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Evaluation of Two Guralp Preamplifiers for GS13 Seismometer Application

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Abstract

Sandia National Laboratories has tested and evaluated a new preamplifier, the Guralp Preamplifier for GS13, manufactured by Guralp. These preamplifiers are used to interface between Guralp digitizers and Geotech GS13 Seismometers. The purpose of the preamplifier 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 Guralp GS13 Preamplifiers are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

ACKNOWLEDGMENTS

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

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NOMENCLATURE

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

1 INTRODUCTION

Sandia National Laboratories has tested and evaluated a new preamplifier, the Guralp Preamplifier for GS13, manufactured by Guralp. These preamplifiers are used to interface between Guralp digitizers and Geotech GS13 Seismometers. The purpose of the preamplifier 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 Guralp GS13 Preamplifiers are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

Figure 1 Guralp Preamplifiers for GS13 Seismometer

The minimum requirements for seismic stations from the IMS operational manual are shown in the table below.

Table 1 Minimum requirements for station specifications

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

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

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

The evaluation of the two digitizers, serial numbers G23511 and G23512, has been performed to compare the evaluated performance against the application requirements above and the datasheet specifications, shown in the table below.

Table 2 Guralp Preamplifier for GS13 Seismometer Specifications

Material	Die-cast Aluminium casing
Dimensions	160 mm × 100 mm × 60 mm
Input voltage	10 V to 36 V DC
Input current	80 mA (at 12 V)
Gain	× 40 (nominal – see individual instrument's calibration document)
Equivalent input noise (with 1 k source resistance)	6 nV/√Hz @ 1 Hz (±1) 3.5 nV/√Hz @ 10 Hz (±0.5)
Frequency response	Flat from DC to 1 kHz (to within 3 dB)
Output	Differential, voltage
Output impedance	47 Ω
Output saturation level	> 20 V peak-to-peak
Calibration amplifier gain	× 8.692 (nominal – see individual instrument's calibration document)
Calibration resistor	200 Ω
Calibration signal	25 mA (into 33 Ω coil)

2 TEST PLAN

2.1 Test Facility

Testing of the Guralp Preamplifiers 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).

Testing was performed within the FACT sites underground bunker due to the bunker's stable temperature.

Figure 2 FACT Site Bunker

Figure 3 Pictures of Guralp Preamplifiers and Digitizer

The temperature was recorded continuously throughout the testing by a calibrated Vaisala PT300U sensor and was maintained at 23 degrees Celsius, +/- 0.3 degrees.

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

Figure 4 GPS Re-broadcaster

Figure 5 Laboratory Power Supply

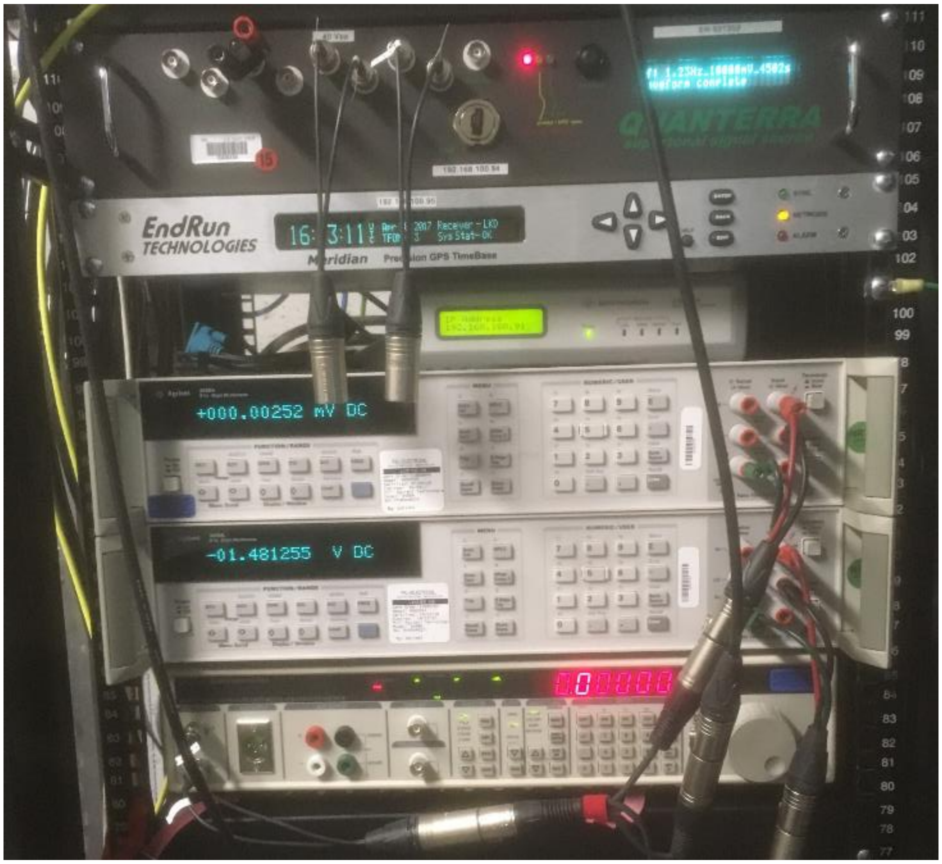

Figure 6 FACT Bunker Digitizer Testbed, Signal Generators and Reference Meters

Testing of the preamplifiers was performed using a Guralp DM24S3AM digitizer, SN A2187 (A3897) for data acquisition. The Guralp DM24 was calibrated against the FACT Digitizer Testbed prior to acquiring data for this evaluation.

Figure 7 Guralp DM24 Digitizer

2.2 Scope and Timeline

The following table lists the tests and resulting evaluations that were performed of the Guralp Preamplifier for GS13 Seismometers at Sandia National Laboratories between April 1 and May 8, 2017

Table 3 Tests performed

Test	G23511	G23512
Power	April 20, 2017, 19:50 – 20:00 UTC	April 20, 2017, 19:28 – 19:47 UTC
Impedance	April 12, 2017, 19:38 - 20:40 UTC	May 8, 2017, 17:50 – 18:05 UTC
DC Accuracy	April 12, 2017, 20:15 – 20:19 UTC	April 18, 2017, 17:22 – 17:26 UTC
AC Accuracy	April 12, 2017, 20:21 – 20:22 UTC	April 18, 2017, 17:28 – 17:29 UTC
AC Full Scale	April 12, 2017, 20:06 UTC	April 18, 2017, 17:31 UTC
AC Over Scale	April 12, 2017, 20:07 UTC	April 18, 2017, 17:33 UTC
Input Shorted Offset	April 20, 2017, 21:30 UTC – April 21, 2017, 17:00 UTC	April 19, 2017, 19:14 UTC – April 20, 2017, 16:00 UTC
Self-Noise	April 20, 2017, 21:30 UTC – April 21, 2017, 17:00 UTC	April 19, 2017, 19:14 UTC – April 20, 2017, 16:00 UTC
Dynamic Range	April 20, 2017, 21:30 UTC – April 21, 2017, 17:00 UTC	April 19, 2017, 19:14 UTC – April 20, 2017, 16:00 UTC
System Noise	April 20, 2017, 21:30 UTC – April 21, 2017, 17:00 UTC	April 19, 2017, 19:14 UTC – April 20, 2017, 16:00 UTC
Tonal Response Verification	April 14, 2017, 12:30 – 16:00 UTC	April 19, 2017, 12:10 – 14:23 UTC
White Response Verification	April 14, 2017 10:00 – 12:30 UTC	April 19, 2017, 09:45 – 12:10 UTC
Relative Transfer Function	April 14, 2017 10:00 – 12:30 UTC	April 19, 2017, 09:45 – 12:10 UTC
Time Tag Accuracy	April 13, 2017, 16:15 – 16:40 UTC	April 18, 2017, 17:38 – 18:02 UTC
Analog Bandwidth	April 14, 2017, 10:00 – 12:30 UTC	April 19, 2017, 09:45 – 12:10 UTC
Total Harmonic Distortion	April 21, 2017 18:55 – 19:25	April 21, 2017, 20:30 – 21:00 UTC
Modified Noise Power Ratio	April 13, 2017, 21::40 UTC – April 14, 2017, 10:00 UTC	April 18, 2017, 21:20 – April 19, 2017, 09:43 UTC
Common Mode Rejection	April 13, 2017 16:47 – 16:48 UTC	April 18, 2017, 18:03 – 19:04 UTC
Calibrator DC Accuracy	April 17, 2017, 18:12 – 18:15 UTC	April 20, 2017, 17:37 – 17:40 UTC
Calibrator AC Accuracy	April 17, 2017, 18:19 UTC	April 20, 2017, 17:42 UTC
Calibrator Response Verification	April 17, 2017, 18:45 – 20:00 UTC	April 20, 2017, 18:05 – 18:45 UTC
Calibrator Relative Transfer	April 17, 2017 18:45 – 20:00 UTC	April 20, 2017, 18:05 – 18:45 UTC

Function		
Calibrator Analog Bandwidth	April 17, 2017 18:45 – 20:00 UTC	April 20, 2017, 18:05 – 18:45 UTC
Calibrator Crosstalk	April 17, 2017 18:30 – 18:40 UTC	April 20, 2017, 17:47 – 18:00 UTC
GS13 Seismometer Calibration	April 28, 2017, 16:24 – 17:40 UTC	April 26, 2017, 16:20 – 23:

2.3 Evaluation Frequencies

The frequency range of the measurements is from 0.01 Hz to 80 Hz. Specifically, the frequencies from the function below which generates standardized octave-band values in Hz (ANSI S1.6-1984) with F_0 = 1 Hz:

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

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

0.01,	0.0125,	0.016,	0.020,	0.025,	0.0315,	0.040,	0.050,	0.063,	0.08,
0.10,	0.125,	0.16,	0.20,	0.25,	0.315,	0.40,	0.50,	0.63,	0.8,
1.0,	1.25,	1.6,	2.0,	2.5,	3.15,	4.0,	5.0,	6.3,	8.0,
10.0,	12.5,	16.0,	20.0,	25.0,	31.5,	40.0,	50.0,	63.0,	80.0

3 TEST EVALUATION

3.1 Power Consumption

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

3.1.1 Measurand

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

3.1.2 Configuration

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

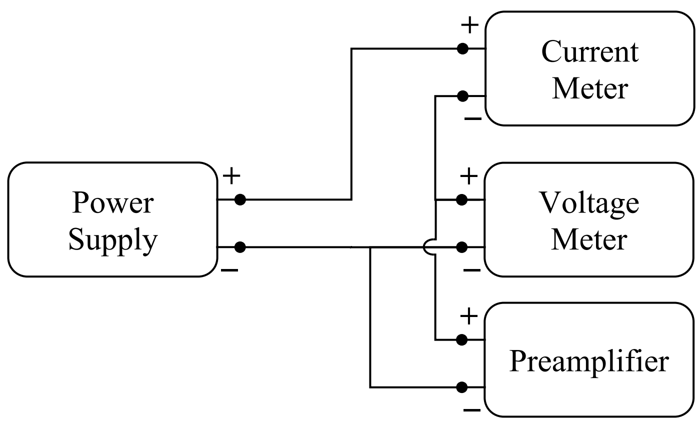

Figure 8 Power Consumption Configuration Diagram

Table 4 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Power Supply	BK Precision 1739	S/N 342D14131	13 V
Voltage Meter	Agilent 3458A	MY45048372	Voltage
Current Meter	Agilent 3458A	MY45048371	Current

Measurements of power consumption were made while the preamplifier was powered on and its inputs were driven with a range of signals:

- Input terminated
- 50 mV 1.0 Hz sine
- 0.25 V 1.0 Hz sine

- 0.5 V 1.0 Hz sine
- white noise with a peak of approximately 0.5 V.

