitoring R&E Departments
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0750

Abstract

Sandia National Laboratories has tested and evaluated a digitizer, the SMART24B, manufactured by Geotech Instruments, LLC. These digitizers are used to record sensor output for seismic and infrasound monitoring applications. The purpose of the digitizer evaluation was to measure the performance characteristics in such areas as power consumption, input impedance, sensitivity, full scale, self-noise, dynamic range, system noise, response, passband, and timing. The SMART24B is Geotech's datalogger intended for borehole deployment in their digitizer product line. The SMART24B is available with either 3 or 6 channels at 24 bit resolution. The digitizer is to be deployed in boreholes, therefore are a minimum number of connections required on the digitizer case as datalogger utilizes a distribution panel, mounted up-hole, serving to breakout power, GPS, serial communications and ethernet connections.

ACKNOWLEDGMENTS

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

CONTENTS

FIGURES

TABLES

NOMENCLATURE

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

1 INTRODUCTION

The evaluation of the two Geotech SMART24B digitizers, serial numbers 2314 and 2453, was performed to determine the performance characteristics of the instruments including sensitivity, self-noise, dynamic range, frequency response, and passband.

Figure 1 SMART24B Digitizer (photo courtesy of Geotech Insturments, LLC)

The SMART24 is a 3 or 6 channel, 24-bit digitizer with variable sample rate and gain level suitable in form-factor for equipment in a borehole or vault style seismic monitoring system deployment.

The evaluation of the two digitizers, serial numbers 2314 and 2453, performed against the digitizer specifications below, has identified that the digitizers' performance are consistent with their manufacturer's specifications. Digitizers serial numbers 2413 and 2453 are 3 channels units, both with 24 bits of resolution.

SMART-24 SERIES SPECIFICATIONS

DATA ACQUISITION

Number of inputs	3 or 6 channels
Input type	Balanced differential with transient protection suitable for both passive and active sensors
Input range	5Vp-p, 20Vp-p and 40Vp-p bipolar differential, 2x1 Mohm
Gain	Software selectable: x1, x2, x4, x8, x16, x32, x64
Common mode rejection	Greater than 90 dB
Digitizer	Over sampled 24-bit Delta Sigma ADC with digital signal processing, 1 per channel
Anti-alias filter	Brickwall digital FIR filter, cutoff at 80% of and 130 dB down at output Nyquist frequency. Causal filter optional.
Dynamic range	Up to 138 dB @ 100 sps
Intermodulation distortion	Less than –110 dB
Sample rates	1, 5, 10, 20, 40, 50, 100, 125, 200, 250, 500, 1000, 2000 sps primary sample rates
Noise	~1 count RMS at up to 200 sps

ACQUISITION MODES

Continuous	User selected start time, ring buffer or until storage full
Timed	16 user programmable recording windows
Triggered	Threshold, STA/LTA (updating or non-updating), and external
Pre-event length	Up to 32,768 data samples
Post-event length	Up to remaining data storage
On board memory	192 MB

DATA STORAGE (SMART-24R® ONLY)

Type	Up to 240 GB hard disk, up to 64 GB industrial grade Compact Flash memory, 1 or 2 partitions
Recording format	Standard FAT32 file system, drives readable directly on a PC, format converters available for 32-bit SUDS, SAC, SEG-Y, SEISAN, MatLab, miniSEED, CSS3.0 and SEED

INTERNAL RECORDING (ALL VERSIONS)

Option for two PC Card slots for Compact Flash storage, non-removable, accessible by any ftp client.

TIMING

TIMING	Voltage controlled TCXO with optional external GPS synch.
Accuracy	<±10 microseconds of UTC with GPS lock
Stability	0.5 PPM (when unlocked)
GPS duty cycle	User programmable GPS power on/off cycle times

INTERFACES

Indicators	Large graphic LCD, protected
Communications	2xRS232, Ethernet, USB2.0 for the removable enclosure
GPS	Dedicated RS-422 serial port
Power	Main power and external battery
Other I/O	5 or 8 12-bit analog inputs, external trigger in/out, 1 PPS in/out
Calibration	Pulse, sine wave, white noise, random binary, step functions, and shorted input
Telemetry	- CD1.1 protocol, 4 independent profiles to 4 different IP servers; - Earthworm protocol on 1 profile; - 64MB internal buffer for backfill; - continuous, events only or both

POWER

Input	10 to 16 VDC
Power consumption	~1 watt average (3 channels @ 100 sps and GPS power cycling)

PHYSICAL

Construction	Rugged machined or extruded Aluminum case, all IP67
Size	11.2 in (284 mm) w x 12.3 in (312 mm) l x 2.9 in (74 mm) h
Weight (24D only)	7.9 lbs (3.6 kg)
Operating temperature	-20°C to +70°C
Humidity	0 to 100% (IP67)

Removable enclosures

AUGUST 2014/ DS-SMART-24®

SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE

Figure 2 Geotech Instuments, LLC, SMART24B Specifications

2 TEST PLAN

2.1 Test Facility

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

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

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

The majority of the SMART24B testing, with the exception of tests performed in the temperature chamber, were performed within the FACT sites underground bunker due to the bunker's stable temperature.

Figure 3 FACT Site Bunker

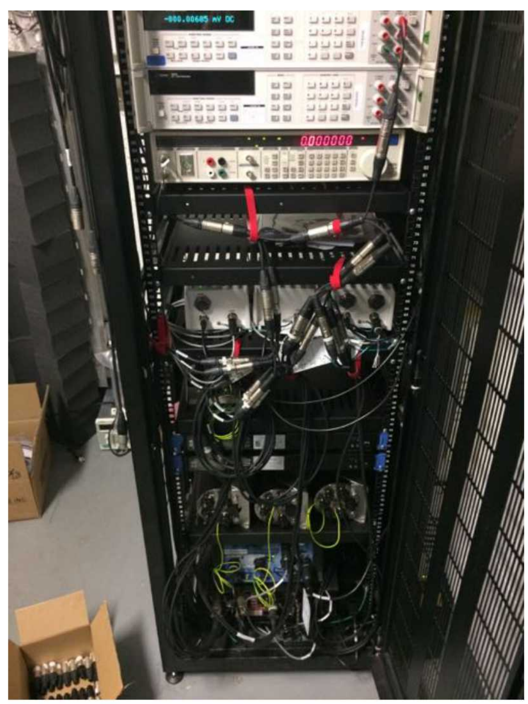

Figure 4 Partial View of Testbed in FACT Site Bunker

The temperature was maintained between 22 and 27 degrees Celsius within the bunker, tending to be on the higher end of the range during the test period of these digitizers.

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

Figure 5 GPS Re-broadcaster

The Guralp Systems digitizers were powered off of a Protek 3005B laboratory power supply providing approximately 13.0 Volts.

Figure 6 Laboratory Power Supply

2.2 Scope

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

Table 1 Tests Performed

Test	Configuration
Input Impedance DC Accuracy AC Accuracy AC Full Scale AC Clip Total Harmonic Distortion (THD) Input Terminated Noise Crosstalk Common Mode Rejection Analog Bandwidth Relative Transfer Function Response Incoherent Noise Time Tag Statistics	SMART24B digitizers: serial numbers 2314 and 2453 40 Vpp input, gain 16x, sample rate 200 sps (100 sps for Analog Band Width, Relative Transfer Function, Response and THD) temperature: 23° C

2.3 Timeline

Testing of the Geotech Instruments digitizers was performed at Sandia National Laboratories between August and September 2018. Testing was performed using SMART24B digitizers, serial numbers 2314 and 2453, in the bunker.

2.4 Evaluation Frequencies

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

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

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

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

3 TEST EVALUATION

3.1 Power Consumption

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

3.1.1 Measurand

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

3.1.2 Configuration

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

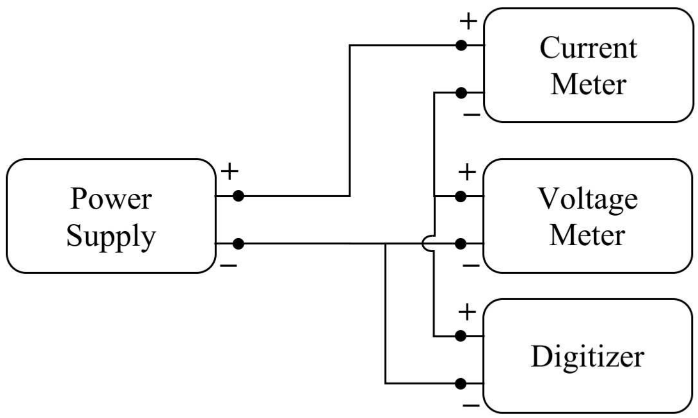

Figure 7 Power Consumption Configuration Diagram

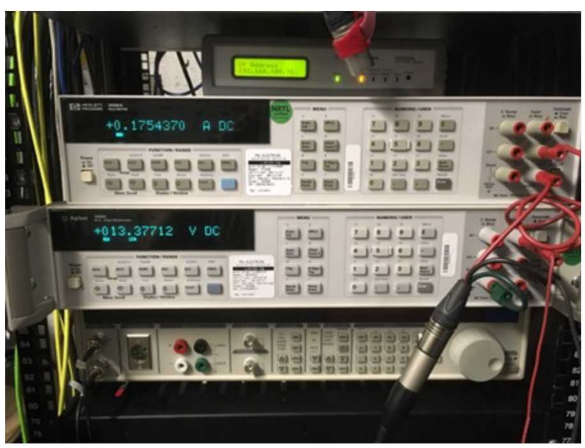

Figure 8 Power Consumption Configuration Picture

Table 2 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
Power Supply	Protek 3005B	AC2074	13.0 V
Current Meter	Agilent 3458A	MY45048371	Amps
Voltage Meter	Agilent 3458A	2823A10915	100 V full scale

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

3.1.3 Analysis

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

$$V \text{ and } I$$

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

$$P = V * I$$

3.1.4 Result

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

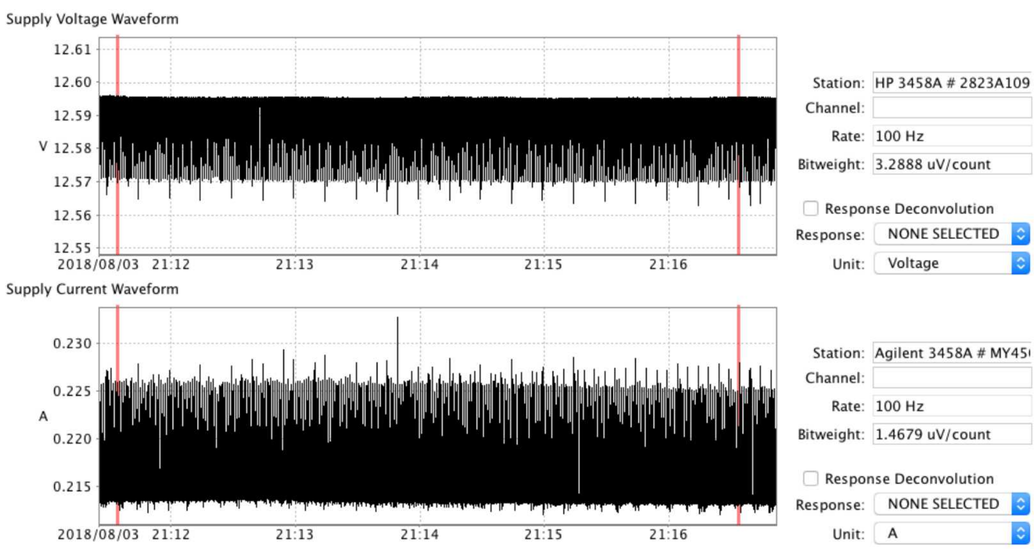

Figure 9 Voltage and Current Recorded Time Series, SMART24B 2314

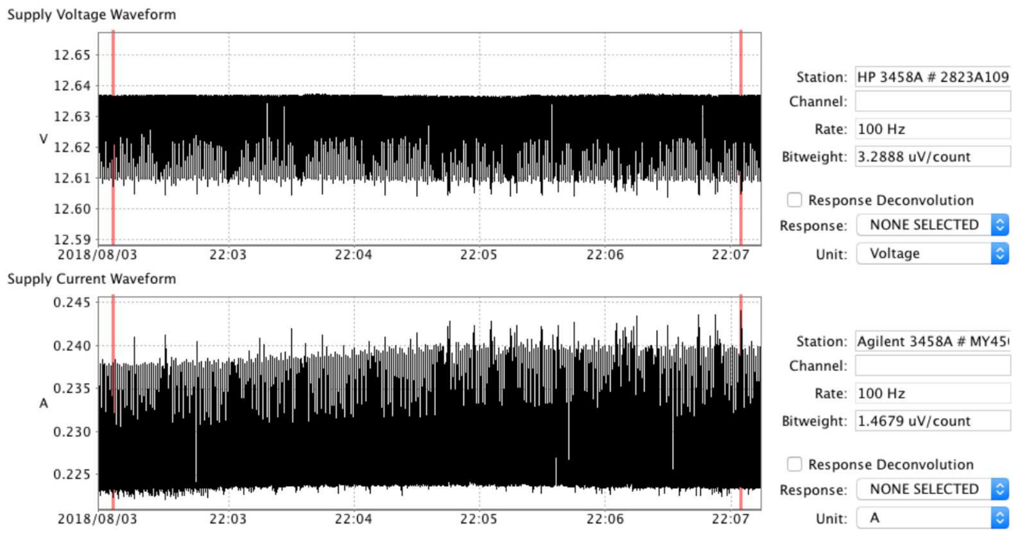

Figure 10 Voltage and Current Recorded Time Series, SMART24B 2453

Table 3 Power Consumption Results

DWR	Supply Voltage	Supply Voltage SD	Supply Current	Supply Current SD	Power Consumption	Power Consumption SD
2453	12.59 V	5.66 mV	0.2149 A	2.796 mA	2.706 W	36.44 mW
2314	12.63 V	7.76 mV	0.2266 A	4.351 mA	2.863 W	56.75 mW

The SMART24B digitizers were observed to consume between 2.706 watts and 2.863 watts of power during operation. Power requirements may increase momentarily beyond that shown.

The average observed power consumption of 2.78 W is significantly higher than the ~1 W provided in the datasheet, however the manufacturer's power consumption specification is with respect to power-cycled GPS receiver operation and ethernet inactive, rather than the tested configuration where the GPS receiver is on continuously and ethernet is active as data are streamed to the SMARTGeoHub system.

3.2 Input Impedance

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

3.2.1 Measurand

The quantity being measured is ohms of impedance.

3.2.2 Configuration

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

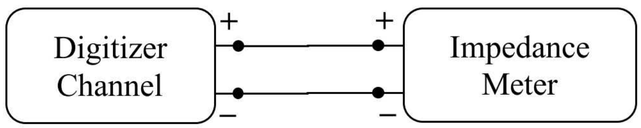

Figure 11 Input Impedance Configuration Diagram

Figure 12 Input Impedance Configuration Picture

Table 4 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Impedance Meter - Bunker	Agilent 3458A	2823A08050	DC Impedance

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 taken from the meter, preferably from a time-series recording.

3.2.4 Result

The measured impedance for each of the digitizer channels while operating in a 23°C environment with a gain of 16x are shown in the table below.

Table 5 Input Impedance Results, Both DWRs (Gain 16x)

DWR	Channel 1	Channel 2	Channel 3
2314	1.168 Mohm	2.129 Mohm	2.129 Mohm
2453	1.168 Mohm	2.129 Mohm	2.129 Mohm

Both dataloggers remained had measured input impedances on channel 1 of 17% over the specified 1 Mohm impedance; channels 2 and 3 over twice the manufacturer's stated impedance.

3.3 DC Accuracy

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

3.3.1 Measurand

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

3.3.2 Configuration

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

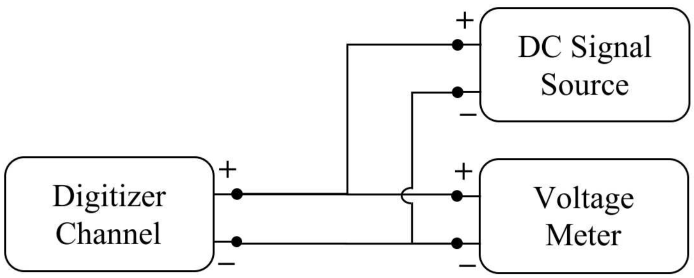

Figure 13 DC Accuracy Configuration Diagram

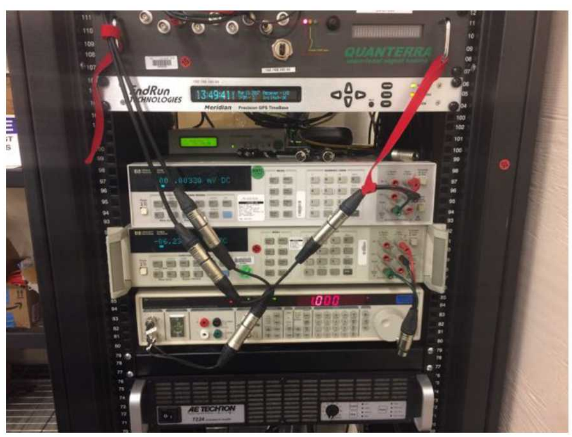

Figure 14 DC Accuracy Configuration

Table 6 DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - Bunker	Agilent 3458A	MY45048371	1 V full scale

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

The meter and the digitizer channel record the described DC voltage signal simultaneously. The recording made on the meter is used as the reference for comparison against the digitizer channel. The meter is configured to record at 100 Hz.

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

3.3.3 Analysis

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

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

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

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

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

The digitizer bit weight in Volts/count is computed:

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

3.3.4 Result

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

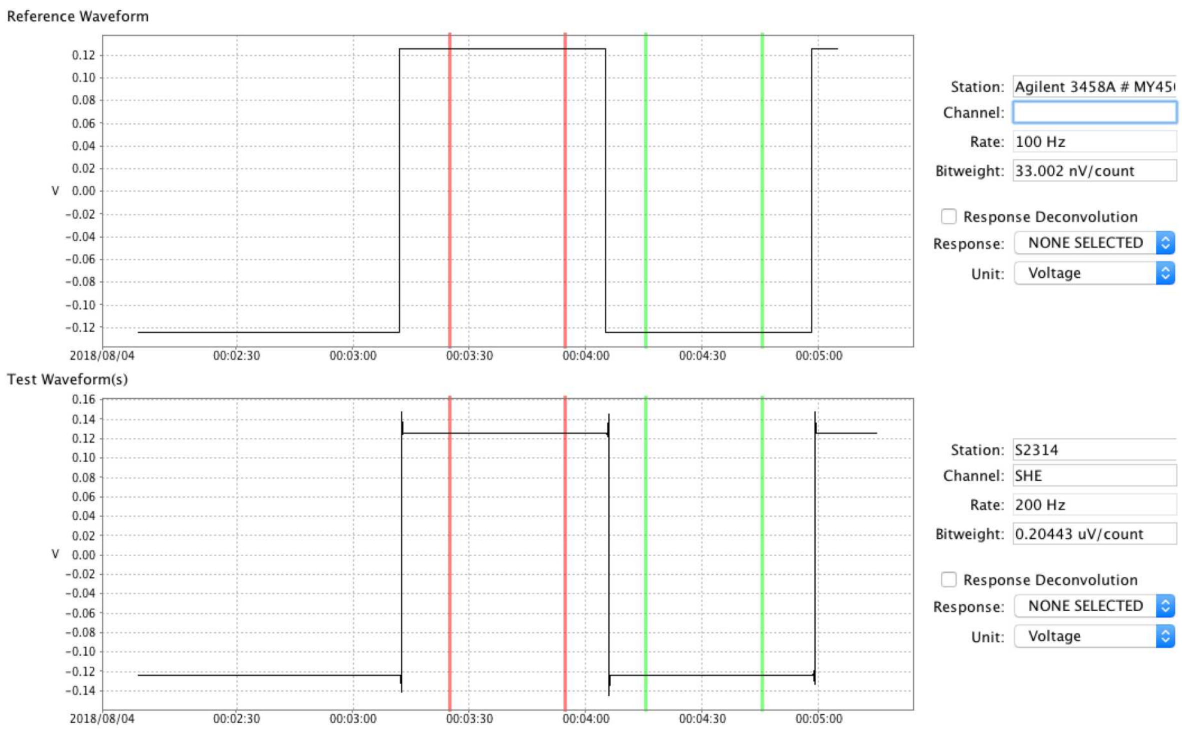

Figure 15 DC Accuracy Test Time series, SMART24B 2314, Channel SHE (Channel 3)

The following tables provide the bitweights, as provided by the manufacturer for each datalogger, and the computed bit weights for each of the channels, at a gain of 16x.

Table 7 Geotech-Provided Bitweights for each DWR (Gain 16x)

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	0.2039 uV/count	0.2045 uV/count	0.2042 uV/count
2453	0.2044 uV/count	0.2044 uV/count	0.2042 uV/count

Table 8 DC Accuracy Bitweight, Both DWRs (Gain 16x)

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	0.2044 uV/count	0.2048 uV/count	0.2044 uV/count
2453	0.2044 uV/count	0.2048 uV/count	0.2048 uV/count

Bit weights of both dataloggers remained very close to the manufacturer-provided bitweights, from 0.00% to 0.29% of the provided values.

3.4 AC Accuracy

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

3.4.1 Measurand

The quantity being measured is the digitizer input channels bitweight in volts/count and DC offset in volts.

3.4.2 Configuration

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

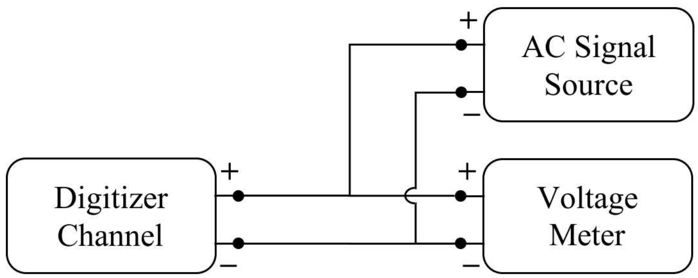

Figure 16 AC Accuracy Configuration Diagram

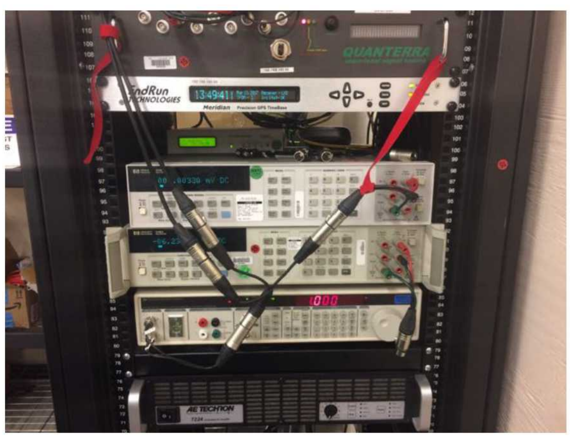

Figure 17 AC Accuracy Configuration Picture

Table 9 AC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - Bunker	Agilent 3458A	MY45048371	1 V full scale

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

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

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

3.4.3 Analysis

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

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

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

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

The digitizer bit weight in Volts/count is computed:

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

3.4.4 Result

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

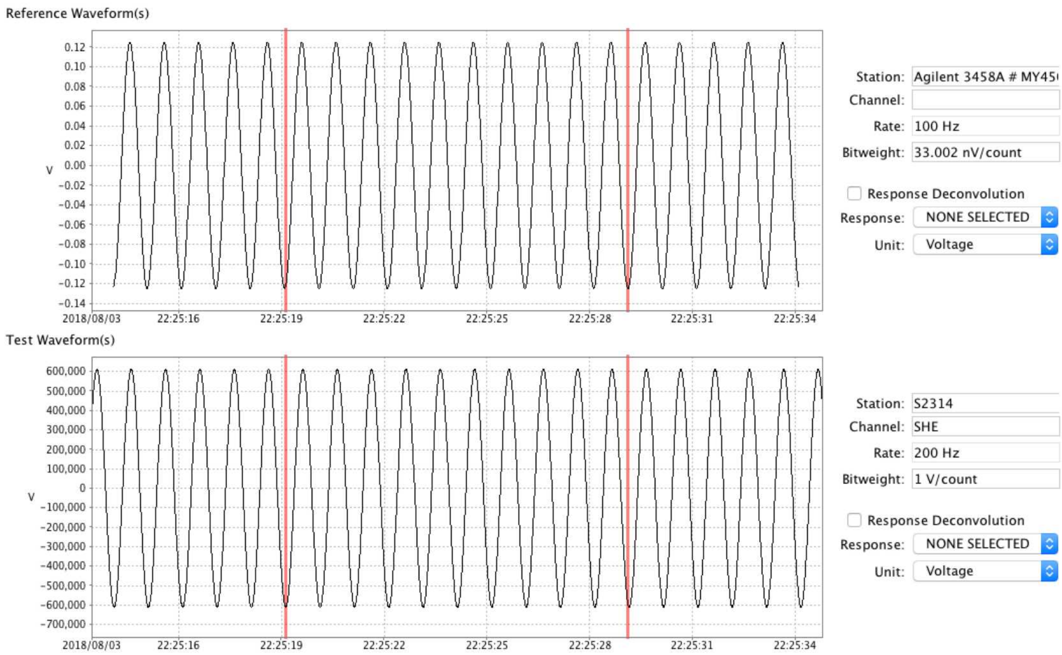

Figure 18 AC Accuracy Time Series

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

Table 10 AC Accuracy Bitweight, both DWRs (Gain 16x)

DWR	SHE (Channel 3)	SHN (Channel 2)	SHE (Channel 1)
2314	0.2044 uV/count	0.2048 uV/count	0.2044 uV/count
2453	0.2044 uV/count	0.2048 uV/count	0.2048 uV/count

As with DC Accuracy Tests, bitweights remained very near the respective manufacturer-provided bitweight, not diverging more than 0.29% from the respective manufacturer-provided bitweight found in Table 7.

3.5 Input Shorted Offset

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

3.5.1 Measurand

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

3.5.2 Configuration

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

Figure 19 Input Shorted Offset Configuration Diagram

Figure 20 Input Shorted Offset Terminators Picture

Table 11 Input Shorted Offset Testbed Equipment

Digitizer	Resistor load
Guralp Systems SMART24B	9.4 kOhm (2x4.7 kOhm)

Approximately 7 hours of data are recorded for tests of both units at 23° C.

3.5.3 Analysis

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

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

The mean value, in volts, is evaluated:

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

3.5.4 Result

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

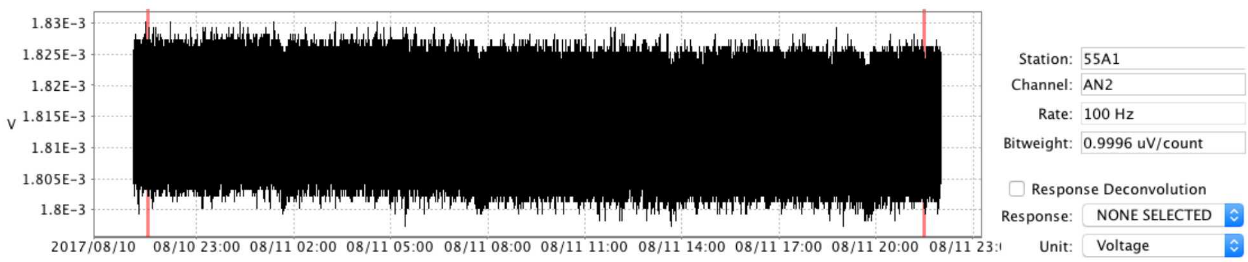

Figure 21 Input Shorted Offset Time Series

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

Table 12 Input Shorted Offset, both DWRs

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	-29.45 uV	-5.47 uV	-33.44 uV
2453	-40.32 uV	20.23 uV	-33.38 uV

The maximum offset observed across dataloggers is -0.0034% of full-scale (1.25 V at 16x gain), observed on datalogger 2453, channel SHE (channel 3).

3.6 AC Full Scale

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

3.6.1 Measurand

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

3.6.2 Configuration

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

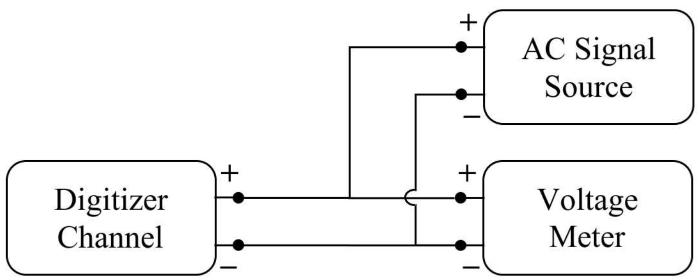

Figure 22 AC Full Scale Configuration Diagram

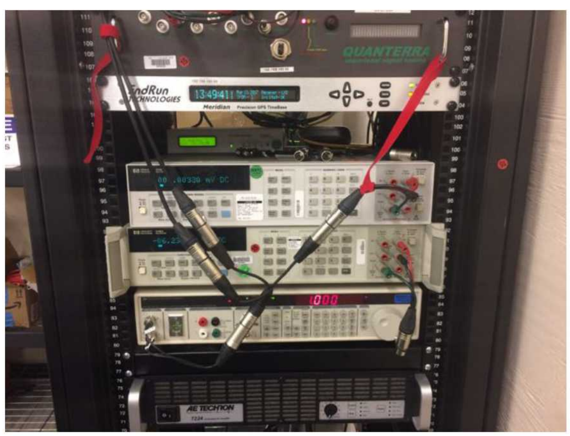

Figure 23 AC Full Scale Configuration Picture

Table 13 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - SB1	Agilent 3458A	MY45048371	1 V full scale

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

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

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

3.6.3 Analysis

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

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

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

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

3.6.4 Result

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

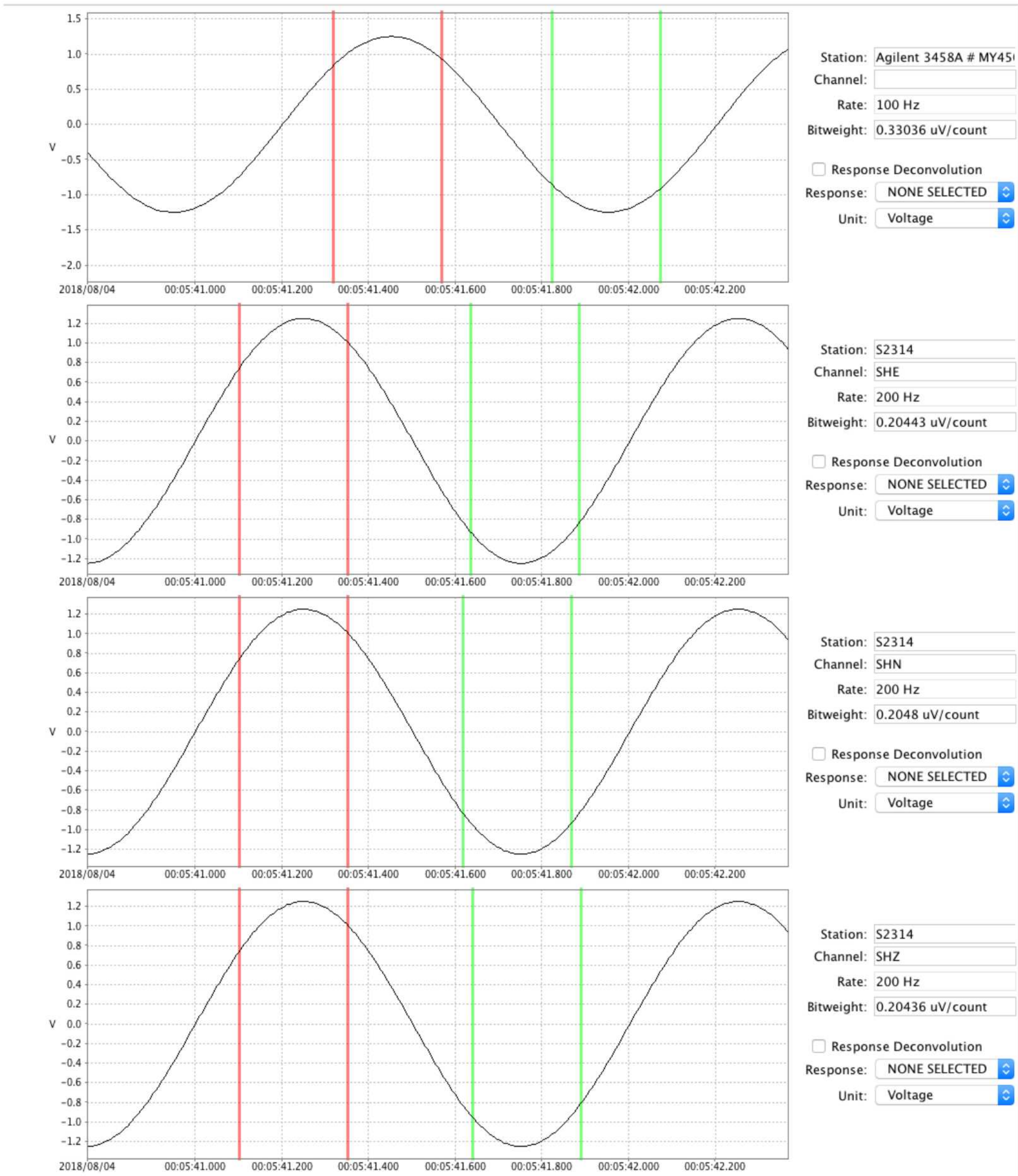

Figure 24 AC Full Scale Time Series, SMART24B 2314

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

Table 14 AC Full Scale Positive Peak

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	1.2477 V	1.2477 V	1.2477 V
2453	1.2478 V	1.2478 V	1.2477 V