These range of inputs span the amplitude input range of the preamplifier and should provide a representative view of the expected power consumption

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

Example plots of the recordings of voltage and current are show in the figure below. The window regions bounded by the red lines indicate the segment of data used to evaluate the data.

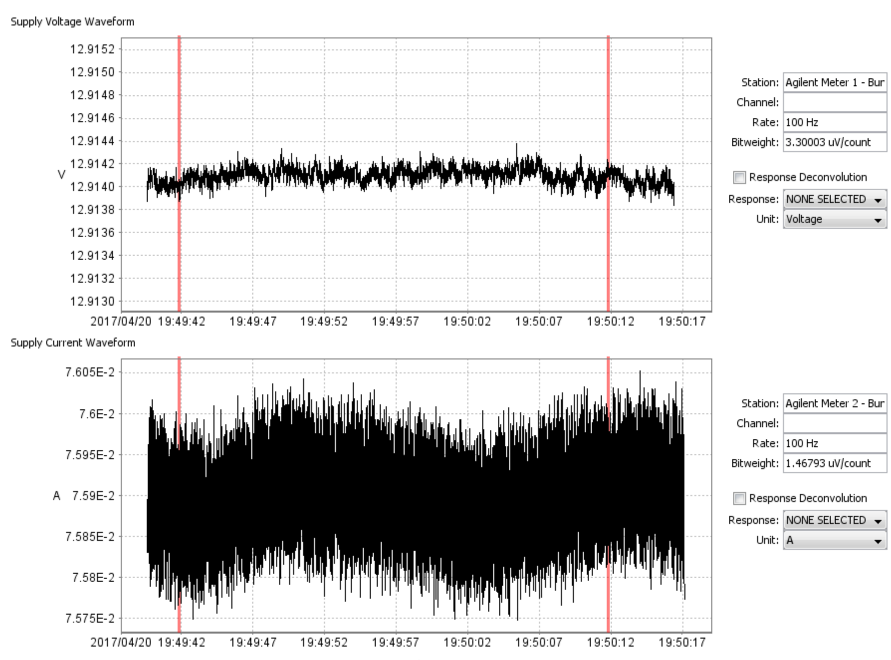

Figure 9 Voltage and Current recorded time series - Input Terminated

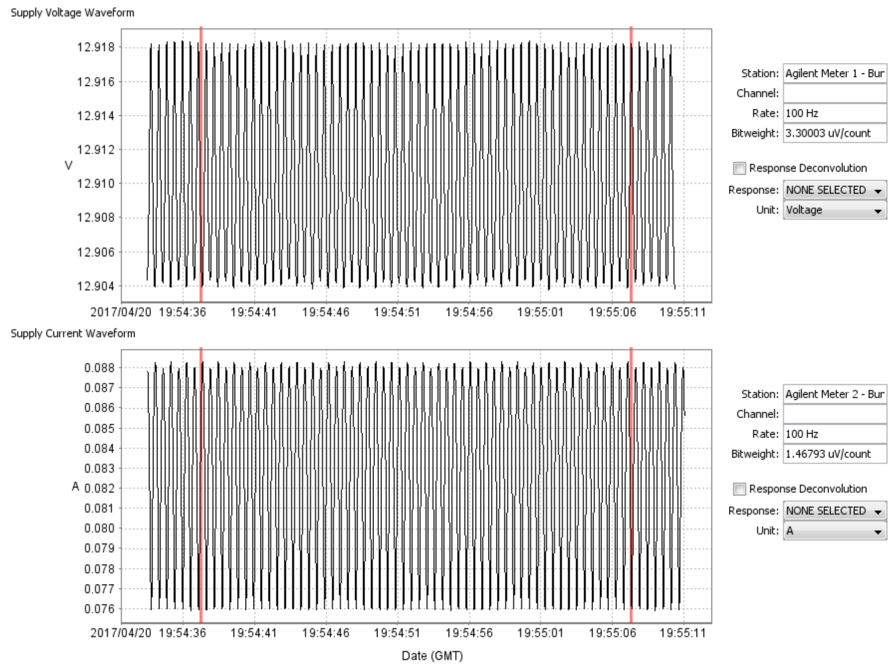

Figure 10 Voltage and Current recorded time series - Full Scale Sinusoid

Note that the instantaneous voltage and current levels were observed to increase proportional to the amplitude of the signal being amplified, as may be seen in Figure 10 when the preamplifier input was being driven with a full scale sinusoid.

The power consumption levels, computed from the mean and standard deviation estimates of voltage and current, are provided in the table below.

Table 5 Power Consumption Results – G23511

	Voltage		Current		Power	
	Mean	Std	Mean	Std	Mean	Std
Input Terminated	12.91 V	0.064 mV	75.89 mA	0.06 mA	0.980 W	0.84 mW
50 mVp Sine	12.92 V	0.170 mV	76.07 mA	0.13 mA	0.983 W	1.65 mW
0.25 Vp Sine	12.92 V	1.923 mV	78.58 mA	1.65 mA	1.015 W	21.51 mW
0.5 Vp Sine	12.91 V	4.780 mV	83.02 mA	4.10 mA	1.072 W	53.42 mW
0.5 Vp White	12.92 V	0.792 mV	77.23 mA	1.41 mA	0.998 W	18.39 mW

Table 6 Power Consumption Results – G235112

	Voltage		Current		Power	
	Mean	Std	Mean	Std	Mean	Std
Input Terminated	12.91 V	0.070 mV	76.20 mA	0.07 mA	0.983 W	0.86 mW
50 mVp Sine	12.91 V	0.184 mV	76.38 mA	0.13 mA	0.986 W	1.66 mW
0.25 Vp Sine	12.90 V	2.206 mV	78.89 mA	1.65 mA	1.018 W	21.49 mW
0.5 Vp Sine	12.90 V	5.473 mV	83.32 mA	4.10 mA	1.074 W	53.41 mW
0.5 Vp White	12.90 V	0.905 mV	77.56 mA	1.46 mA	1.001 W	18.80 mW

The preamplifiers were found to consume approximately 0.98 W of power with only very slight increases in power consumption, of approximately 90 mW, up to a maximum of 1.07 W when driven with a full-scale signal. These results are in agreement with Guralp's datasheet specification of the preamplifier consuming 80 mA at 12 V (0.96 W).

3.2 Impedance
The Impedance test is used to measure the real DC impedance of a channel during its operation.

3.2.1 Measurand

The quantity being measured is ohms of impedance.

3.2.2 Configuration

The preamplifier inputs and outputs were connected to a meter configured to measure impedance as shown in the diagram below.

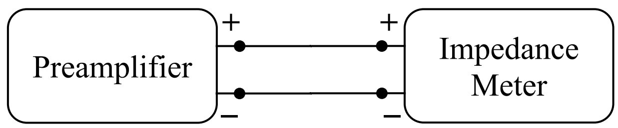

Figure 11 Input Impedance Configuration Diagram

Table 7 Input Impedance Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Impedance Meter	Agilent 3458A	MY45048372	Impedance (ohms)

Measurements of both the input and output impedance were made on the preamplifiers signal and calibration lines. Note that on the calibration lines, the measurements were made with both the calibration enable line non-active and active as the preamplifier is supposed to enable a relay to enable the calibrator.

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

3.2.3 Analysis

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

3.2.4 Result

Example plots of the recordings of impedance are show in the figure below. The window regions bounded by the red lines indicate the segment of data used to evaluate the data.

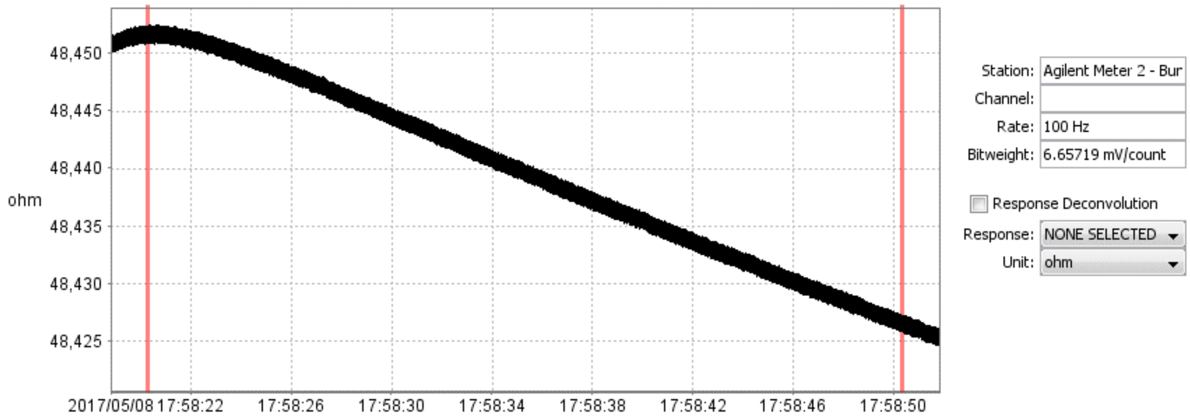

Figure 12 Signal Input Impedance time series

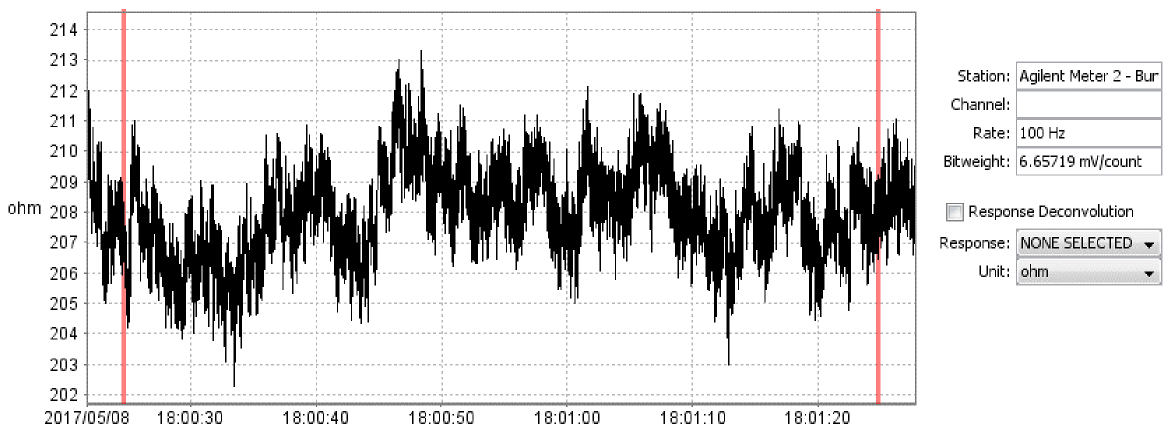

Figure 13 Signal Output Impedance time series

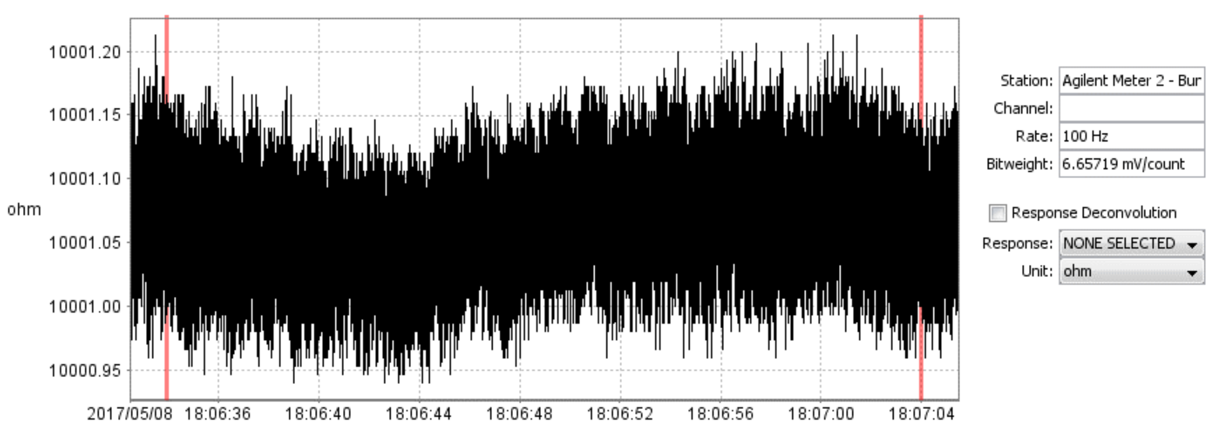

Figure 14 Calibrator Input Impedance time series

The measured impedances for each of the preamplifiers are shown in the table below.

Table 8 Impedance Results

	Nominal	G23511	G23512
Signal Input	47.00 kohm	48.24 kohm	48.44 kohm
Signal Output	Not specified	209.56 kohm	207.94 kohm
Calibration Input - Nonactive	Not specified	10.00 kohm	10.00 kohm
Calibration Input - Active	Not specified	10.00 kohm	10.00 kohm
Calibration Output - Nonactive	Open	Open - no reading	Open - no reading
Calibration Output - Active	200.0 ohm	207.6 ohm	200.2 ohm

The measured input impedance of the preamplifiers was between 48.24 and 48.44 kohm, which is near the specified input impedance of 47 kohm. The signal output and calibration input line impedances were not specified within the datasheet, but were found to have values of approximately 200 kohm and 10 kohm, respectively.

As reported in the datasheet for the preamplifier, the calibration output to the GS13 Seismometer does indeed measure as being open when calibration is not enabled, indicating that the preamplifier calibration relay is performing as described. When calibration was enabled, the output impedance measured between 200.2 and 207.6 ohms, which is consistent with the specification of 200 ohms.

3.3 DC Accuracy

The DC Accuracy test is used to measure the gain of a preamplifier channel by recording a known positive and negative dc signal at a reference voltage at both the preamplifier input and output using a precision voltage source.

3.3.1 Measurand

The quantity being measured is the unitless preamplifier gain at DC.

3.3.2 Configuration

The preamplifier is connected to a DC signal source and meters are configured to measure voltage as shown in the diagram below.

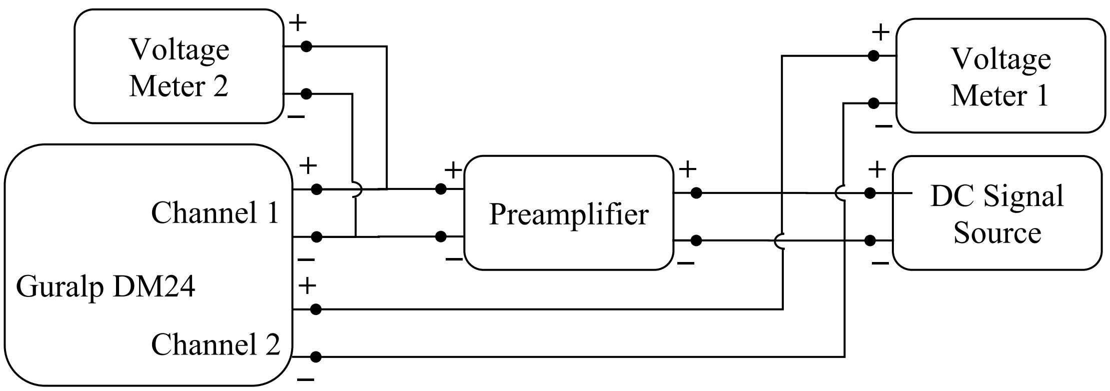

Figure 15 DC Accuracy Configuration Diagram

Table 9 DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	SRS DS360	S/N 123672	+50 mV / - 50 mV
Voltage Meter 1	Agilent 3458A	MY45048372	0.1 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	10 V Full Scale Mode

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

The meters and the digitizer channels record the described DC voltage signal simultaneously. The recording made on the meters was used as the reference for comparison of the amplifier input and output. The meters were configured to record at 100 Hz.

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

3.3.3 Analysis

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

The average of each of the positive and negative segments are computed from the reference meter in volts:
V_{pos} *and* V_{neg}

The average of each of the positive and negative segments are computed from the digitizer channel in counts:
C_{pos} *and* C_{neg}

The digitizer bit weight in Volts / count is computed:

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

The digitizer DC offset is computed:

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

3.3.4 Result

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

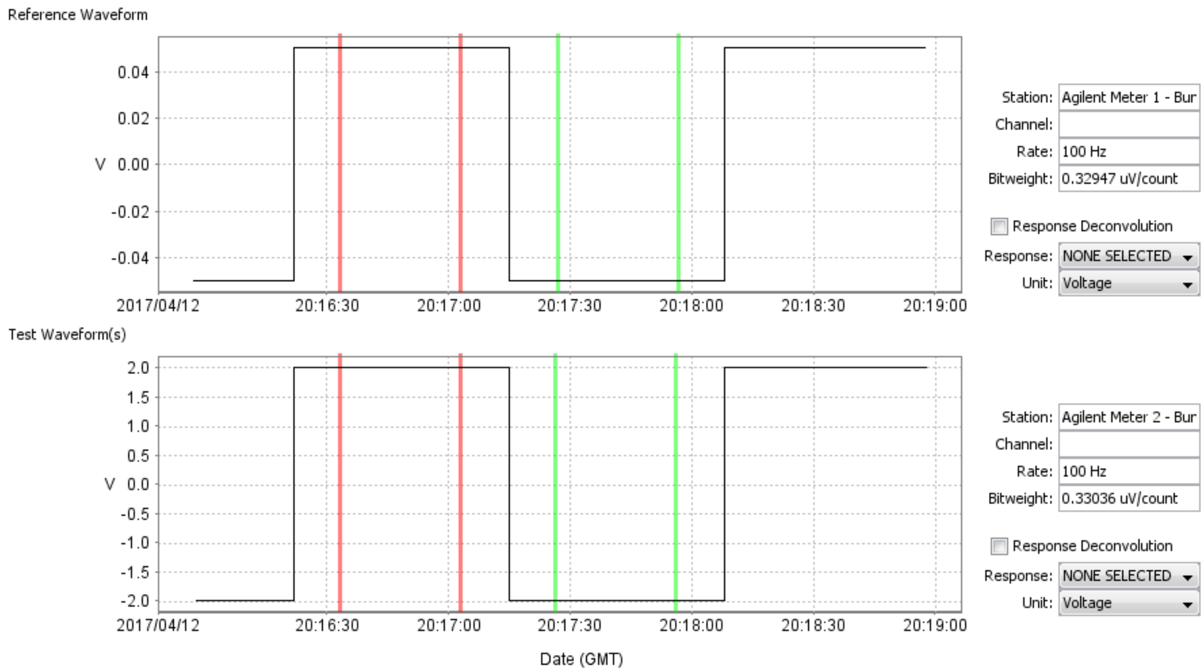

Figure 16 DC Accuracy Time Series

The following table contains the recorded amplitudes and gain levels for the two amplifiers.

Table 10 DC Accuracy

	G23511	G23512
Meter 2, Preamplifier Input Peak-to-peak	3.9916 V	3.9875 V
Meter 1 Peak-to-peak	0.1000 V	0.1000 V
Measured Gain	39.9274	39.8819
Nominal Gain	40.0000	40.0000
Difference	-0.18%	-0.30%

The nominal gain provided by Guralp was specified to be 40. The observed DC gain of the two amplifiers differed from nominal by less than 0.3 %.

3.4 AC Accuracy

The AC Accuracy test is used to measure the gain of a preamplifier channel by recording a known AC signal at a reference voltage at both the preamplifier input and output using a precision voltage source.

3.4.1 Measurand

The quantity being measured is the unitless preamplifier gain at 1 Hz.

3.4.2 Configuration

The amplifier is connected to an AC signal source and meters configured to measure voltage as shown in the diagram below.

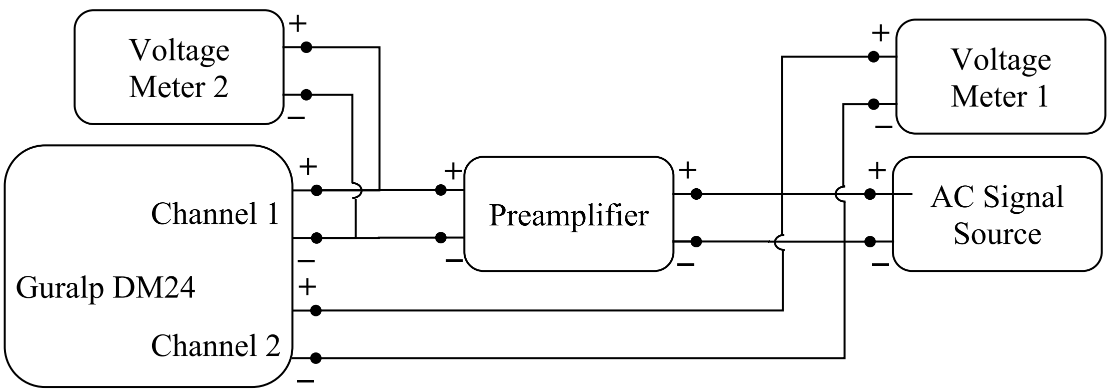

Figure 17 AC Accuracy Configuration Diagram

Table 11 AC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	S/N 123672	+50 mV 1.0 Hz Sine
Voltage Meter 1	Agilent 3458A	MY45048372	0.1 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	10 V Full Scale Mode

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

The meters and the digitizer channels record the described AC voltage signal simultaneously. The recording made on the meters is used as the reference for comparison of the amplifier input and output. The meters are 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 data recorded at the input and output of the preamplifier order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

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

The preamplifier gain is computed:

$$gain=\frac{V_{out}}{V_{in}}$$

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.