Table 15 AC Full Scale Negative Peak

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	-1.2506 V	-1.2506 V	-1.2507 V
2453	-1.2507 V	-1.2507 V	-1.2507 V

Table 16 AC Full Scale Peak-to-Peak

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	2.4983 V	2.4983 V	2.4984 V
2453	2.4985 V	2.4985 V	2.4984 V

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

3.7 Self-Noise

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

3.7.1 Measurand

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

3.7.2 Configuration

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

Figure 25 Self Noise Configuration Diagram

Figure 26 Self Noise Configuration Picture

Table 17 Self Noise Testbed Equipment

	Impedance
resistor	9.4 kOhm (2x4.7 kOhm)

24 hours of data are generally utilized for this test.

3.7.3 Analysis

The measured bit-weight at 1 Hz, from Section 3.4, AC Accuracy, 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 Hann window of length 4k, 8k, and 16k for the 20 Hz, 40 Hz, and 100 Hz sample rates, respectively. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation pass-band of 0.01 Hz and the 90% confidence interval is less than 0.5 dB.

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

Over frequencies (in Hertz):

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

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

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

Where:

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

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

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

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

3.7.4 Result

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

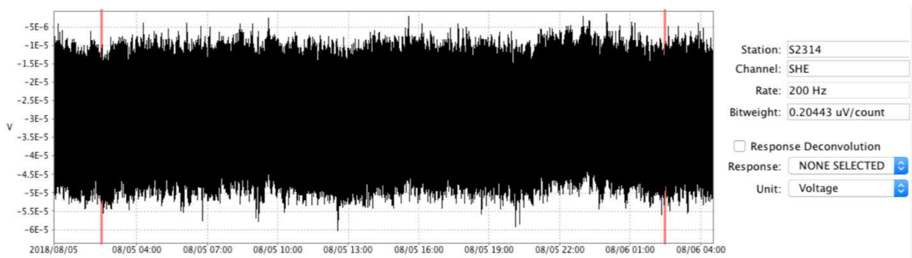

Figure 27 Self Noise Time Series Example, SMART24B 2314, SHE (Channel 3)

The computed self noise of all dataloggers while exposed to 23° C follows. The data window is 24 hrs long and the computation has 90% confidence level of 0.43 dB in each case.

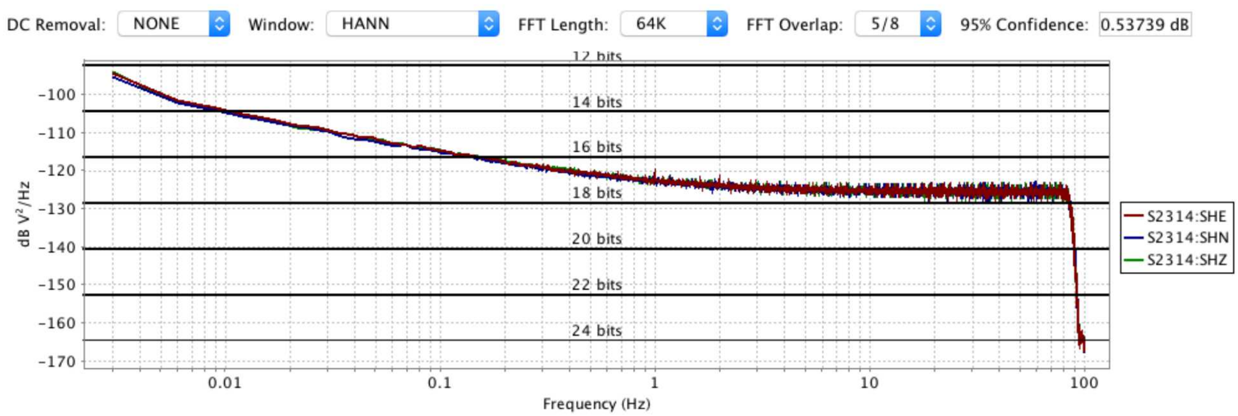

Figure 28 Self Noise Power Spectra SMART24B 2314, 200 sps

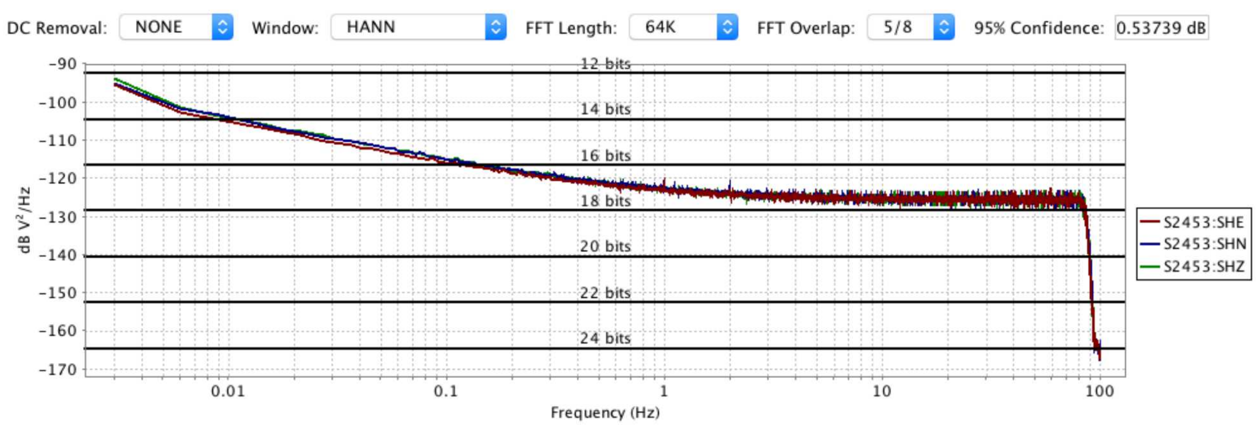

Figure 29 Self Noise Power Spectra SMART24B 2453, 200 sps

Channels SHE and SHZ on datalogger 2314 have slightly increased noise over that of SHN in mid-period band, from approximately 0.21 Hz to 0.37 Hz Hz, as much as 0.9 dB at 0.33 Hz. Otherwise the digitizer self noise power spectra are essentially uniform, to least the 95% confidence interval of the measurement.

Channel SHN and SHZ on datalogger 2453 have slightly increased noise over that of SHE below 0.2 Hz, as much as 1.2 dB at 0.27 Hz.

The plots' comparison of self-noise to bits of resolution illustrate the disadvantage of increasing a digitizer's gain to capture desired signals from a sensor, rather than installing a pre-amplifier in series with the sensor to utilize the full voltage range of the digitizer (40 Vpp).

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

Table 18 Self Noise RMS over 0.02 Hz – 1 Hz, both DWRs

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	1.1832 uV rms	1.1244 uV rms	1.1774 uV rms
	5.79 counts rms	5.49 counts rms	5.76 counts rms
2453	1.0679 uV rms	1.1673 uV rms	1.1719 uV rms
	5.23 counts rms	5.70 counts rms	5.72 counts rms

Table 19 Self Noise RMS over 0.5 Hz – 16 Hz, both DWRs

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	2.2224 uV rms	2.1948 uV rms	2.2170 uV rms
	10.87 counts rms	10.72 counts rms	10.85 counts rms
2453	2.1697 uV rms	2.2191 uV rms	2.2065 uV rms
	10.62 counts rms	10.84 counts rms	10.78 counts rms

Table 20 Self Noise RMS over 0.02 Hz – 16 Hz, both DWRs

DWR	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	2.4528 uV rms	2.4045 uV rms	2.4448 uV rms
	12.00 counts rms	11.74 counts rms	11.96 counts rms
2453	2.3606 uV rms	2.4443 uV rms	2.4357 uV rms
	11.55 counts rms	11.94 counts rms	11.89 counts rms

Average self noise over all channels are as follows: over the low passband 1.1487 uV rms (~6 counts rms), over the high passband 2.4238 uV rms (~12 counts rms) and over the broad passband 2.2049 uV rms (~11 counts rms).

Self noise values remained relatively consistent within the high and broad passbands, within 1.60% and 2.61% of the average across all dataloggers and channels respectively, however over the low passband self noise estimates varied more, as much as 7.03%.

3.8 Dynamic Range

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

3.8.1 Measurand

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

3.8.2 Configuration

There is no test configuration for the dynamic range test.

The full scale value used for the largest signal comes from the manufacturer's nominal specifications, validated in section 3.6, AC Full Scale. The value for the smallest signal comes from the evaluated digitizer channel self noise determined in section 3.7, Self Noise.

3.8.3 Analysis

The dynamic range over a given pass-band is:

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

Where

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

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

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

3.8.4 Result

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

Table 21 Dynamic Range, Both DWRs

DWR	Passband	SHE (Channel 3)	SHN (Channel 2)	SHZ (Channel 1)
2314	20 mHz - 1 Hz	120.19 dB	120.63 dB	120.23 dB
	20 mHz - 16 Hz	113.86 dB	114.03 dB	113.88 dB
	0.5 Hz - 16 Hz	114.71 dB	114.82 dB	114.73 dB
2453	20 mHz - 1 Hz	121.08 dB	120.31 dB	120.27 dB
	20 mHz - 16 Hz	114.19 dB	113.89 dB	113.92 dB
	0.5 Hz - 16 Hz	114.92 dB	114.73 dB	114.78 dB

The observed dynamic range values across all dataloggers and channels, recording at a gain of 16x while exposed to 23° C, were between 120.19 dB and 121.08 dB over the 0.02 Hz to 1.0 Hz passband, 114.71 dB and 114.92 dB over the 0.5 Hz to 16 Hz passband and 113.86 dB and 114.19 dB over the 0.02 Hz and 16 Hz passband.

Observed dynamic range values were relatively tightly clustered around their average. The most variation in dynamic range occurred over the 0.02 Hz to 1.0 Hz passband, where variations were as high as 0.52% from the average of 120.45 dB for the passband; over the 0.5 Hz to 16 Hz passband, dynamic ranges varied 0.12% from 114.78 dB, the average over this passband; and finally, over the broad passband, 0.02 Hz and 16 Hz, variations were within 0.20% of the average of 113.96 dB over the broad passband.

3.9 System Noise

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

3.9.1 Measurand

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

3.9.2 Configuration

There is no test configuration for the dynamic range test.

The time-series data and PSD are obtained from the evaluated digitizer channel self noise determined in Section 3.7, Self Noise, are corrected for a desired sensor's amplitude response model. The resulting PSD in the sensor's geophysical unit is then compared against an application requirement or background noise model to determine whether the resulting system noise meets the requirement.

3.9.3 Result

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

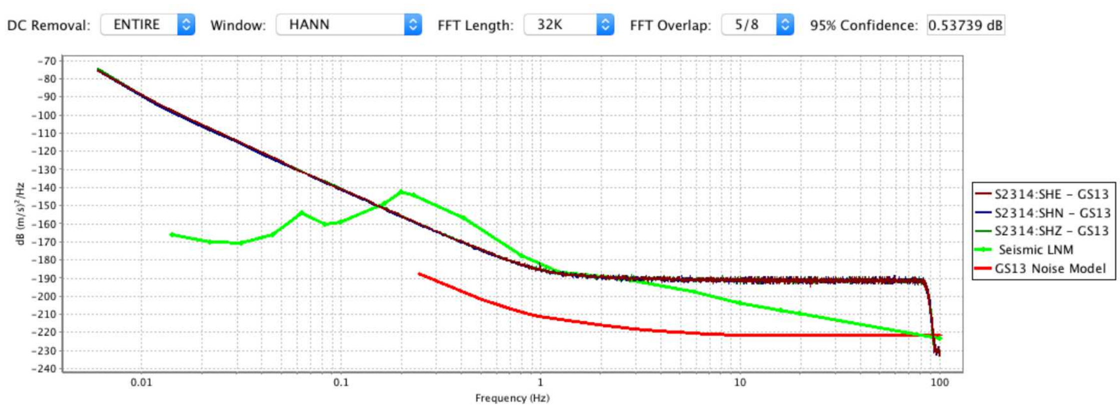

Figure 30 Seismic System Noise SMART24B 2314

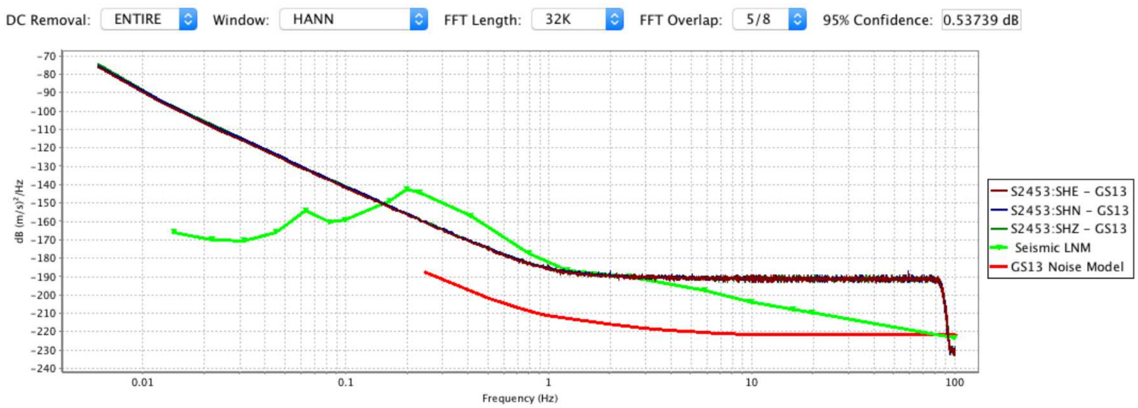

Figure 31 Seismic System Noise SMART24B 2453

Equivalent seismic system noise of both SMART24B dataloggers recording at a gain of 16x exceeds the self-noise models of the GS-13 over the entire spectrum of interest. This result brings to mind the relevance of utilizing a pre-amplifier in series with the GS-13 and reducing the gain of the digitizer to improve equivalent seismic system noise.

3.10 Response Verification

The Response Verification test measures the amplitude and phase response versus frequency that is present on the digitizer channels, relative to a reference channel.

3.10.1 Measurand

The quantity being measured is the unit-less relative amplitude and relative phase in degrees versus frequency for each digitizer channel relative to the first channel.

3.10.2 Configuration

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

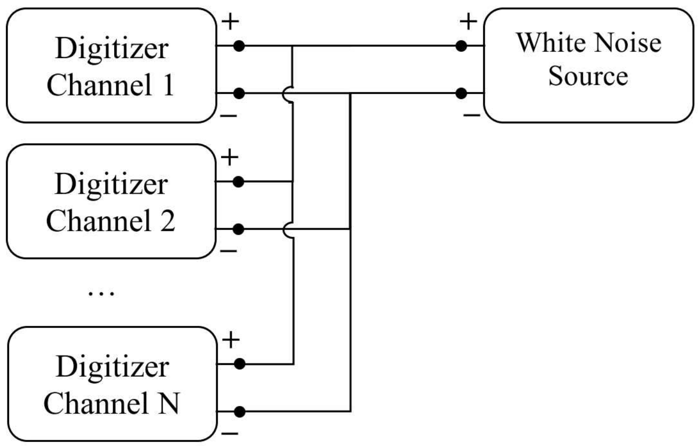

Figure 32 Response Verification Configuration Diagram

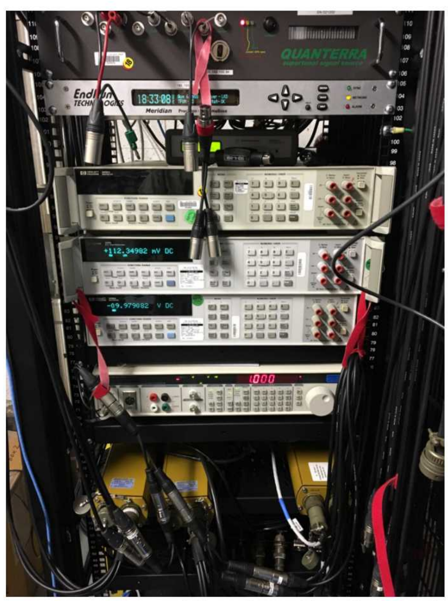

Figure 33 Response Verification Configuration Picture

Table 22 Response Verification Testbed Equipment

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

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

3.10.3 Analysis

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

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

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

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

3.10.4 Result

The coherence and relative amplitude and phase response were computed between channel 1 and the remaining two channels for all of the evaluated sample rate and gain configurations utilizing a 7 hour window of data.

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

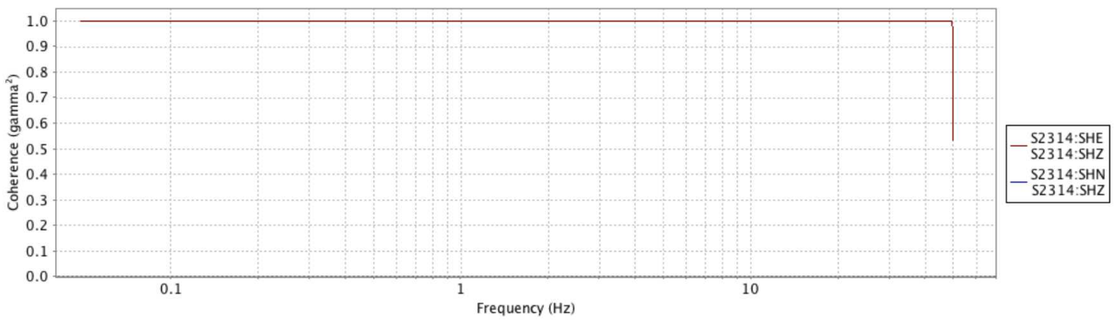

Figure 34 White Noise Coherence SMART24B 2314

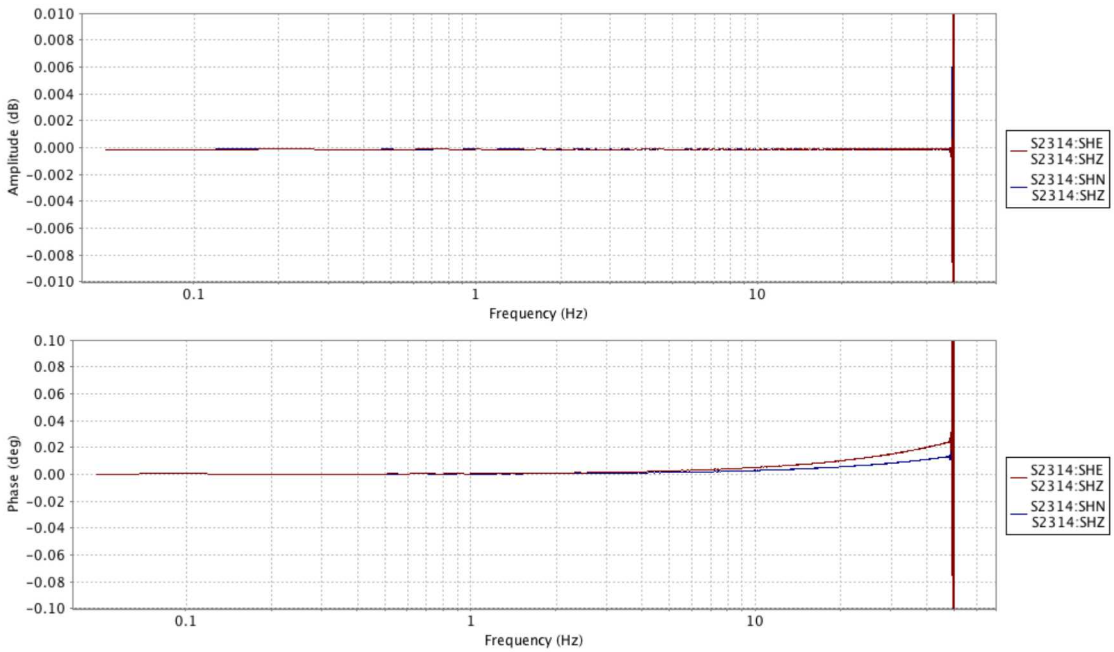

Figure 35 Relative Magnitude and Phase SMART24B 2314

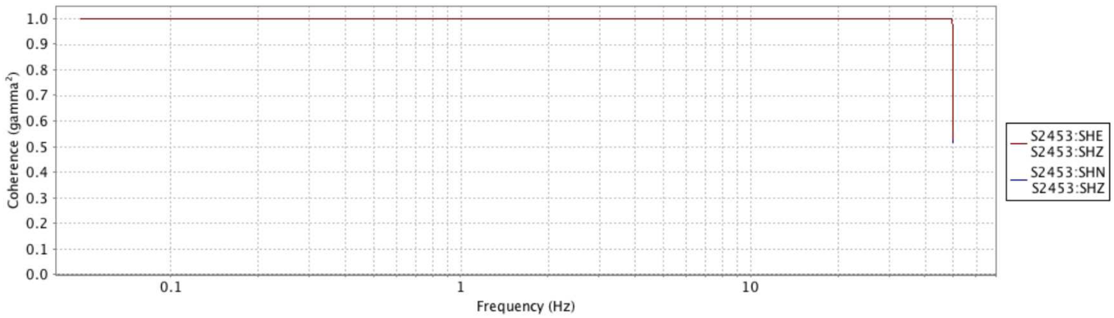

Figure 36 White Noise Coherence SMART24B 2453

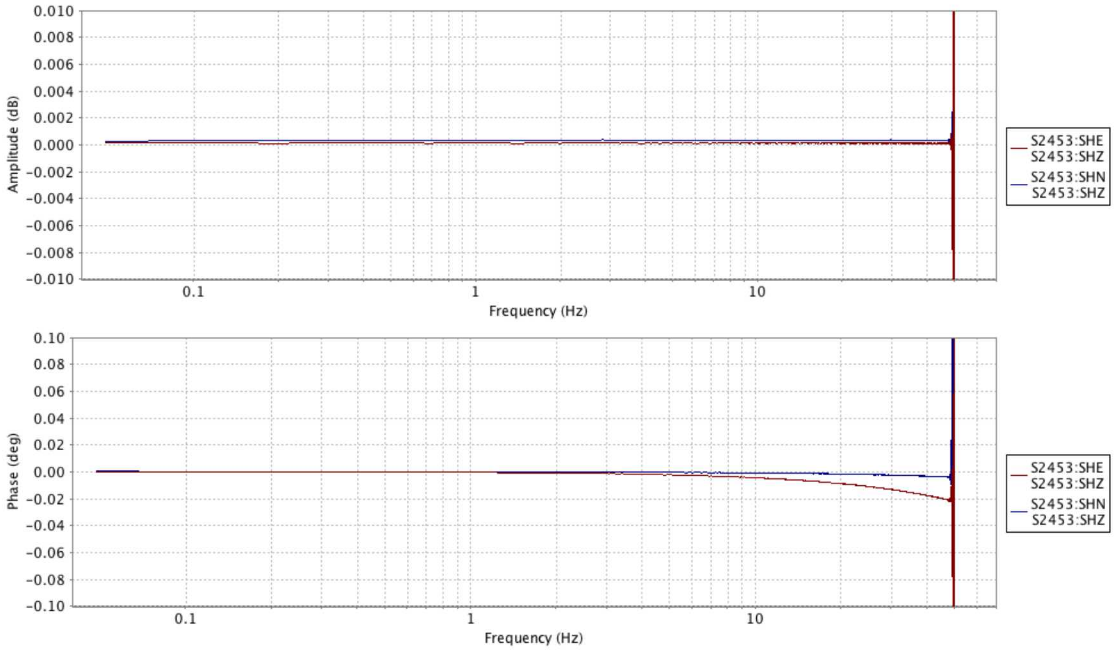

Figure 37 Relative Magnitude and Phase SMART24B 2453

The coherence was identically 1.0 across the pass-band for each datalogger. Amplitude differences were very small across channels (< 0.001 dB). Phase differences were also very small (<0.05°), with some variation in the amount of the roll-off between channels. This roll-off in phase may be attributed to slight differences in timing, which will be investigated further in the

Relative Transfer Function section.

3.11 Relative Transfer Function

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

3.11.1 Measurand

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

3.11.2 Configuration

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

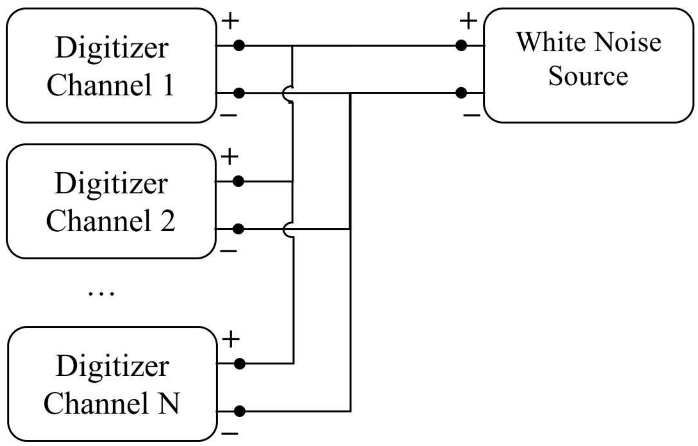

Figure 38 Relative Transfer Function Configuration Diagram

Table 23 Relative Transfer Function Testbed Equipment

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

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

3.11.3 Analysis

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

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

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

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

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

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

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

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

3.11.4 Result

The phase delay versus frequency is shown for evaluated sample rate (100 sps). To the extent that the delay is a constant time offset, the phase delay is observed to be linear with respect to frequency.

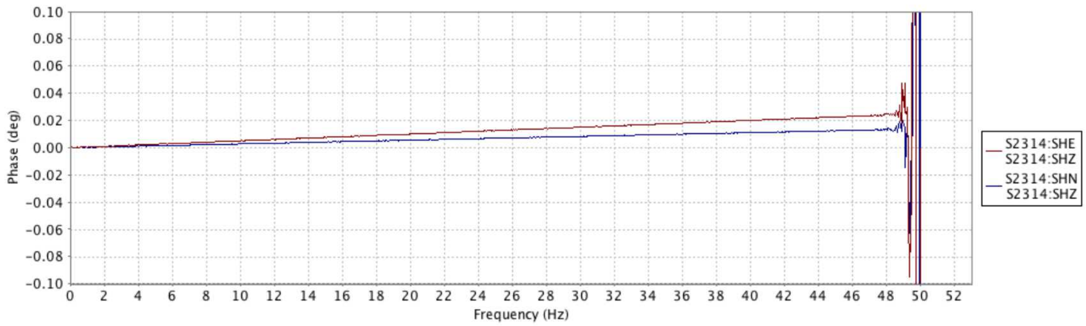

Figure 39 Relative Transfer Function, SMART24B 2314

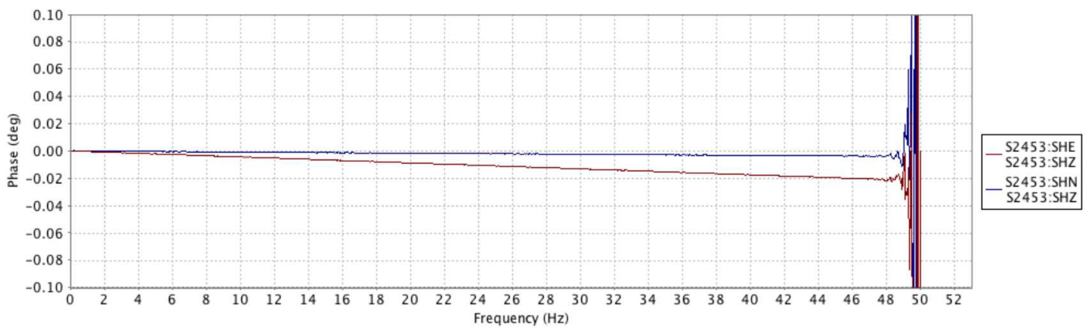

Figure 40 Relative Transfer Function, SMART24B 2453

Phase delays are linear with respect to frequency for both dataloggers. The constant channel-to-channel timing skew corresponding to these phase delays is shown in the tables below.

Table 24 Relative Transfer Function Timing Skew

DWR	SHE (channel 3)	SHN (channel 2)
2314	1.22 us	0.52 us
2453	-1.22 us	-0.22 us

Timing skews were consistently of larger in absolute magnitude for the SHE channels relative to the SHN channels. Absolute values of the timing skews did not exceed 1.22 microseconds.

3.12 Analog Bandwidth

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

3.12.1 Measurand

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

3.12.2 Configuration

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

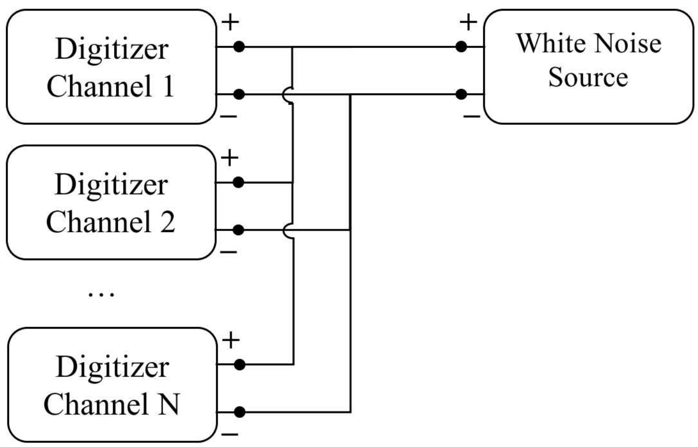

Figure 41 Analog Bandwidth Configuration Diagram

Table 25 Analog Bandwidth Testbed Equipment

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

The white noise source is configured to generate a band-width limited white noise voltage with an amplitude equal to approximately 10% of the digitizer input channel's full scale. One hour data recordings were utilized for the evaluation across all dataloggers and for evaluations at select temperatures, gains and sample rates, respectively.

3.12.3 Analysis

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

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

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

3.12.4 Result

The power spectra of the white noise signal recorded on the SMART24B digitizer channels are shown in the plots below.