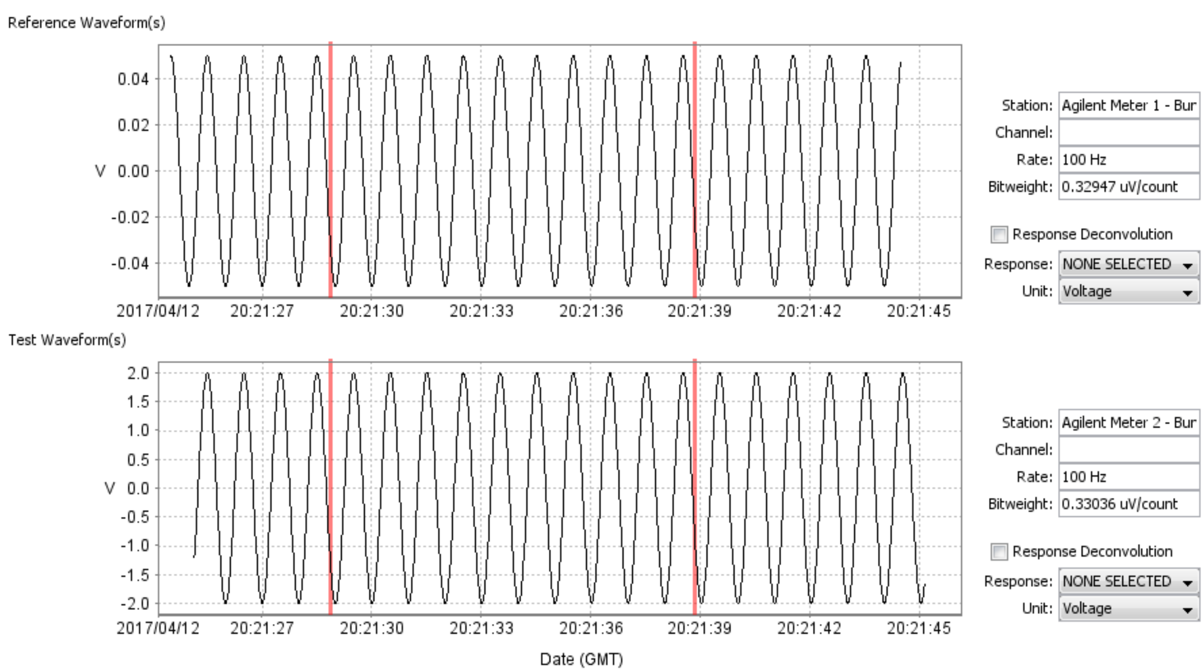

Figure 18 AC Accuracy Time Series

The following table contains the recorded amplitudes and gain levels for the two amplifiers.

Table 12 AC Accuracy Gain

	G23511	G23512
Meter 2 Peak-to-peak	3.9886 V	3.9843 V
Meter 1 Peak-to-peak	0.0999 V	0.0999 V
Gain	39.9267	39.8820
Nominal Gain	40.0000	40.0000
Difference	-0.18%	-0.29%

The nominal gain provided by Guralp was specified to be 40. The observed AC gain of the two amplifiers differed from nominal by less than 0.29 %.

3.5 AC Full Scale

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

3.5.1 Measurand

The quantity being measured is the amplifier input channel's full scale in volts.

3.5.2 Configuration

The amplifier is connected to an AC signal source and meters configured to measure voltage as shown in the diagram below.

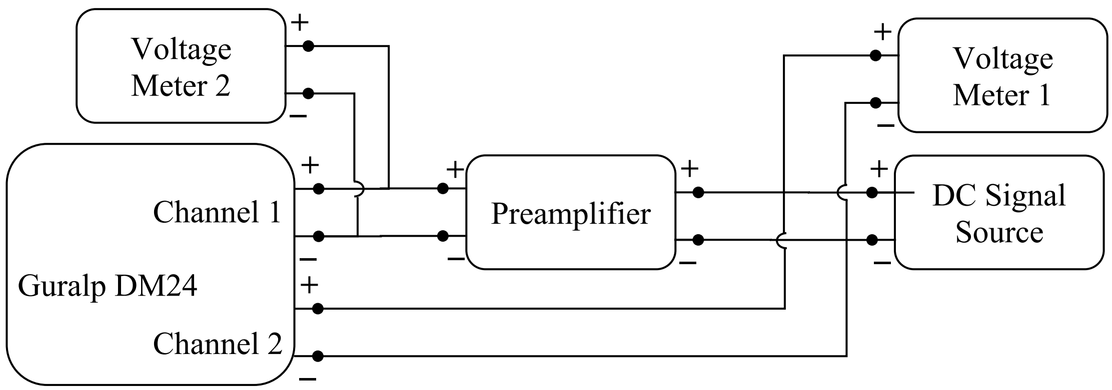

Figure 19 AC Full Scale Configuration Diagram

Table 13 AC Full Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	S/N 123672	+0.5 V 1.0 Hz Sine
Voltage Meter 1	Agilent 3458A	MY45048372	0.1 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	10 V Full Scale Mode

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. 10 seconds of data is recorded.

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

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

3.5.3 Analysis

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

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

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

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

3.5.4 Result

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

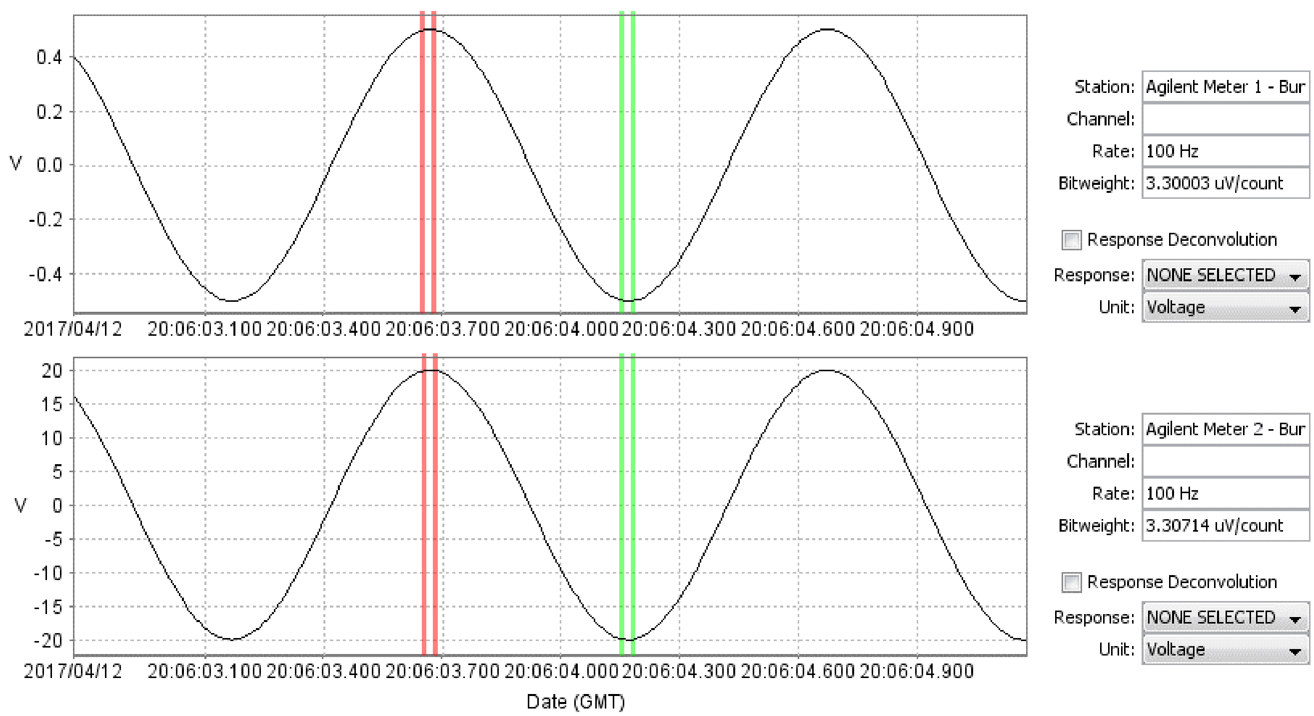

Figure 20 AC Full Scale Time Series

The following tables contain the computed positive peak and negative peak voltages.

Table 14 AC Full Scale Positive and Negative Peak

	G23511	G23512
Input Positive Value	0.4970 V	0.4986 V
Output Positive Value	19.8918 V	19.8835 V
Input Negative Value	-0.4994 V	-0.4998 V
Output Negative Value	-19.9366 V	-19.9178 V

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

This result is consistent with the preamplifier having an input and output peak full scale in excess of 0.5 V and 20 V, respectively.

3.6 AC Over Scale

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

3.6.1 Measurand

The quantity being measured is the amplifier input channel full scale in volts.

3.6.2 Configuration

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

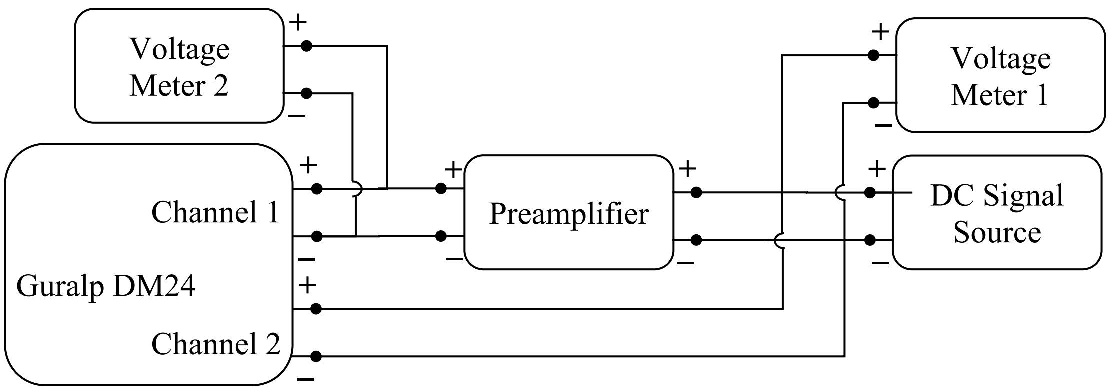

Figure 21 AC Over Scale Configuration Diagram

Table 15 AC Over Scale Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	S/N 123672	+1.0 V 1.0 Hz Sine
Voltage Meter 1	Agilent 3458A	MY45048372	1.0 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	100 V Full Scale Mode

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

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

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

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

3.6.3 Analysis

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

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

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.

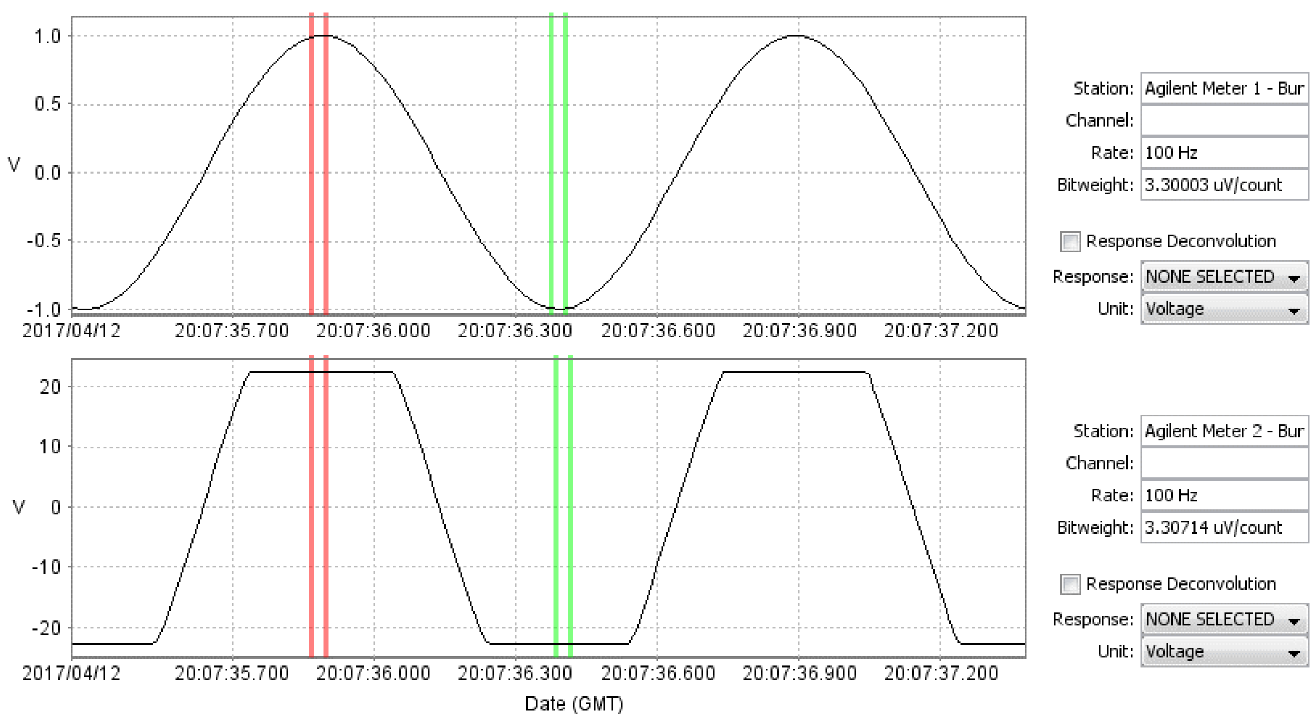

Figure 22 AC Over Scale Time Series

The following tables contain the computed positive peak and negative peak voltages ranges for each of the amplifiers.