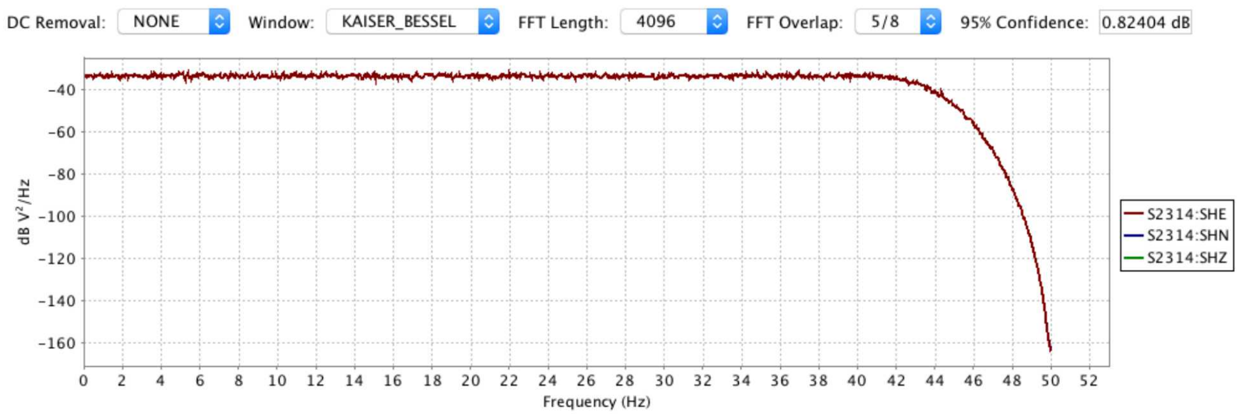

Figure 42 Analog Bandwidth, SMART24B 2314

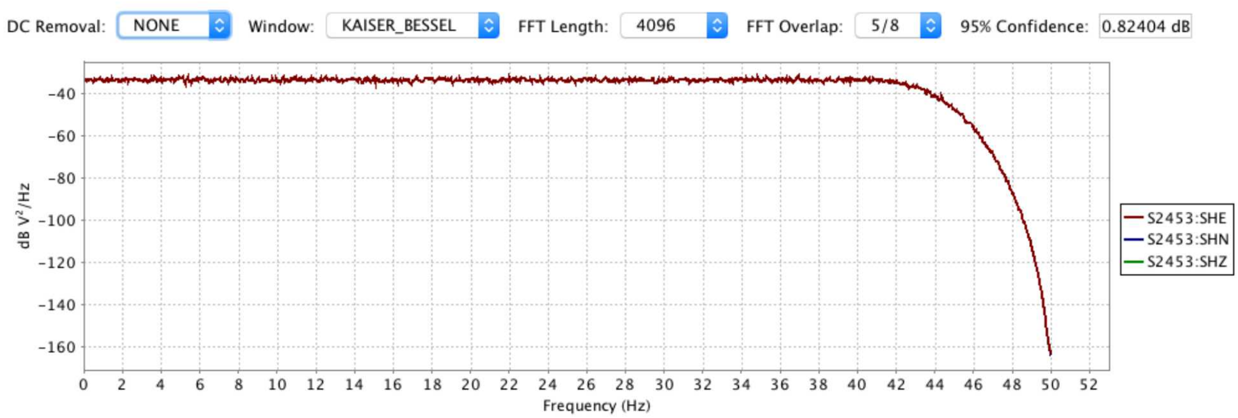

Figure 43 Analog Bandwidth, SMART24B 2453

Table 26 Analog Bandwidth, both DWRs

DWR	SHE (channel 3)	SHN (channel 6)	SHZ (channel 1)	% Nyquist Frequency
2314	42.7 Hz	42.7 Hz	42.7 Hz	85.4 %
2453	42.7 Hz	42.7 Hz	42.7 Hz	85.4 %

The observed pass-band limit of all the dataloggers while recording 100 sps, with a 16x gain, while exposed to 23° C, was 85.4% of the 50 Hz Nyquist Frequency.

3.13 Total Harmonic Distortion

The Total Harmonic Distortion test is used to measure the linearity of a digitizer channel by recording a known AC signal at a reference voltage from an ultra-low distortion oscillator.

3.13.1 Measurand

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

3.13.2 Configuration

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

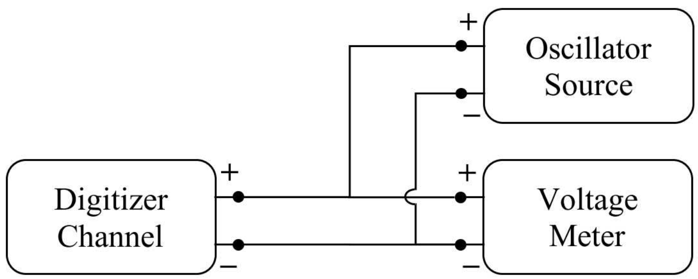

Figure 44 THD Configuration Diagram

Figure 45 Total Harmonic Distortion Configuration

Table 27 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Oscillator Source - Bunker	End Run Technologies/Meridian GPS 3025-0101 Quanterra/Supertonal Signal Source	12010020 021202	+0.64 V / -0.64 V
Voltage Meter - Bunker	Agilent 3458A	MY45048371	1.0 V full scale

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

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

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

A minimum of 1 hour of data is recorded.

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

3.13.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a Kaiser-Bessel window varying in length from 4k to 16k window dependent upon on the sample rate of the data recorded. A Kaiser-Bessel window is used to minimize the width of the main lobe and the amplitude of side-lobes. The window length and data duration were chosen to provide sufficient frequency resolution around the primary harmonic and to ensure that the 90% confidence interval ideally 0.5 db or below, though in practice the 90% confidence interval ranged between 0.39 dB and 0.89 dB; at the lowest sample rate the 90% confidence interval increases to has high as 1.43 dB.

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

Over frequencies (in Hertz):

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

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

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

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

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

3.13.4 Result

The figure below shows a short segment of a representative waveform time series recorded on both the reference meter and a digitizer channel under test of the sinusoid that was used to measure harmonic distortion.

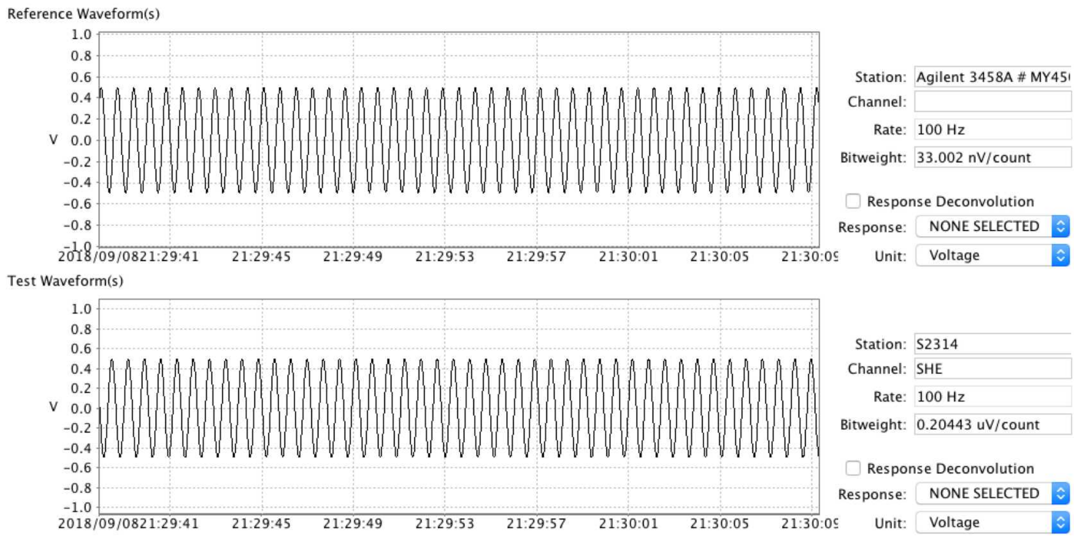

Figure 46 THD Time Series

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

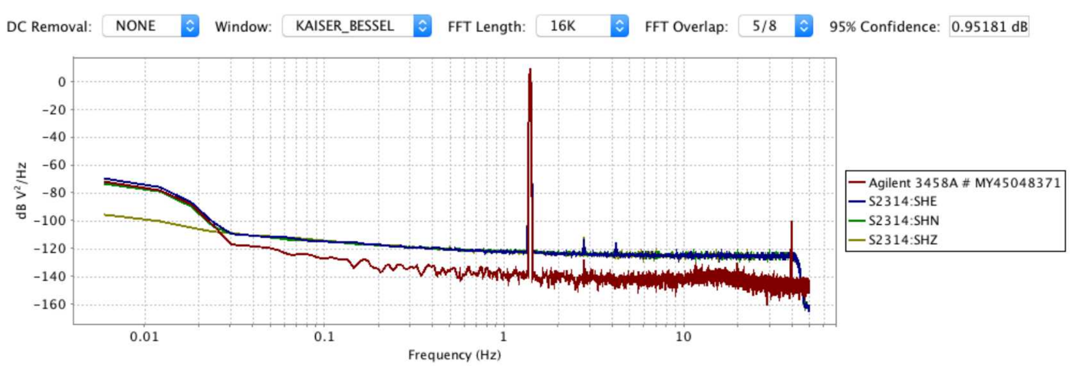

Figure 47 THD Power Spectra SMART24B 2314, 16x Gain

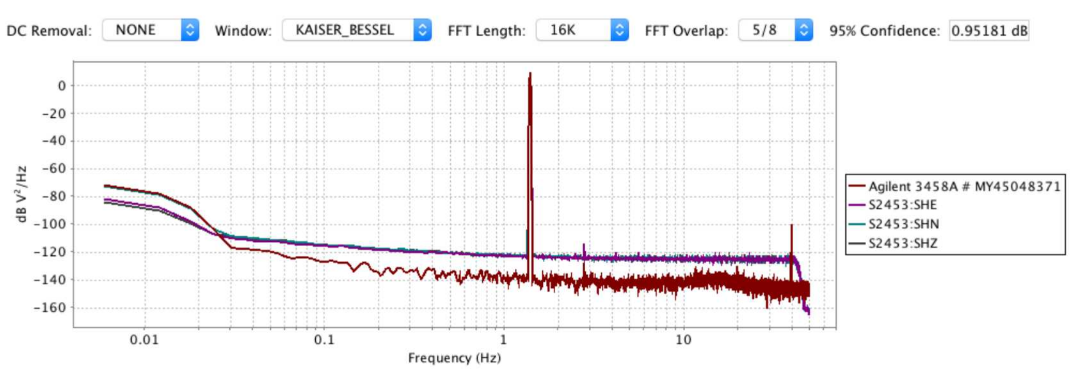

Figure 48 THD Power Spectra SMART24B 2453 16x Gain

Table 28 Total Harmonic Distortion, both DWRs

DWR	Reference Meter	SHE (chan 3)	SHN (chan 2)	SHZ (chan 1)
2314	-136.92 dB	-117.72 dB	-121.85 dB	-119.07 dB
2453	-136.92 dB	-120.23 dB	-124.9 dB	-128.98 dB

In all cases, the reference measurement of the signal generated by the low distortion oscillator exceeded the measurement made on the digitizer channel indicating that the distortion observed is due to the digitizer. No observable systemic relationship between channel and THD observed exists.

The observed harmonic distortion ranged between -117.72 dB (SN 2314, SHE) and -128.98 dB (SN 2453, SHE). The relatively low THD of the dataloggers may be attributed to the limited penetration of the harmonic distortion (spikes) above the relatively high noise floor of the 16x gain digitizer.

3.14 Common Mode Rejection

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

3.14.1 Measurand

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

3.14.2 Configuration

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

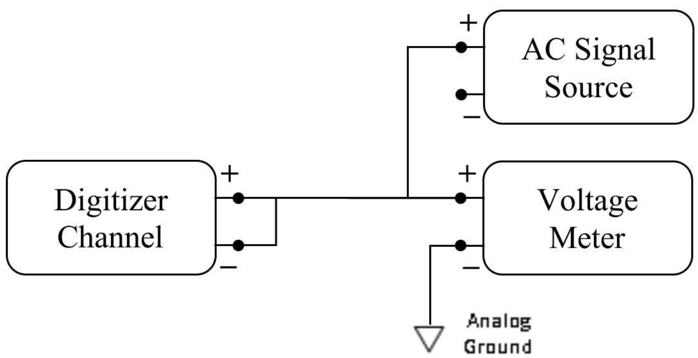

Figure 49 Common Mode Rejection Configuration Diagram

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

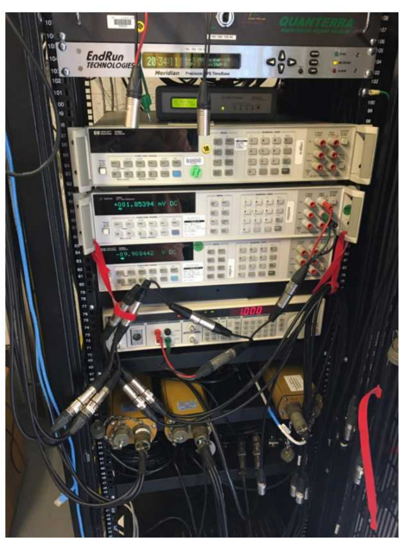

Figure 50 Common Mode Rejection Configuration

Table 29 Common Mode Rejection Testbed Equipment

	Manufacturer / Model	Serial Number	Configuration
DC Signal Source - Bunker	Stanford Research Systems DS360	123672	+1V / - 1 V
Voltage Meter - Bunker	Agilent 3458A	MY45048371	1 V full scale

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

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

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

3.14.3 Analysis

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

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

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

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

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

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

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

3.14.4 Result

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

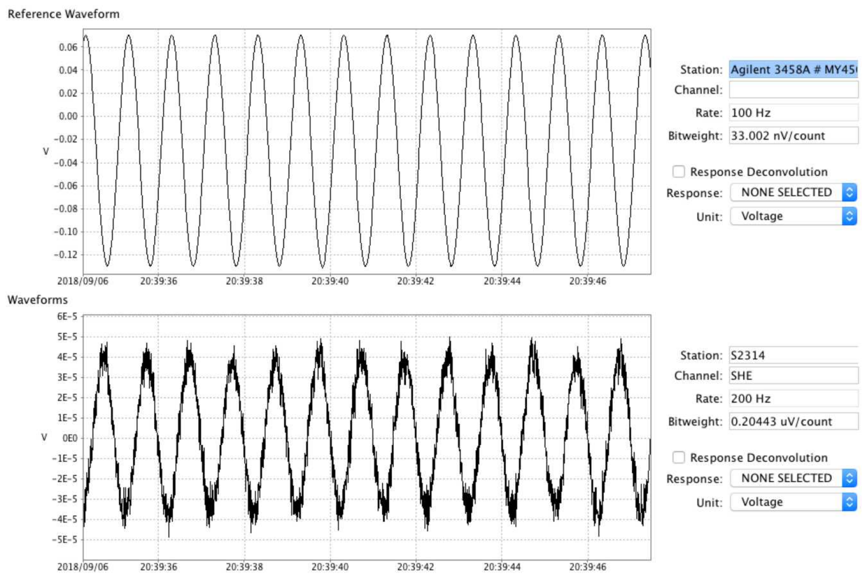

Figure 51 Common Mode Rejection Time Series

The following table contains the computed common mode noise and rejection ratio.

Table 30 Common Mode Rejection Ratio, both DWRs

DWR		SHE (chan 3)	SHN (chan 2)	SHZ (chan 1)
2314	Amplitude	37.39 uV	14.49 uV	4.96 uV
	Rejection Gain	68.51 dB	76.75 dB	86.05 dB
2453	Amplitude	34.81 uV	104.32 uV	16.42 uV
	Rejection Gain	69.13 dB	59.60 dB	75.66 dB

The observed common mode rejection across dataloggers ranged from 59.60 dB to 86.05 dB while configured with a gain of 16x.

3.15 Crosstalk

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

3.15.1 Measurand

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

3.15.2 Configuration

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

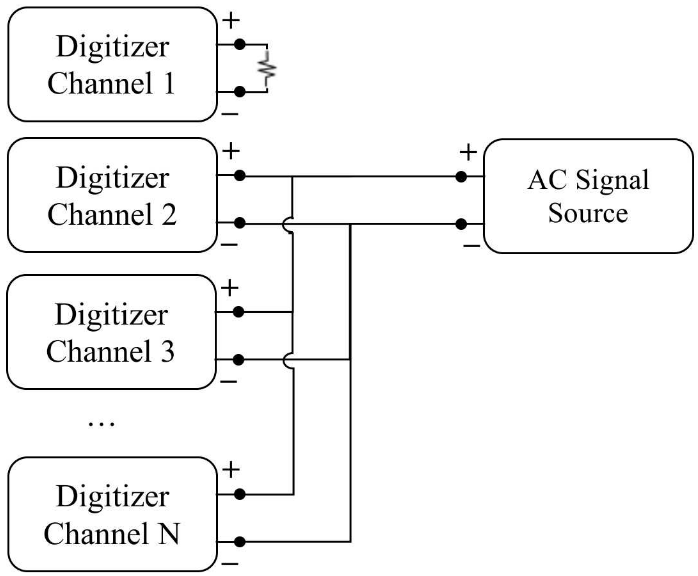

Figure 52 Crosstalk Configuration Diagram

Figure 53 Crosstalk Configuration

Table 31 Crosstalk Testbed Equipment

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

The AC Signal Source is configured to generate a AC voltage with an amplitude of approximately 50% of the digitizer input channel's full scale and a frequency equal to the calibration frequency of 1 Hz. Approximately 1.2 minutes of data are recorded.

3.15.3 Analysis

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

$$x[n]$$

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

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

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:

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

3.15.4 Result

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

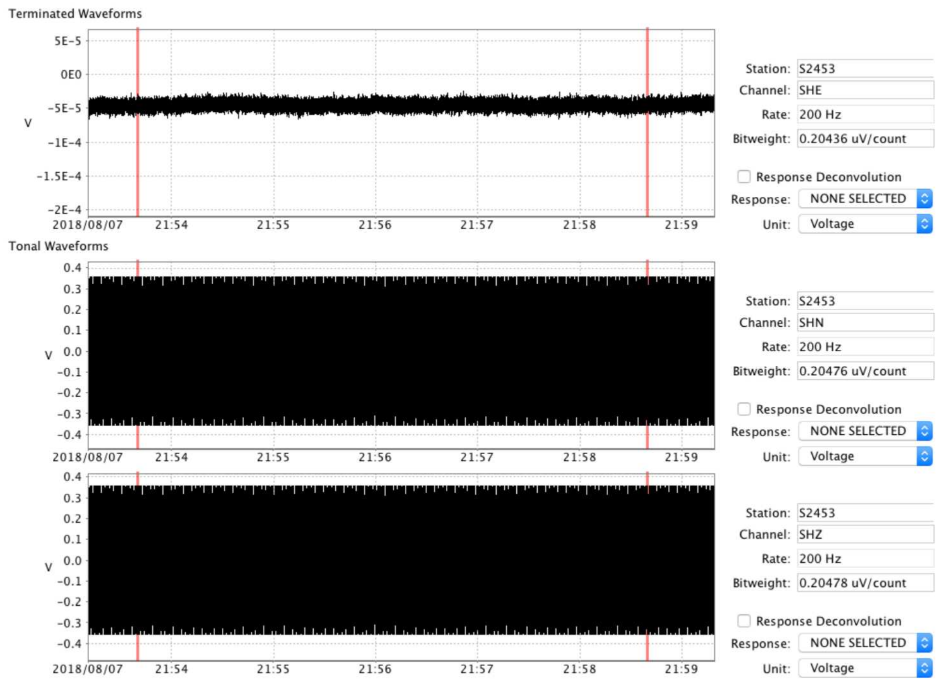

Figure 54 Crosstalk Time Series Example, SMART24B 2453

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

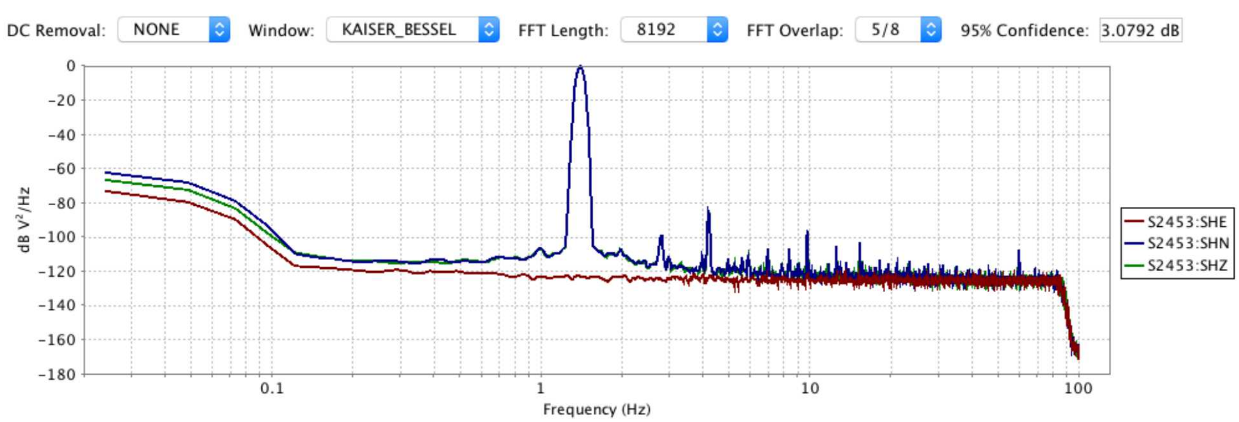

Figure 55 Crosstalk Power Spectra

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

Table 32 Crosstalk*, both DWRs

DWR	SHE (chan 3)	SHN (chan 2)	SHZ (chan 1)
2314	-122.74 dB	-119.11 dB	-127.61 dB
2453	-121.68 dB	-120.70 dB	-126.47 dB

No peak is observable in the terminated channel's power spectra, therefore the values represent the maximum possible observable crosstalk. The maximum possible observable levels of crosstalk were all between -119.11 dB and -127.61 dB while the dataloggers were configured with a gain of 16x.

3.16 Time Tag Accuracy

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

3.16.1 Measurand

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

3.16.2 Configuration

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

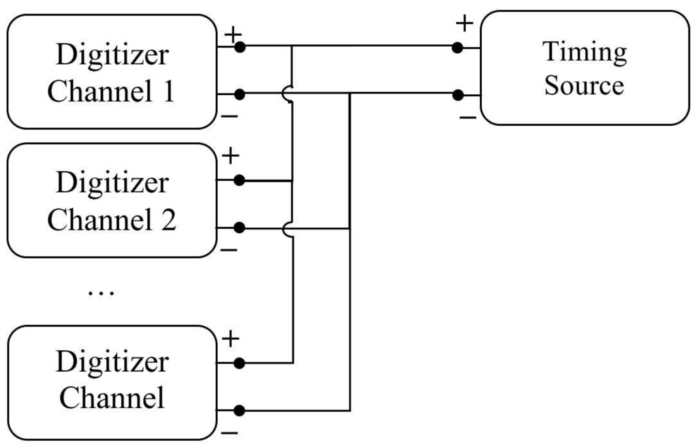

Figure 56 Time Tag Configuration Diagram

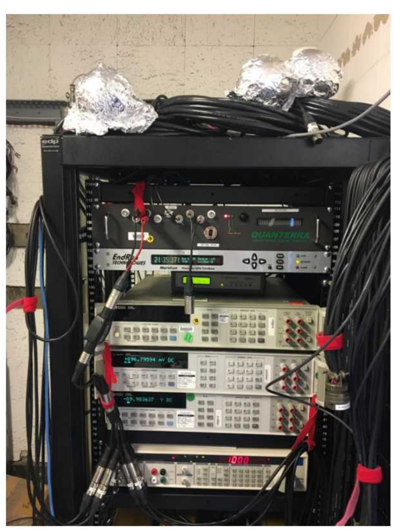

Figure 57 Time Tag Configuration Picture

Table 33 Time Tag Testbed Equipment

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

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

3.16.3 Analysis

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

3.16.4 Result

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

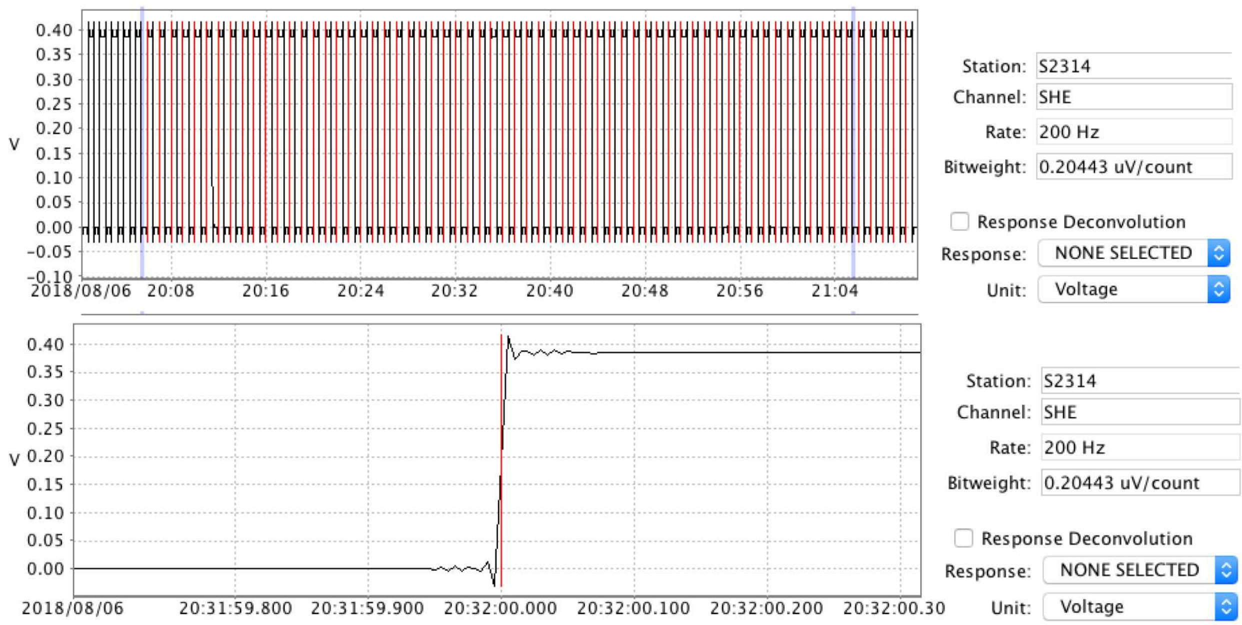

Figure 58 Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets as measured from the testing configuration as shown in Figure 56.

Table 34 Time Tag Accuracy, both DWRs

DWR	SHE (chan 3)	SHN (chan 2)	SHZ (chan 1)
2314	46.25 us	46.97 us	48.16 us
2453	47.68 us	46.25 us	46.73 us

Both dataloggers' timing tag offsets were tightly clustered, ranging from 46.16 us to 48.16 us.

The following histogram of time tag errors for SN 2314 channel SHN is representative of the other two channels' errrors and hence are not shown here.

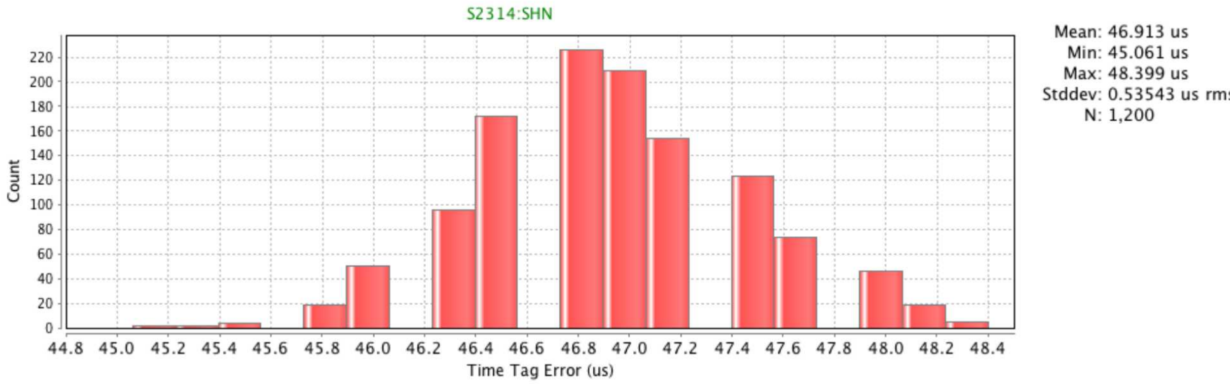

Figure 59 Historgram of Time Tag Errors

3.17 Timing Drift

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

3.17.1 Measurand

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

3.17.2 Configuration

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

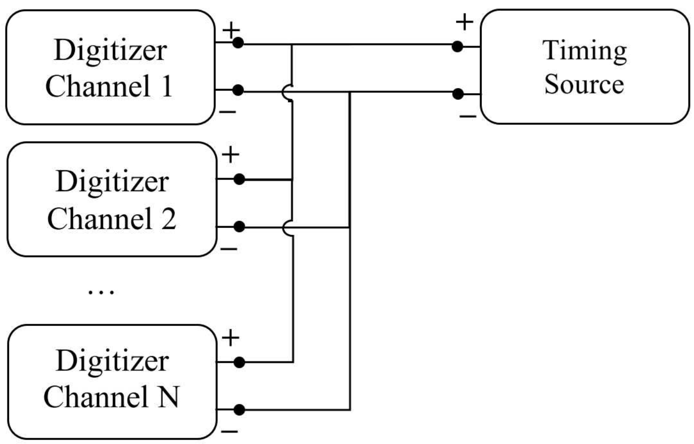

Figure 60 Timing Drift Configuration Diagram

Table 35 Timing Drift Testbed Equipment

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

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

The digitizer clock is allowed to stabilize before the GPS antenna is covered, which results in the digitizer losing timing lock. The digitizer is allowed to drift before the GPS antenna uncovered and then regains its timing lock and corrects for drift.

3.17.3 Analysis

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

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

3.17.4 Result

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

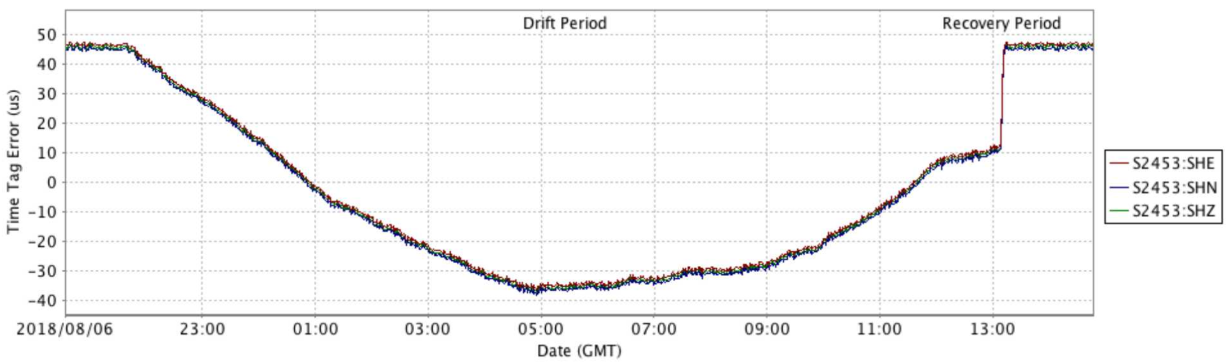

Figure 61 Time Tag Drift, SMART24B 2453, 23° C

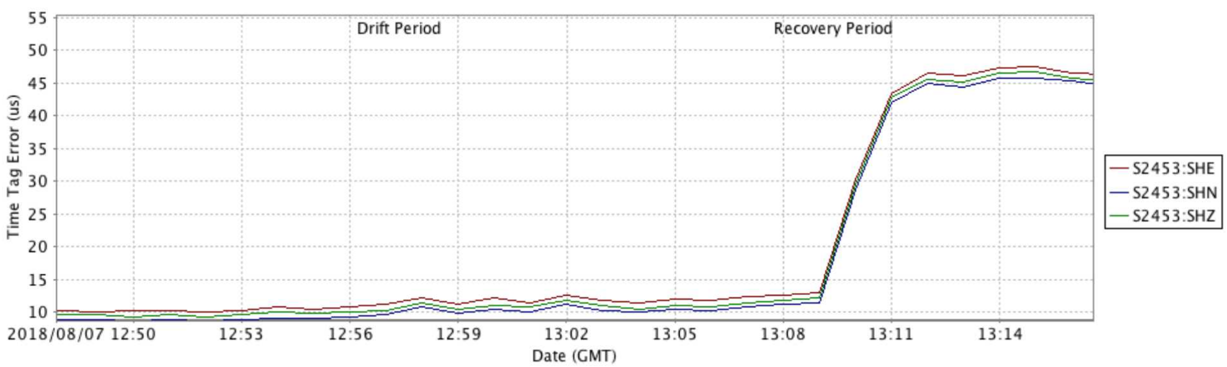

Figure 62 Time Tag Recovery SMART24B 2453, 23° C

The following table contains the computed timing offsets with the GPS unlocked and the estimated rate at which the digitizer was observed to drift prior to recovering GPS lock.