Table 16 AC Over Scale Positive and Negative Peak

	G23511	G23512
Input Positive Amplitude	0.9930 V	0.9961 V
Output Positive Amplitude	22.4088 V	22.4874 V
Input Negative Amplitude	-0.9984 V	-0.9984 V
Output Negative Amplitude	-22.7797 V	-22.7885 V

The amplifier channels were determined to have a full scale amplitude that exceeded the nominally specified full scale of 20 Vpp.

The measured full scale exceeded 45 Vpp (or 22.5 Vp) on the output which corresponds to an amplifier input full scale in excess of 1.125 Vpp (or 0.5625 Vp) for a nominal gain of 40x.

3.7 Input Shorted Offset

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

3.7.1 Measurand

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

3.7.2 Configuration

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

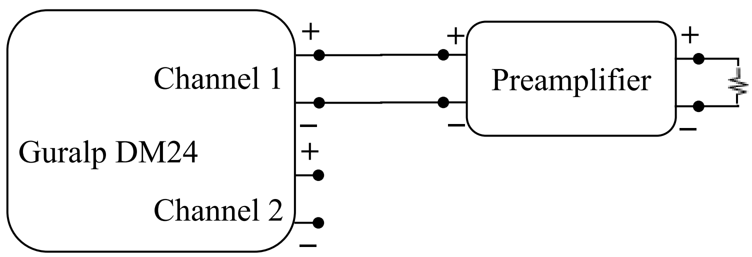

Figure 23 Input Shorted Offset Configuration Diagram

Table 17 Input Shorted Offset Testbed Equipment

	Impedance
Resistor	10 kohm

Over 12 hours of data is recorded.

3.7.3 Analysis

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

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

The mean value, in volts, is evaluated:

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

3.7.4 Result

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

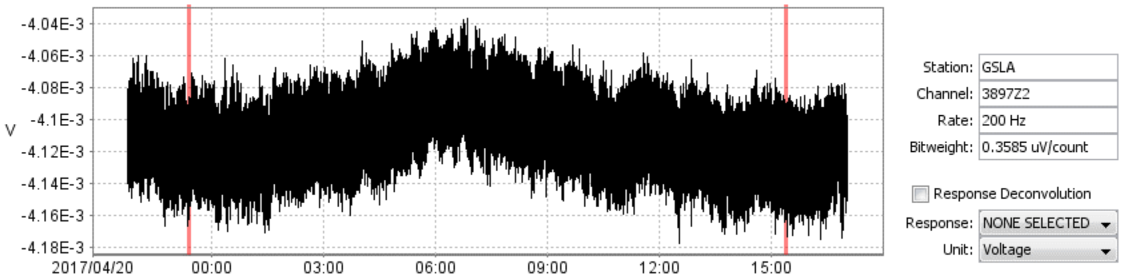

Figure 24 Input Shorted Offset Time Series – G23511

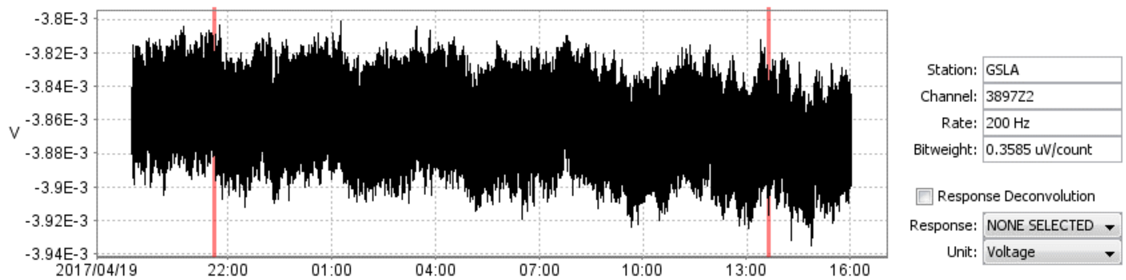

Figure 25 Input Shorted Offset Time Series – G23512

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

Table 18 Input Shorted Offset

	G23511	G23512
Input Shorted Offset	-4.1084 mV	-3.8621 mV

The observed Input Shorted Offsets on the preamplifier output corresponds to approximately 0.018 % of the full-scale output.

3.8 Self-Noise

The Self-Noise test measures the amount of noise present on an amplifier 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 amplifier.

3.8.1 Measurand

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

3.8.2 Configuration

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

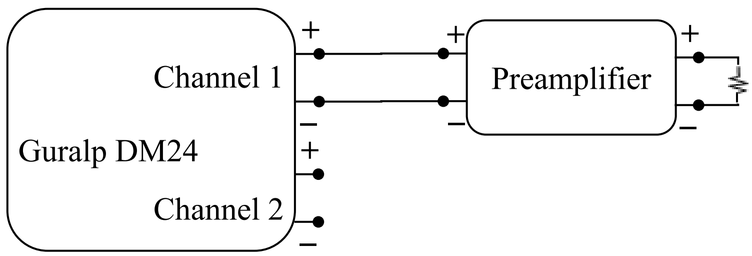

Figure 26 Self Noise Configuration Diagram

Figure 27 Self Noise Configuration Picture

Table 19 Self Noise Testbed Equipment

	Impedance
Resistor	10k (5k x 2) ohm

For the purpose of recording the preamplifier self-noise, the Guralp DM24 digitizer was set to a gain of 8x so as to assure that any noise present would not be due to the digitizer. In addition, measurements were made separately of the digitizer self-noise at gains of 1x, 2x, 4x, and 8x to compare against the preamplifier self-noise. Between 12 and 24 hours of data is recorded.

3.8.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 32k-sample Hann window. 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. The resulting 90% confidence interval was determined to be 0.37 dB.

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

Over frequencies (in Hertz):

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

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

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

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

3.8.4 Result

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

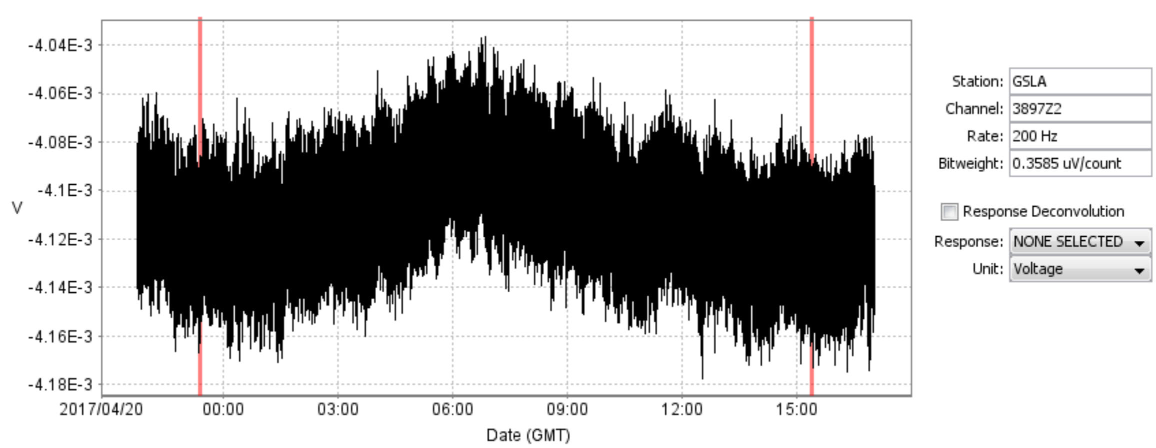

Figure 28 Self Noise Time Series – G23511

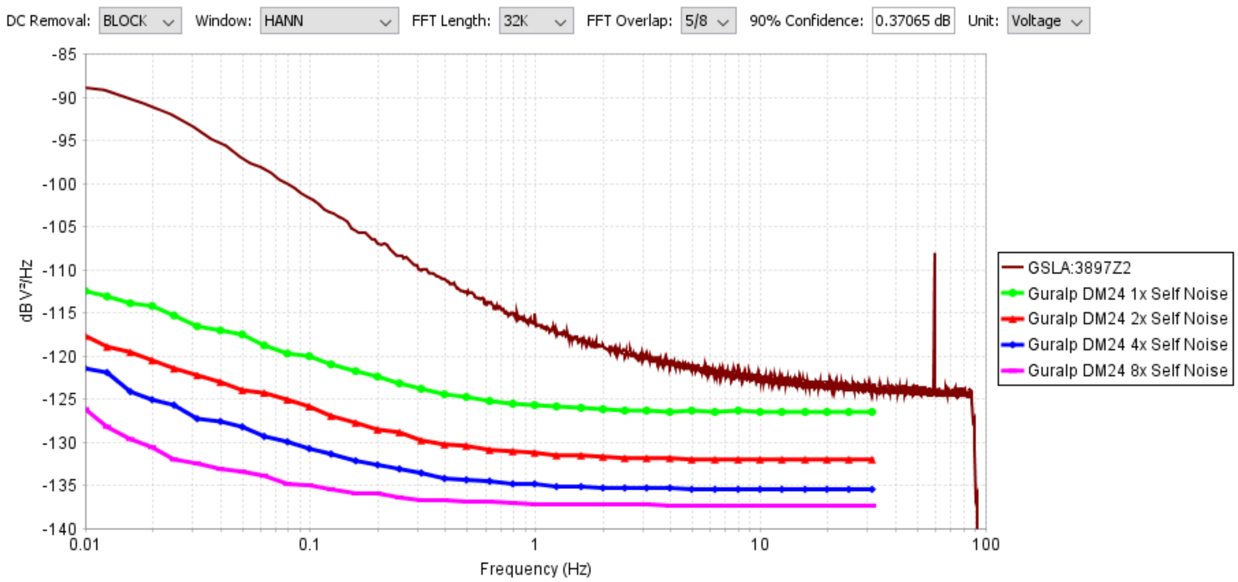

Figure 29 Self Noise Power Spectra – G23511

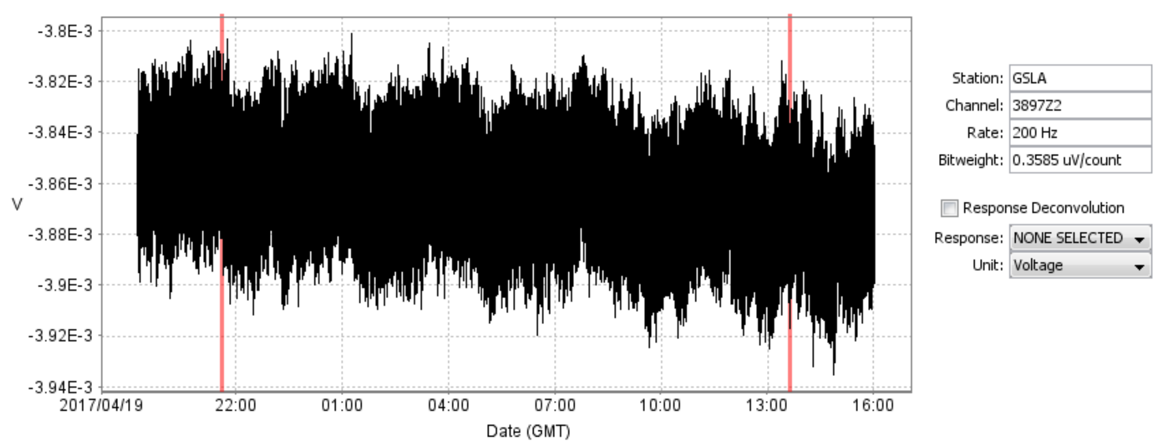

Figure 30 Self Noise Time Series – G23512

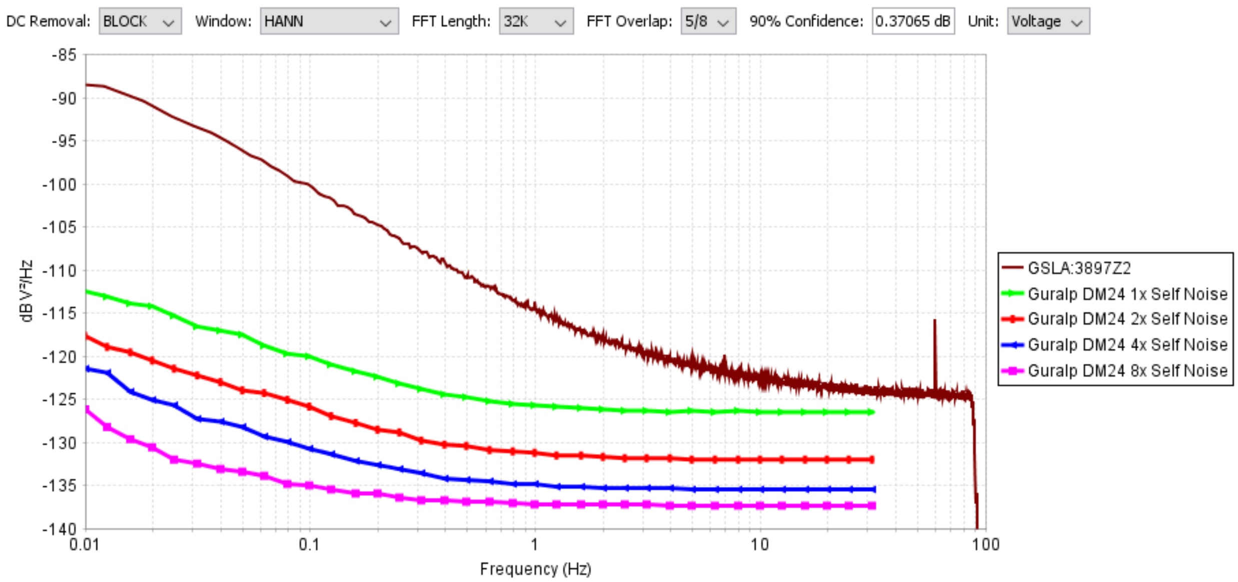

Figure 31 Self Noise Power Spectra – G23512

The following tables contains the computed RMS noise levels in volts for each of the evaluated preamplifiers. A frequency pass-band consistent with the application requirements for the short-period seismic application was selected.

Table 20 Self Noise RMS

	G23511	G23512
0.5 - 16 Hz	3.4945 uV rms	3.7866 uV rms
0.5 - 80 Hz	6.1970 uV rms	6.2388 uV rms
0.01 - 80 Hz	8.5285 uV rms	8.9130 uV rms

As may be seen in the power spectra plots, the self-noise of the preamplifier is greater than the self-noise of the Guralp DM24 in any of its gain settings. However, at a gain of 1x, the DM24 is within less than 5 dB of the preamplifier at frequencies above 10 Hz. Since the noise is additive, total system noise could be reduced very slightly above 10 Hz by increasing the DM24 gain to 2x. However, this will come at the expense of reducing the full scale of the system.

Beyond a gain of 2x, decreasing the digitizer noise level will not result in significantly improved system noise and would only serve to further reduce full scale.

The table below contains the preamplifier self-noise PSD values expressed in dB relative to 1 V^2/Hz.

Table 21 Self Noise Power Spectral Densities

Frequency	G23511	G23512
0.0100 Hz	-88.92 dB	-88.62 dB
0.0125 Hz	-89.66 dB	-89.37 dB
0.0160 Hz	-90.09 dB	-89.54 dB
0.0200 Hz	-91.37 dB	-91.71 dB
0.0250 Hz	-92.15 dB	-92.00 dB
0.0315 Hz	-93.76 dB	-93.85 dB
0.0400 Hz	-95.25 dB	-95.34 dB
0.0500 Hz	-97.60 dB	-95.98 dB
0.0630 Hz	-98.39 dB	-97.64 dB
0.0800 Hz	-99.87 dB	-99.32 dB
0.1000 Hz	-101.72 dB	-100.04 dB
0.1250 Hz	-103.34 dB	-101.52 dB
0.1600 Hz	-105.48 dB	-103.16 dB
0.2000 Hz	-106.94 dB	-104.70 dB
0.2500 Hz	-108.34 dB	-106.41 dB
0.3150 Hz	-110.06 dB	-107.89 dB
0.4000 Hz	-111.09 dB	-109.23 dB
0.5000 Hz	-112.85 dB	-110.89 dB
0.6300 Hz	-113.76 dB	-112.07 dB
0.8000 Hz	-115.16 dB	-113.44 dB
1.0000 Hz	-116.41 dB	-114.50 dB
1.2500 Hz	-117.24 dB	-115.75 dB
1.6000 Hz	-118.14 dB	-116.87 dB
2.0000 Hz	-119.01 dB	-117.95 dB
2.5000 Hz	-119.63 dB	-118.91 dB
3.1500 Hz	-120.18 dB	-119.73 dB
4.0000 Hz	-120.92 dB	-120.37 dB
5.0000 Hz	-121.40 dB	-121.02 dB
6.3000 Hz	-121.81 dB	-121.68 dB
8.0000 Hz	-122.30 dB	-122.18 dB
10.0000 Hz	-122.71 dB	-122.57 dB
12.5000 Hz	-123.00 dB	-122.93 dB
16.0000 Hz	-123.28 dB	-123.30 dB
20.0000 Hz	-123.50 dB	-123.54 dB
25.0000 Hz	-123.66 dB	-123.76 dB
31.5000 Hz	-123.85 dB	-124.00 dB
40.0000 Hz	-123.96 dB	-124.18 dB
50.0000 Hz	-124.11 dB	-124.30 dB
63.0000 Hz	-124.23 dB	-124.46 dB
80.0000 Hz	-124.34 dB	-124.58 dB

3.9 Dynamic Range

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

3.9.1 Measurand

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

3.9.2 Configuration

There is no test configuration for the dynamic range test.

The full scale value used for the largest signal comes from the manufacturer's nominal specifications, validated during testing. The value for the smallest signal comes from the evaluated digitizer channel self-noise.

3.9.3 Analysis

The dynamic range over a given pass-band is:

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

Where

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

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

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

3.9.4 Result

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

Table 22 Dynamic Range

	G23511			G23512		
Passband	Full Scale (Peak)	Self Noise	Dynamic Range	Full Scale (peak)	Self Noise	Dynamic Range
0.5 Hz - 16 Hz	22.50 V	3.4945 uV rms	133.17 dB	22.50 V	3.7866 uV rms	132.47 dB
0.5 Hz - 80 Hz	22.50 V	6.1970 uV rms	128.19 dB	22.50 V	6.2388 uV rms	128.13 dB
0.01 Hz - 80 Hz	22.50 V	8.5285 uV rms	125.42 dB	22.50 V	8.9130 uV rms	125.03 dB

The measured dynamic range values were better than 132 dB over the IMS seismic short-period passband of 0.5 – 16 Hz. Over wider passbands the dynamic range is lower, between 125 and 128 dB, as additional self-noise is included in the passband.

Note that these measures of dynamic range presume that the digitizer does not limit the full-scale output of the preamplifier. The Guralp DM24 has a full-scale peak amplitude at gains of 1x, 2x, 4 x, and 8x of approximately 24 V, 12 V, 6 V, and 3V, respectively. Therefore, the preamplifier output amplitude will be limited by the digitizer full scale at any gain beyond 1x.

The table below provides estimates of system dynamic range for digitizer gains of 1x, 2x, 4x, and 8x.

Table 23 Dynamic Range including DM24 Digitizer Gain

		G23511, 0.5 - 16 Hz		G23512, 0.5 - 16 Hz	
Gain	Full Scale	Self Noise	Dynamic Range	Self Noise	Dynamic Range
1x	22.5 V	3.4945 uV rms	133.17 dB	3.7866 uV rms	132.47 dB
2x	12.0 V	3.4945 uV rms	127.71 dB	3.7866 uV rms	127.01 dB
4x	6.0 V	3.4945 uV rms	121.68 dB	3.7866 uV rms	120.99 dB
8x	3.0 V	3.4945 uV rms	115.66 dB	3.7866 uV rms	114.97 dB

There is observed to be a slightly less than 6 dB reduction in dynamic range at each doubling of the gain, which is to be expected as the full-scale is cut in half at each step.

3.10 System Noise

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

3.10.1 Measurand

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

3.10.2 Configuration

There is no test configuration for the dynamic range test.

The time-series data and PSD are obtained from the evaluated digitizer channel self-noise.

3.10.3 Analysis

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

3.10.4 Result

The PSD of the system noise is shown in the plots below using a response model that incorporates both the GS13 Seismometer response and the nominal 40x gain of the preamplifier. The Seismic Low Noise Model, Geotech GS13 Noise Model, GERES Low Noise Model, and digitizer noise models are provided for comparison.