Table 36 Time Tag Drift and Recovery

Digitizer	Config/Conditions	Timing Offset	Drift Rate
2314	-	-	-
2453	200 sps, gain 16x, 23° C	-37 us	2.07 us/h

Datalogger 2453 had remarkably little drift over the ~15 hour period during which the antenna was covered with foil to simulate an antenna's sky view being blocked. The drift rate reverses approximately 7 hours after covering the antenna, at which time the timing begins to drifting in the opposite direction.

The mean drift rate over the time during which the antenna was covered is 2.07 us/h. The observed timing offset with GPS-locked timing is approximately 46 us (ahead of actual time). During the GPS-unlocked time period the timing offset was -37 us (behind actual time). Upon uncovering the antenna at 1307 UTC, the timing quickly recovered to its pre-unlocked timing offset, within approximately 4 minutes (the antenna was uncovered at 1307 UTC).

4 SUMMARY

Power Consumption
The average observed power consumption of 2.78 W is significantly higher than the ~1 W provided in the datasheet specification, however the manufacturer's power consumption is with respect to power-cycled GPS receiver operation, rather than the tested configuration of continuous GPS receiver operation.

Input Impedance
Both dataloggers remained had measured input impedances on channel 1 of 17% over the specified 1 Mohm impedance; channels 2 and 3 over twice the manufacturer's stated impedance.

DC Accuracy
Bit weights of both dataloggers remained very close to the manufacturer-provided bitweights, from 0.00% to 0.29% of the provided values.

AC Accuracy
As with DC Accuracy Tests, bitweights remained very near the respective manufacturer-provided bitweight, not diverging more than 0.29% from the respective manufacturer-provided bitweight.

Input Shorted Offset
The maximum offset observed across dataloggers is -0.0034% of full-scale (1.25 V at 16x gain), observed on datalogger 2453, channel SHE (channel 3).

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

Self-Noise
Self noise values remained relatively consistent within the high and broad passbands, within 1.60% and 2.61% of the average across all dataloggers and channels respectively, however over the low passband self noise estimates varied more, as much as 7.03%.

Dynamic Range
Observed dynamic range values were relatively tightly clustered around their average. The most variation in dynamic range occurred over the 0.02 Hz to 1.0 Hz passband, where variations were as high as 0.52% from the average of 120.45 dB for the passband; over the 0.5 Hz to 16 Hz passband, dynamic ranges varied 0.12% from 114.78 dB, the average over this passband; and finally, over the broad passband, 0.02 Hz and 16 Hz, variations were within 0.20% of the average of 113.96 dB over the broad passband.

System Noise
Equivalent seismic system noise of both SMART24B dataloggers recording at a gain of 16x exceeds the self-noise models of the GS-13 over the entire spectrum of interest. This result

brings to mind the relevance of utilizing a pre-amplifier in series with the GS-13 and reducing the gain of the digitizer to improve equivalent seismic system noise.

Response Verification

Amplitude differences were very small across channels (< 0.001 dB). Phase differences were very small also (<0.005°), with some variation in the amount of the roll-off between channels.

Relative Transfer Function

Timing skews were consistently of larger in absolute magnitude for the SHE channels relative to the SHN channels. Absolute values of the timing skews did not exceed 1.22 microseconds.

Analog Bandwidth

The observed pass-band limit of all the dataloggers while recording 100 sps, with a 16x gain, while exposed to 23° C, was 85.4% of the 50 Hz Nyquist Frequency.

Total Harmonic Distortion

The observed harmonic distortion ranged between -117.72 dB (SN 2314, SHE) and -128.98 dB (SN 2453, SHE). The relatively low THD of the dataloggers may be attributed to the limited penetration of the harmonic distortion (spikes) above the relatively high noise floor of the 16x gain digitizer.

Common Mode Rejection

The observed common mode rejection across dataloggers ranged from 59.60 dB to 86.05 dB while configured with a gain of 16x.

Crosstalk

No peak is observable in the terminated channel's power spectra, therefore the values represent the maximum possible observable crosstalk. The maximum possible observable levels of crosstalk were all between -119.11 dB and -127.61 dB while the dataloggers were configured with a gain of 16x.

Time Tag Accuracy

Over all test configurations and conditions, timing offsets varied from -25 us to -41 us, with no correlation of offset with temperature or sample rate.

Time Tag Drift

Drift rates varied widely across dataloggers, from as little as 187 us/h to as much as -411 us/h. In every instance of connecting the GPS antenna to the receiver, GPS receivers locked and timing was corrected, to essentially the same measured timing offset as that prior to the drift test, within just a few minutes.

REFERENCES

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

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

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

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

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

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

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

APPENDIX A: SELF-NOISE

Digitizer self-noise values are reported in units of dB relative to 1 V^2/Hz at the defined octave-band frequencies. The 90% uncertainty of the provided estimates are 0.54 .

Table 37 SMART24B Digitizer Noise Model, 16x Gain

Frequency (Hz)	SHE (chan 3)	SHN (chan 2)	SHZ (chan 1)
0.0315	-110.1 dB	-109.9 dB	-109.8 dB
0.04	-111.5 dB	-111.3 dB	-110.9 dB
0.05	-112.2 dB	-112.1 dB	-111.8 dB
0.063	-113.6 dB	-113.4 dB	-113.1 dB
0.08	-114.4 dB	-114.2 dB	-114.0 dB
0.1	-115.5 dB	-115.3 dB	-115.0 dB
0.125	-116.4 dB	-116.2 dB	-115.9 dB
0.16	-117.3 dB	-117.1 dB	-117.0 dB
0.2	-118.3 dB	-118.1 dB	-117.9 dB
0.25	-119.1 dB	-118.9 dB	-118.7 dB
0.315	-119.8 dB	-119.7 dB	-119.5 dB
0.4	-120.6 dB	-120.6 dB	-120.3 dB
0.5	-121.2 dB	-121.2 dB	-121.0 dB
0.63	-121.9 dB	-121.9 dB	-121.7 dB
0.8	-122.6 dB	-122.5 dB	-122.3 dB
1	-123.1 dB	-122.9 dB	-122.8 dB
1.25	-123.5 dB	-123.4 dB	-123.3 dB
1.6	-123.9 dB	-123.8 dB	-123.8 dB
2	-124.2 dB	-124.1 dB	-124.1 dB
2.5	-124.5 dB	-124.5 dB	-124.5 dB
3.15	-124.8 dB	-124.7 dB	-124.7 dB
4	-125.0 dB	-124.9 dB	-124.9 dB
5	-125.2 dB	-125.1 dB	-125.1 dB
6.3	-125.3 dB	-125.3 dB	-125.2 dB
8	-125.4 dB	-125.4 dB	-125.4 dB
10	-125.5 dB	-125.5 dB	-125.5 dB
12.5	-125.6 dB	-125.6 dB	-125.5 dB
16	-125.6 dB	-125.6 dB	-125.6 dB
20	-125.7 dB	-125.7 dB	-125.7 dB
25	-125.7 dB	-125.7 dB	-125.7 dB
31.5	-125.7 dB	-125.8 dB	-125.8 dB
40	-125.8 dB	-125.8 dB	-125.8 dB

APPENDIX B: RESPONSE MODELS

4.1 Geotech GS-13 Response

Geotech GS-13 seismometer amplitude and phase response.

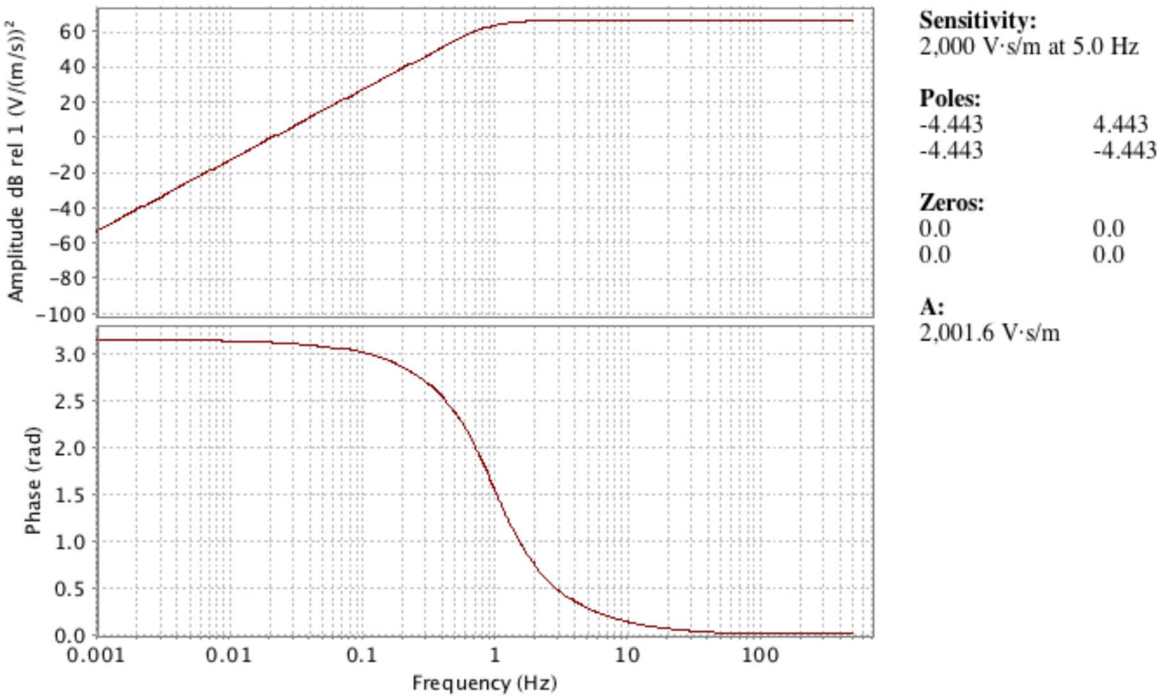

Figure 63 GS-13 Amplitude and Phase Response

APPENDIX C: TESTBED CALIBRATIONS

Agilent 3458A # MY45048371

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 6652541_11726859

Item Identification

Asset Number	6652541
Description	Multimeter,Digital
Model	3458A
Serial #	MY45048371
Manufacturer	Agilent Technologies
Customer Asset Id	N/A
Purchase Order	N/A
Customer	Ground-Based Monitoring R&E 06752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1044
Date of Receipt	November 07, 2017
Dates Tested (Start – End)	November 29, 2017 - November 29, 2017
Date Approved	November 29, 2017
Calibration Expiration Date	November 29, 2018

Calibration Description

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

Page 1 of 8
6652541_11726859

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

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

AC Current:

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

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

Asset #	Description	Due Date
11123	Keithley 5155-9 1 Gohm resistor	5/10/2018
20174	Fluke 5725A Amplifier	8/10/2018
20563	FLUKE 5790A CALIBRATOR	10/19/2018
6651332	Agilent 33250A Funtion/Arbitrary Waveform Generato	2/15/2018
6664631	Fluke 5730A Multifunction Calibrator	12/4/2017

Test Results

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

~~~~~~

MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

~~~~~~

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

DC Volts

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
1000.00000 V		999.98900	1000.00799	1000.01100	V	2.42#	73	
DC Current								
100.000 nA		91.597	100.049	108.403	nA	1.85#	1	
1.000000 µA		0.969900	1.000067	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999948	10.030100	µA	5.2	0	
100.00000 µA		99.95000	99.99883	100.05000	µA	5.7	2	
1.0000000 mA		0.9997500	0.9999948	1.0002500	mA	7.6	2	
10.000000 mA		9.997500	9.999983	10.002500	mA	8.1	1	
100.00000 mA		99.97500	100.00057	100.02500	mA	6.1	2	
1.0000000 A		0.9995000	1.0000207	1.0005000	A	7.6	4	
Resistance								
10.00000 Ohm	10.000277	9.99918	10.00030	10.00138	Ohm	5.8	2	
100.00000 Ohm	100.003650	99.99815	100.00422	100.00915	Ohm	6.5	10	
1.0000000 kOhm	0.99998440	0.9999334	0.9999891	1.0000354	kOhm	9.1	9	
10.000000 kOhm	9.9998260	9.999316	9.999897	10.000336	kOhm	9.4	14	
100.00000 kOhm	100.000560	99.99546	100.00140	100.00566	kOhm	8.2	17	
1.0000000 MOhm	0.99995920	0.9998572	0.9999694	1.0000612	MOhm	9.3	10	
10.000000 MOhm	9.9982190	9.996119	9.998373	10.000319	MOhm	7.2	7	
100.00000 MOhm	100.006930	99.95593	100.00600	100.05793	MOhm	6.0	2	
1.00192000 GOhm		0.9818716	0.9996921	1.0219684	GOhm	>10	11	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9427	100.1700	µA	7.4	34	
100.0000 µA @ 45 Hz		99.8300	99.9874	100.1700	µA	10.0	7	
100.0000 µA @ 1 kHz		99.8300	99.9872	100.1700	µA	10.0	8	
1.000000 mA @ 20 Hz		0.998300	0.999523	1.001700	mA	10.0	28	
1.000000 mA @ 45 Hz		0.998300	0.999984	1.001700	mA	>10	1	
1.000000 mA @ 5 kHz		0.998300	1.000265	1.001700	mA	6.3	16	
1.000000 mA @ 10 kHz		0.995013	1.000560	1.004987	mA	3.47#	11	
10.00000 mA @ 20 Hz		9.98300	9.99528	10.01700	mA	10.0	28	
10.00000 mA @ 45 Hz		9.98300	9.99990	10.01700	mA	>10	1	
10.00000 mA @ 5 kHz		9.98300	10.00167	10.01700	mA	7.7	10	
10.00000 mA @ 10 kHz		9.94970	10.00290	10.05030	mA	4.0	6	
100.0000 mA @ 20 Hz		99.8300	99.9567	100.1700	mA	10.0	26	
100.0000 mA @ 45 Hz		99.8300	100.0027	100.1700	mA	>10	2	
100.0000 mA @ 5 kHz		99.8300	100.0353	100.1700	mA	8.5	21	
100.0000 mA @ 10 kHz		99.4800	100.0627	100.5200	mA	5.5	12	
1.000000 A @ 40 Hz		0.998300	0.999954	1.001700	A	6.8	3	
1.000000 A @ 5 kHz		0.998357	1.000907	1.001643	A	3.95#	55	
AC Volts								
10.00000 mV @ 10 Hz	9.997800	9.97760	9.99878	10.01800	mV	7.2	5	
10.00000 mV @ 40 Hz	9.997700	9.99328	9.99833	10.00212	mV	2.94#	14	
10.00000 mV @ 20 kHz	9.998400	9.99398	9.99897	10.00282	mV	2.94#	13	
10.00000 mV @ 50 kHz	9.998800	9.98770	9.99729	10.00990	mV	4.1	14	
10.00000 mV @ 100 kHz	10.001500	9.95039	9.98880	10.05261	mV	>10	25	
10.00000 mV @ 300 kHz	9.999500	9.59752	9.88451	10.40148	mV	>10	29	
100.0000 mV @ 10 Hz	99.99400	99.7920	99.9914	100.1960	mV	>10	1	
100.0000 mV @ 40 Hz	99.99360	99.9466	99.9962	100.0406	mV	>10	6	
100.0000 mV @ 20 kHz	99.99500	99.9480	99.9897	100.0420	mV	>10	11	
100.0000 mV @ 50 kHz	99.99490	99.8929	99.9937	100.0969	mV	>10	1	
100.0000 mV @ 100 kHz	99.99750	99.7955	99.9850	100.1995	mV	>10	6	
100.0000 mV @ 300 kHz	100.00640	98.9963	99.9423	101.0165	mV	>10	6	
1.000000 V @ 10 Hz	1.0000200	0.998000	1.000062	1.002040	V	>10	2	
1.000000 V @ 40 Hz	0.9999989	0.999529	1.000040	1.000469	V	>10	9	
1.000000 V @ 20 kHz	0.9999984	0.999528	0.999971	1.000468	V	>10	6	
1.000000 V @ 50 kHz	1.0000149	0.998995	1.000070	1.001035	V	>10	5	
1.000000 V @ 100 kHz	1.0000389	0.998019	1.000195	1.002059	V	>10	8	
1.000000 V @ 300 kHz	1.0003754	0.990272	1.001898	1.010479	V	>10	15	
10.00000 V @ 10 Hz	10.000108	9.97991	10.00036	10.02031	V	>10	1	
10.00000 V @ 40 Hz	9.999949	9.99525	10.00038	10.00465	V	>10	9	
10.00000 V @ 20 kHz	10.000001	9.99530	9.99975	10.00470	V	>10	5	
10.00000 V @ 50 kHz	10.000081	9.98988	10.00058	10.01028	V	>10	5	