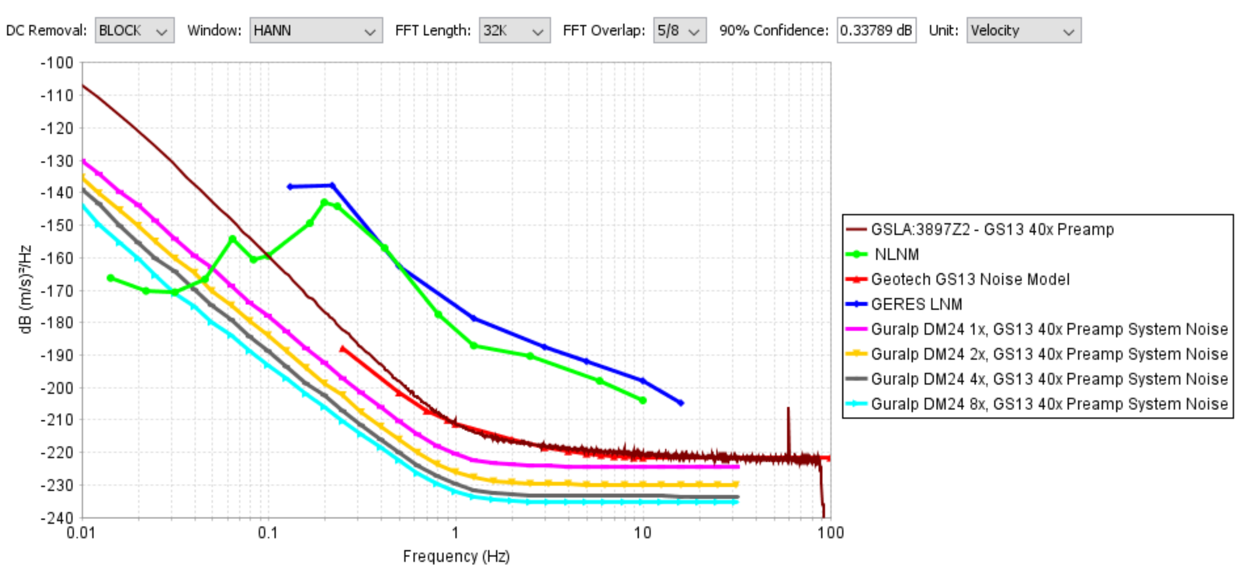

Figure 32 GS13 Seismic System Noise – G23511

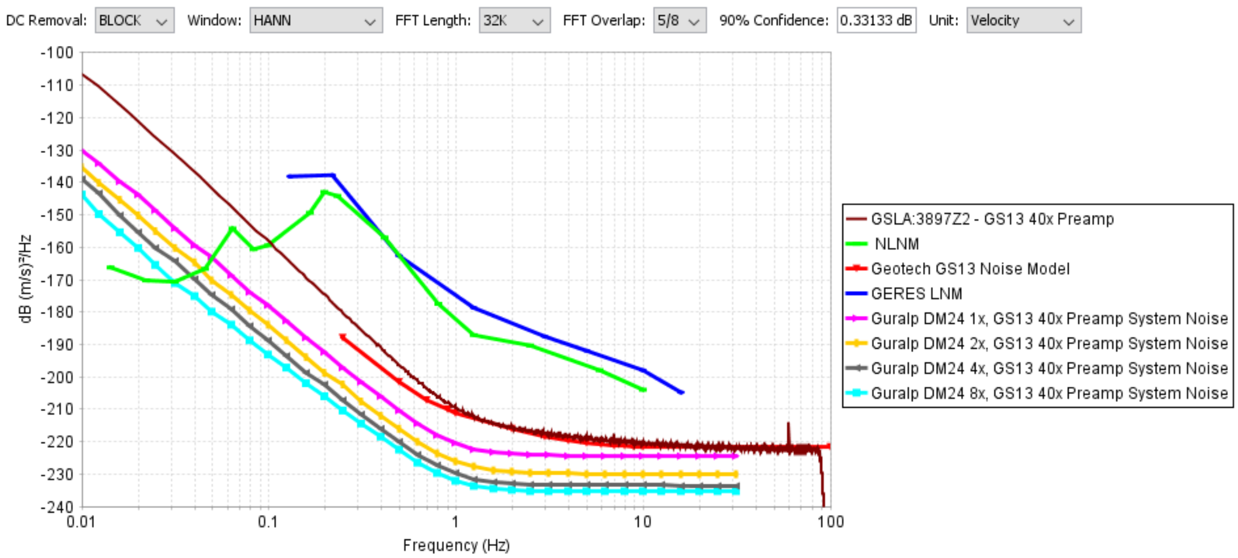

Figure 33 GS13 Seismic System Noise – G23512

Examining the system noise plots, it appears that the self-noise of the preamplifiers is well matched to the expected self-noise of the GS13 seismometer once the 40x gain of the amplifier has been applied. Note that the spike visible at 60 Hz is due to electrical interference from the on-site electrical service and is commonly seen.

Because the self-noise of the preamplifier and seismometer are approximately equal, it should be expected that the combined self-noise of the pair will be approximately 6 dB higher since the self-noise is additive. Note that under such an assumption the combined self-noise of the GS13 Seismometer and the Guralp preamplifier are more than 10 dB below the GERES Low Noise Model and more than 10 dB above the Guralp DM24 digitizer self-noise across the short-period passband of 0.5 to 16 Hz.

Also included in the system noise plots are the GS13 response corrected Guralp DM24 self-noise levels for each of the gains of 1x, 2x, 4x, and 8x. At the 16 Hz upper end of the IMS seismic short-period pass-band, the self-noise of just the Guralp GS13 preamplifier is greater than the Guralp DM24 digitizer self-noise by more than 3.3 dB at 1x gain, 8.8 dB at 2x gain, 12.4 dB at 4x gain, and 14.2 dB at 8x gain. These values are expected to be 6 dB greater when compared against the total noise of the preamplifier and GS13 seismometer.

The table below contains the preamplifier GS13 System Noise PSD values expressed in dB relative to 1 $(m/s)^2/Hz$.

Table 24 GS13 System Noise Power Spectral Densities

Frequency	G23511	G23512
0.0100 Hz	-106.61 dB	-106.05 dB
0.0125 Hz	-110.92 dB	-110.92 dB
0.0160 Hz	-115.90 dB	-115.75 dB
0.0200 Hz	-121.79 dB	-120.83 dB
0.0250 Hz	-126.61 dB	-126.73 dB
0.0315 Hz	-131.42 dB	-131.69 dB
0.0400 Hz	-137.32 dB	-136.46 dB
0.0500 Hz	-144.03 dB	-142.21 dB
0.0630 Hz	-148.73 dB	-148.09 dB
0.0800 Hz	-154.07 dB	-153.52 dB
0.1000 Hz	-159.87 dB	-158.41 dB
0.1250 Hz	-165.13 dB	-163.49 dB
0.1600 Hz	-171.86 dB	-169.70 dB
0.2000 Hz	-176.96 dB	-174.94 dB
0.2500 Hz	-182.40 dB	-180.64 dB
0.3150 Hz	-188.06 dB	-186.04 dB
0.4000 Hz	-193.23 dB	-191.27 dB
0.5000 Hz	-198.30 dB	-196.67 dB
0.6300 Hz	-203.36 dB	-201.51 dB
0.8000 Hz	-207.84 dB	-206.20 dB
1.0000 Hz	-211.35 dB	-209.72 dB
1.2500 Hz	-213.78 dB	-212.40 dB
1.6000 Hz	-215.61 dB	-214.49 dB
2.0000 Hz	-216.79 dB	-215.87 dB
2.5000 Hz	-217.59 dB	-216.83 dB
3.1500 Hz	-218.35 dB	-217.73 dB
4.0000 Hz	-219.00 dB	-218.56 dB
5.0000 Hz	-219.46 dB	-219.17 dB
6.3000 Hz	-219.96 dB	-219.74 dB
8.0000 Hz	-220.40 dB	-220.26 dB
10.0000 Hz	-220.77 dB	-220.67 dB
12.5000 Hz	-221.07 dB	-221.02 dB
16.0000 Hz	-221.33 dB	-221.38 dB
20.0000 Hz	-221.55 dB	-221.64 dB
25.0000 Hz	-221.73 dB	-221.87 dB
31.5000 Hz	-221.91 dB	-222.09 dB
40.0000 Hz	-222.05 dB	-222.27 dB
50.0000 Hz	-222.18 dB	-222.42 dB
63.0000 Hz	-222.30 dB	-222.54 dB
80.0000 Hz	-222.46 dB	-222.69 dB

3.11 Tonal Response Verification

The Tonal Response Verification test measures the amplitude and phase response at discrete frequencies using sinusoidal tones.

3.11.1 Measurand

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

3.11.2 Configuration

Multiple digitizer channels are connected to an AC signal source as shown in the diagram below.

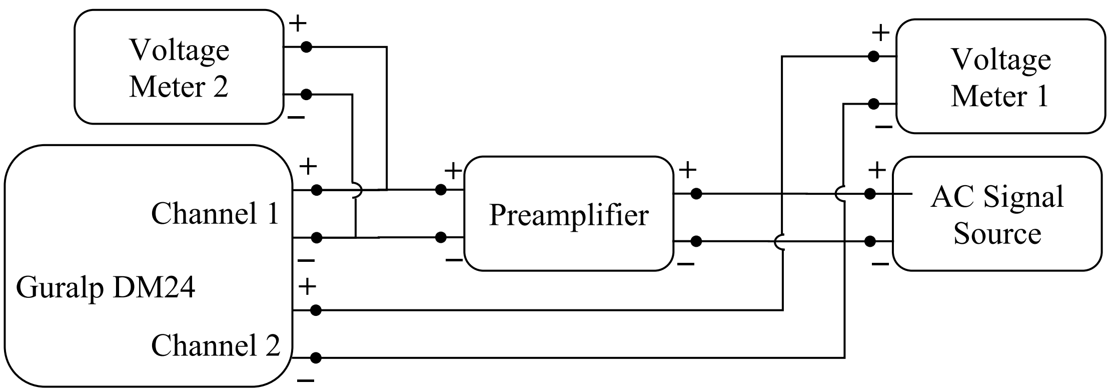

Figure 34 Tonal Response Verification Configuration Diagram

Table 25 Tonal Response Verification Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	S/N 123672	+50 mV 1.0 Hz Sine
Voltage Meter 1	Agilent 3458A	MY45048372	0.1 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	10 V Full Scale Mode

As the two Guralp DM24 channels are configured identically with the same sample rate and gain and since the two channels have been calibrated against a reference meter, any difference in the recordings of the channels is assumed to be due to the contribution of the preamplifier.

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

The meters and the digitizer channels record the described AC voltage signal simultaneously. The recording made on the meters is used as the reference for comparison of the amplifier input and output. The meters are configured to record at a minimum of 100 times the frequency of the signal of interest in order to reduce the Agilent 3458A Meter's response roll-off to less than 0.01 %.

3.11.3 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 data recorded at the input and output of the preamplifier order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

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

The preamplifier gain is computed:

$$gain = \frac{V_{out}}{V_{in}}$$

The preamplifier phase delay is computed:

$$phase\ delay = \theta_{out} - \theta_{in}$$

3.11.4 Result

The figure below shows a representative waveform time series for the recording made on the reference meter. The window regions bounded by the colored vertical lines indicate the segments of data used for analysis.

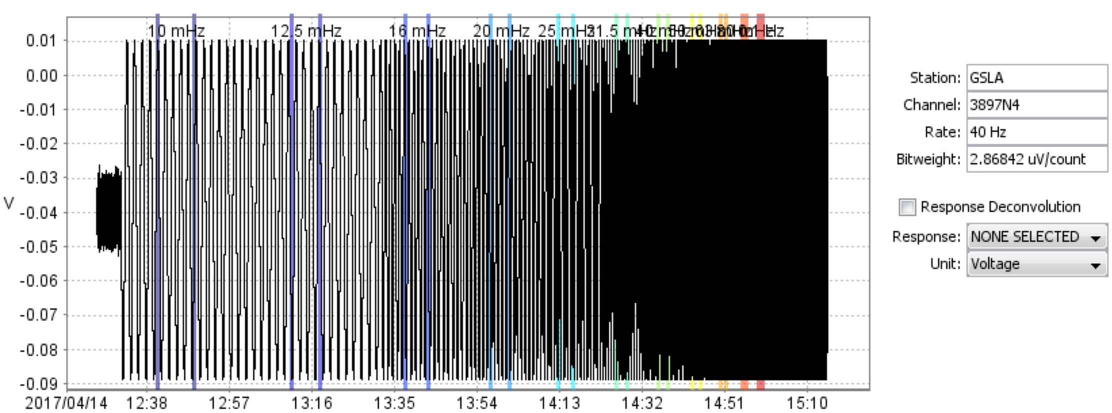

Figure 35 Tonal Response Time Series

The following plots contains the recorded gain and phase response for the two amplifiers.

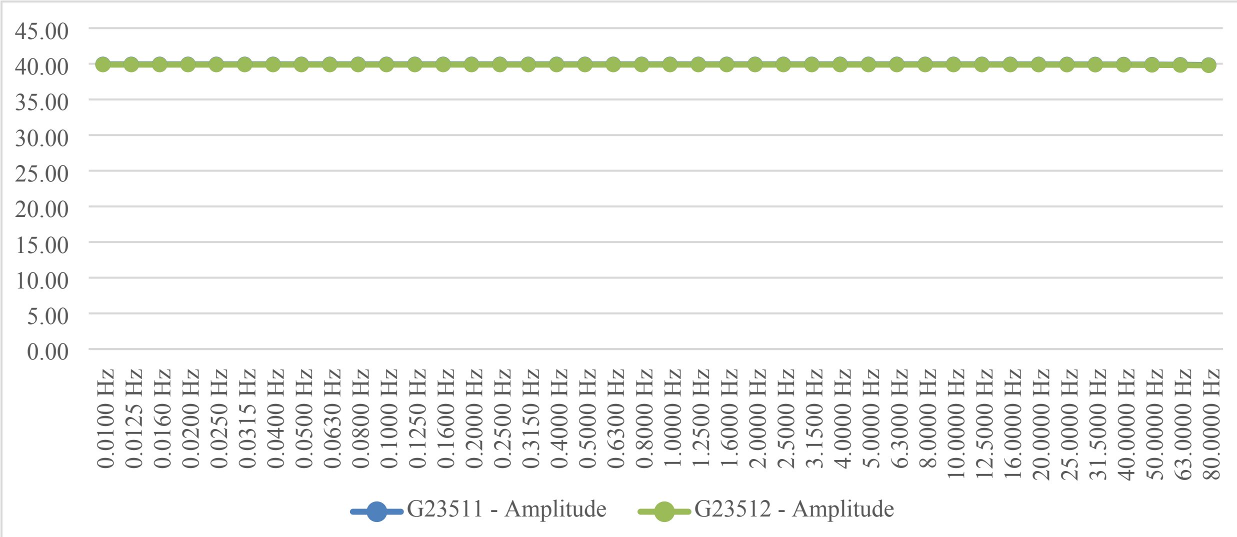

Figure 36 Tonal Response – Amplitude (unitless)

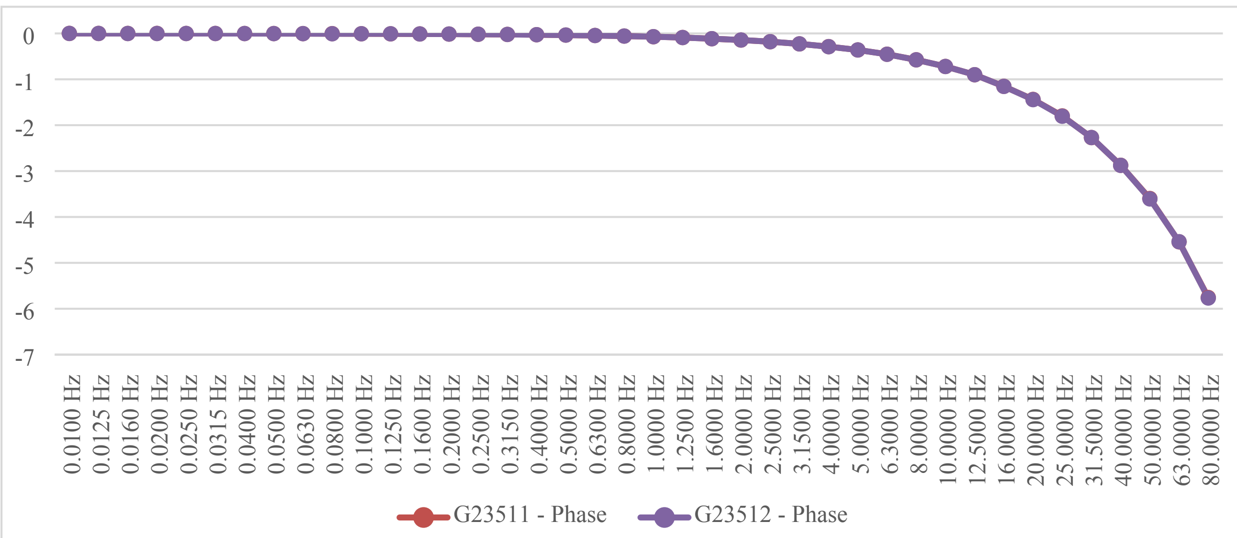

Figure 37 Tonal Response – Phase (degrees)

The measured gain was approximately 39.93x and 39.88x for G23511 and G23512, respectively. The amplitude response was effectively flat across the measured pass-band with only a very slightly roll-off of about 0.25 % (0.02 dB) at 80 Hz.

The phase response was nearly identical for both preamplifiers. There were some slight roll-offs in the phase response. However, this phase delay is indicative of a small difference in timing between the channels, as further investigated in section 3.13 Relative Transfer Function.

The table below contains the preamplifier GS13 tonal amplitude and phase response values expressed in unit-less gain ratio and degrees.

Table 26 Tonal Amplitude and Phase Response

	G23511		G23512	
Frequency	Amplitude	Phase	Amplitude	Phase
0.0100 Hz	39.93	-0.00037	39.88	-0.00049
0.0125 Hz	39.93	-0.00096	39.88	-0.00076
0.0160 Hz	39.93	-0.00139	39.88	-0.00179
0.0200 Hz	39.93	-0.0007	39.88	-0.00181
0.0250 Hz	39.93	-0.00166	39.88	-0.0017
0.0315 Hz	39.93	-0.00188	39.88	-0.00185
0.0400 Hz	39.93	-0.00272	39.88	-0.00277
0.0500 Hz	39.93	-0.00335	39.88	-0.0039
0.0630 Hz	39.93	-0.00444	39.88	-0.00488
0.0800 Hz	39.93	-0.00511	39.88	-0.00747
0.1000 Hz	39.93	-0.00724	39.88	-0.00738
0.1250 Hz	39.93	-0.00923	39.88	-0.00819
0.1600 Hz	39.93	-0.01145	39.88	-0.01149
0.2000 Hz	39.93	-0.01426	39.88	-0.01368
0.2500 Hz	39.93	-0.01823	39.88	-0.01798
0.3150 Hz	39.93	-0.02235	39.88	-0.02209
0.4000 Hz	39.93	-0.0281	39.88	-0.02805
0.5000 Hz	39.93	-0.03622	39.88	-0.03583
0.6300 Hz	39.93	-0.04538	39.88	-0.0456
0.8000 Hz	39.93	-0.05769	39.88	-0.05778
1.0000 Hz	39.93	-0.07222	39.88	-0.07137
1.2500 Hz	39.93	-0.08947	39.88	-0.09
1.6000 Hz	39.93	-0.11526	39.88	-0.1153
2.0000 Hz	39.93	-0.14461	39.88	-0.14337
2.5000 Hz	39.93	-0.18046	39.88	-0.18046
3.1500 Hz	39.93	-0.22809	39.88	-0.22782
4.0000 Hz	39.93	-0.28789	39.88	-0.28937
5.0000 Hz	39.93	-0.36054	39.88	-0.36016
6.3000 Hz	39.93	-0.45385	39.88	-0.45498
8.0000 Hz	39.93	-0.57501	39.88	-0.5758
10.0000 Hz	39.93	-0.72012	39.88	-0.72075
12.5000 Hz	39.92	-0.90044	39.88	-0.90005
16.0000 Hz	39.92	-1.15299	39.88	-1.15442
20.0000 Hz	39.92	-1.43836	39.88	-1.44277
25.0000 Hz	39.92	-1.79811	39.87	-1.80475
31.5000 Hz	39.91	-2.27001	39.87	-2.26902
40.0000 Hz	39.90	-2.8738	39.86	-2.87529
50.0000 Hz	39.89	-3.59762	39.84	-3.60666
63.0000 Hz	39.86	-4.5415	39.82	-4.53968
80.0000 Hz	39.82	-5.75483	39.78	-5.76649

3.12 Response Verification

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

3.12.1 Measurand

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

3.12.2 Configuration

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

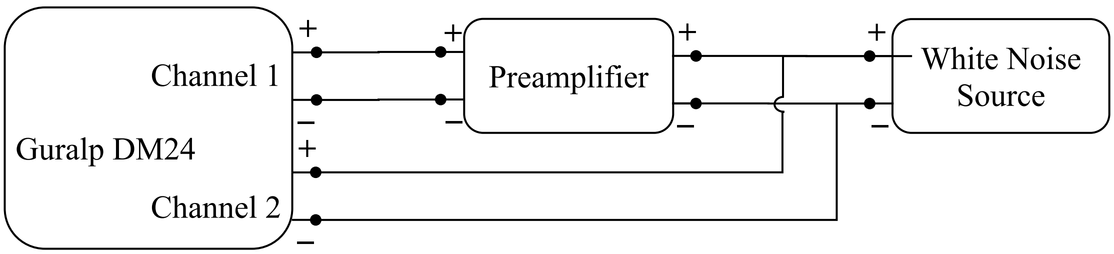

Figure 38 Response Verification Configuration Diagram

Table 27 Response Verification Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal, +/- 50 mV

As the two Guralp DM24 channels are configured identically with the same sample rate and gain and since the two channels have been calibrated against a reference meter, any difference in the recordings of the channels is assumed to be due to the contribution of the preamplifier.

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. Two hours of data is recorded.

3.12.3 Analysis

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

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

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

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

3.12.4 Result

The coherence and relative amplitude and phase response were computed between the preamplifier recording channel and the reference recording channel. In all cases, the coherence was identically 1.0 across the entire pass-band. The power spectra, coherence, relative amplitude, and phase are shown in the plots below.

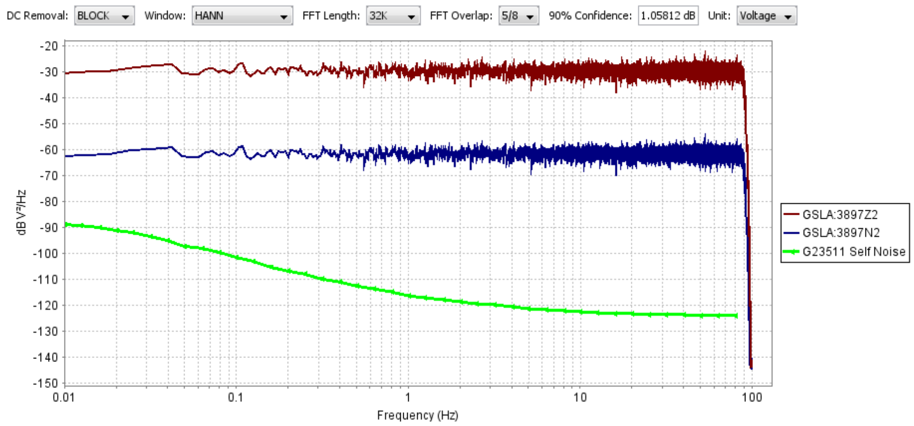

Figure 39 Power Spectra – G23511