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 100 kHz	10.000453	9.98025	9.99993	10.02065	V	>10	3	
10.00000 V @ 300 kHz	10.004297	9.90325	10.00300	10.10534	V	>10	1	
100.0000 V @ 10 Hz	100.00065	99.7986	100.0055	100.2027	V	>10	2	
100.0000 V @ 40 Hz	99.99960	99.9526	100.0038	100.0466	V	>10	9	
100.0000 V @ 20 kHz	100.00240	99.9554	100.0023	100.0494	V	>10	0	
100.0000 V @ 50 kHz	100.00624	99.9042	100.0144	100.1082	V	>10	8	
100.0000 V @ 100 kHz	100.01079	99.8088	100.0147	100.2128	V	>10	2	
100.0000 V @ 200 kHz	100.06064	99.0500	100.0514	101.0712	V	>10	1	
700.0000 V @ 40 Hz	700.01210	699.4321	700.0015	700.5921	V	>10	2	
700.0000 V @ 20 kHz	700.00580	699.4258	699.7836	700.5858	V	>10	38	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000139	10.005000	Hz	>10	3	
40.00000 Hz @ 1 V		39.996000	40.000503	40.004000	Hz	>10	13	
100.00000 Hz @ 1 V		99.990000	100.001152	100.010000	Hz	>10	12	
1000.0000 Hz @ 1 V		999.90000	1000.00887	1000.10000	Hz	>10	9	
10000.0000 Hz @ 1 V		9999.00000	10000.08774	10001.00000	Hz	>10	9	
20000.0000 Hz @ 1 V		19998.00000	20000.17738	20002.00000	Hz	>10	9	
50000.0000 Hz @ 1 V		49995.00000	50000.43868	50005.00000	Hz	>10	9	
100.00000 kHz @ 1 V		99.990000	100.000877	100.010000	kHz	>10	9	
500.00000 kHz @ 1 V		499.950000	500.004435	500.050000	kHz	>10	9	
1.000000 MHz @ 1 V		0.9999000	1.0000088	1.0001000	MHz	>10	9	
2.000000 MHz @ 1 V		1.9998000	2.0000177	2.0002000	MHz	>10	9	
4.000000 MHz @ 1 V		3.9996000	4.0000355	4.0004000	MHz	>10	9	
6.000000 MHz @ 1 V		5.9994000	6.0000532	6.0006000	MHz	>10	9	
8.000000 MHz @ 1 V		7.9992000	8.0000702	8.0008000	MHz	>10	9	
10.000000 MHz @ 1 V		9.9990000	10.0000877	10.0010000	MHz	>10	9	

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limitations

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

Equipment (Standard) Used

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Traceability

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

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

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

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

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

Authorization

Calibrated By:	Approved By:
Chance, Jason Metrologist	Johnson, Raegan Lynn QA Representative

End-of-Document

Hewlett Packard 3458A # 2823A08050

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 20006_11719425

Item Identification

Asset Number	20006
Description	Meter,Multifunction
Model	3458A
Serial #	2823A08050
Manufacturer	Hewlett Packard Co
Customer Asset Id	N/A
Purchase Order	N/A
Customer	Ground-Based Monitoring R&E 06752
Custodian	Slad, George William
Location	SNLNM/TA1/758/1044
Date of Receipt	July 27, 2017
Dates Tested (Start – End)	August 10, 2017 - August 10, 2017
Date Approved	August 11, 2017
Calibration Expiration Date	August 11, 2018

Calibration Description

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

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

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

AC Current:

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

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

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

Unit Under Test:	HP 3458A Multimeter	Test Result:	**PASS**
Asset Number:	20006	Test Type:	FOUND-LEFT
Serial Number:	2823A08050	Calibration Date:	8/10/2017
Procedure Name:	HP 3458A	Temperature:	23 °C
Revision:	4.2	Humidity:	40 %
Calibrated By:	Jason Chance		

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

COMMENTS:

Standards Used

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

Test Results

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

```
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

The internal temperature of the 3458A is 38.5 deg.C
DC Volts
```

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
100.00000 mV		99.99812	99.99994	100.00188	mV	2.26#	3	
-100.00000 mV		-100.00188	-99.99991	-99.99812	mV	2.26#	5	
1.00000000 V		0.99998965	1.00000025	1.00001035	V	2.97#	2	
-1.00000000 V		-1.00001035	-1.00000073	-0.99998965	V	2.97#	7	
-10.0000000 V		-10.0000987	-10.0000090	-9.9999013	V	3.92#	9	
-5.0000000 V		-5.0000501	-5.0000052	-4.9999499	V	3.71#	10	
-2.0000000 V		-2.0000209	-2.0000008	-1.9999791	V	3.24#	4	
2.0000000 V		1.9999791	2.0000002	2.0000209	V	3.24#	1	
5.0000000 V		4.9999499	5.0000040	5.0000501	V	3.71#	8	
10.0000000 V		9.9999013	10.0000064	10.0000987	V	3.92#	7	
100.000000 V		99.998821	100.000257	100.001179	V	3.51#	22	

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
1000.00000 V		999.98900	1000.00211	1000.01100	V	2.42#	19	
DC Current								
100.000 nA		91.597	100.005	108.403	nA	1.85#	0	
1.000000 µA		0.969900	1.000039	1.030100	µA	5.5	0	
10.000000 µA		9.969900	9.999885	10.030100	µA	5.2	0	
100.00000 µA		99.95000	99.99907	100.05000	µA	5.7	2	
1.0000000 mA		0.9997500	0.9999976	1.0002500	mA	7.6	1	
10.000000 mA		9.997500	10.000009	10.002500	mA	8.1	0	
100.00000 mA		99.97500	100.00107	100.02500	mA	6.1	4	
1.0000000 A		0.9995000	1.0000137	1.0005000	A	7.6	3	
Resistance								
10.00000 Ohm	10.000270	9.99917	10.00020	10.00137	Ohm	5.8	6	
100.00000 Ohm	100.003620	99.99812	100.00351	100.00912	Ohm	6.5	2	
1.0000000 kOhm	0.99998460	0.9999336	0.9999827	1.0000356	kOhm	7.3	4	
10.000000 kOhm	9.9998320	9.999322	9.999833	10.000342	kOhm	7.3	0	
100.00000 kOhm	100.000630	99.99553	100.00076	100.00573	kOhm	6.0	3	
1.0000000 MOhm	0.99996060	0.9998586	0.9999622	1.0000626	MOhm	7.3	2	
10.000000 MOhm	9.9982380	9.996138	9.998227	10.000338	MOhm	7.2	1	
100.00000 MOhm	100.008520	99.95752	100.01111	100.05952	MOhm	6.0	5	
1.00192000 GOhm		0.9818716	1.0014771	1.0219684	GOhm	>10	2	
AC Current								
100.0000 µA @ 20 Hz		99.8300	99.9451	100.1700	µA	7.4	32	
100.0000 µA @ 45 Hz		99.8300	99.9885	100.1700	µA	9.4	7	
100.0000 µA @ 1 kHz		99.8300	99.9897	100.1700	µA	9.4	6	
1.000000 mA @ 20 Hz		0.998300	0.999464	1.001700	mA	10.0	32	
1.000000 mA @ 45 Hz		0.998300	0.999910	1.001700	mA	>10	5	
1.000000 mA @ 5 kHz		0.998300	1.000174	1.001700	mA	6.3	10	
1.000000 mA @ 10 kHz		0.995013	1.000350	1.004987	mA	3.47#	7	
10.00000 mA @ 20 Hz		9.98300	9.99472	10.01700	mA	10.0	31	
10.00000 mA @ 45 Hz		9.98300	9.99910	10.01700	mA	>10	5	
10.00000 mA @ 5 kHz		9.98300	10.00114	10.01700	mA	7.7	7	
10.00000 mA @ 10 kHz		9.94970	10.00212	10.05030	mA	4.0	4	
100.0000 mA @ 20 Hz		99.8300	99.9464	100.1700	mA	10.0	32	
100.0000 mA @ 45 Hz		99.8300	99.9928	100.1700	mA	>10	4	
100.0000 mA @ 5 kHz		99.8300	100.0242	100.1700	mA	8.5	14	
100.0000 mA @ 10 kHz		99.4800	100.0475	100.5200	mA	5.5	9	
1.000000 A @ 40 Hz		0.998300	0.999907	1.001700	A	6.5	5	
1.000000 A @ 5 kHz		0.998357	1.000915	1.001643	A	3.95#	56	
AC Volts								
10.00000 mV @ 10 Hz	10.006000	9.98579	9.99875	10.02621	mV	7.2	36	
10.00000 mV @ 40 Hz	9.998000	9.99358	9.99851	10.00242	mV	2.94#	12	
10.00000 mV @ 20 kHz	9.997000	9.99258	9.99744	10.00142	mV	2.94#	10	
10.00000 mV @ 50 kHz	9.997600	9.98650	9.99428	10.00870	mV	4.1	30	
10.00000 mV @ 100 kHz	10.000100	9.94900	9.97982	10.05120	mV	>10	40	
10.00000 mV @ 300 kHz	9.997300	9.59541	9.81902	10.39919	mV	>10	44	
100.0000 mV @ 10 Hz	100.07250	99.8704	99.9996	100.2746	mV	>10	36	
100.0000 mV @ 40 Hz	99.99460	99.9476	99.9954	100.0416	mV	>10	2	
100.0000 mV @ 20 kHz	99.97840	99.9314	99.9921	100.0254	mV	>10	29	
100.0000 mV @ 50 kHz	99.98210	99.8801	99.9879	100.0841	mV	>10	6	
100.0000 mV @ 100 kHz	99.98530	99.7833	99.9600	100.1873	mV	>10	13	
100.0000 mV @ 300 kHz	99.98880	98.9789	99.8345	100.9987	mV	>10	15	
1.000000 V @ 10 Hz	0.9999963	0.997976	1.000029	1.002016	V	>10	2	
1.000000 V @ 40 Hz	0.9999942	0.999524	1.000011	1.000464	V	>10	4	
1.000000 V @ 20 kHz	0.9999962	0.999526	0.999953	1.000466	V	>10	9	
1.000000 V @ 50 kHz	1.0000174	0.998997	0.999985	1.001037	V	>10	3	
1.000000 V @ 100 kHz	1.0000339	0.998014	1.000056	1.002054	V	>10	1	
1.000000 V @ 300 kHz	1.0003704	0.990267	1.001576	1.010474	V	>10	12	
10.00000 V @ 10 Hz	9.999919	9.97972	10.00059	10.02012	V	>10	3	
10.00000 V @ 40 Hz	9.999991	9.99529	10.00029	10.00469	V	>10	6	
10.00000 V @ 20 kHz	10.000049	9.99535	9.99963	10.00475	V	>10	9	
10.00000 V @ 50 kHz	10.000228	9.99003	9.99855	10.01043	V	>10	17	

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 100 kHz	10.000649	9.98045	9.99453	10.02085	V	>10	30	
10.00000 V @ 300 kHz	10.003541	9.90251	9.97991	10.10458	V	>10	23	
100.0000 V @ 10 Hz	100.00001	99.7980	100.0038	100.2020	V	>10	2	
100.0000 V @ 40 Hz	100.00021	99.9532	100.0002	100.0472	V	>10	0	
100.0000 V @ 20 kHz	100.00242	99.9554	99.9961	100.0494	V	>10	14	
100.0000 V @ 50 kHz	100.00743	99.9054	99.9950	100.1094	V	>10	12	
100.0000 V @ 100 kHz	100.01261	99.8106	99.9763	100.2146	V	>10	18	
100.0000 V @ 200 kHz	100.06311	99.0525	99.9860	101.0737	V	>10	8	
700.0000 V @ 40 Hz	700.02270	699.4427	699.9122	700.6027	V	>10	19	
700.0000 V @ 20 kHz	700.03000	699.4500	699.8439	700.6100	V	>10	32	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	9.999835	10.005000	Hz	>10	3	
40.00000 Hz @ 1 V		39.996000	39.999894	40.004000	Hz	>10	3	
100.00000 Hz @ 1 V		99.990000	100.000125	100.010000	Hz	>10	1	
1000.0000 Hz @ 1 V		999.90000	1000.00067	1000.10000	Hz	>10	1	
10000.0000 Hz @ 1 V		9999.00000	10000.00668	10001.00000	Hz	>10	1	
20000.0000 Hz @ 1 V		19998.00000	20000.01336	20002.00000	Hz	>10	1	
50000.0000 Hz @ 1 V		49995.00000	50000.03338	50005.00000	Hz	>10	1	
100.00000 kHz @ 1 V		99.990000	100.000057	100.010000	kHz	>10	1	
500.00000 kHz @ 1 V		499.950000	500.000286	500.050000	kHz	>10	1	
1.000000 MHz @ 1 V		0.9999000	1.0000007	1.0001000	MHz	>10	1	
2.000000 MHz @ 1 V		1.9998000	2.0000011	2.0002000	MHz	>10	1	
4.000000 MHz @ 1 V		3.9996000	4.0000023	4.0004000	MHz	>10	1	
6.000000 MHz @ 1 V		5.9994000	6.0000036	6.0006000	MHz	>10	1	
8.000000 MHz @ 1 V		7.9992000	8.0000053	8.0008000	MHz	>10	1	
10.000000 MHz @ 1 V		9.9990000	10.0000057	10.0010000	MHz	>10	1	

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

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

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

Equipment (Standard) Used

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Traceability

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

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

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

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

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

Authorization

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

End-of-Document

Hewlett Packard 3458A # 2823A10915

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 41628_11719482

Item Identification

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

Calibration Description

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

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

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

AC Current:

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

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

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

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

Test Results

```
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

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

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

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

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

Primary Electrical Lab TUR Report version 06/14/17

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

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

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

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

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

Equipment (Standard) Used

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

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

Traceability

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

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

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

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

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

Authorization

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

End-of-Document

Distribution

1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories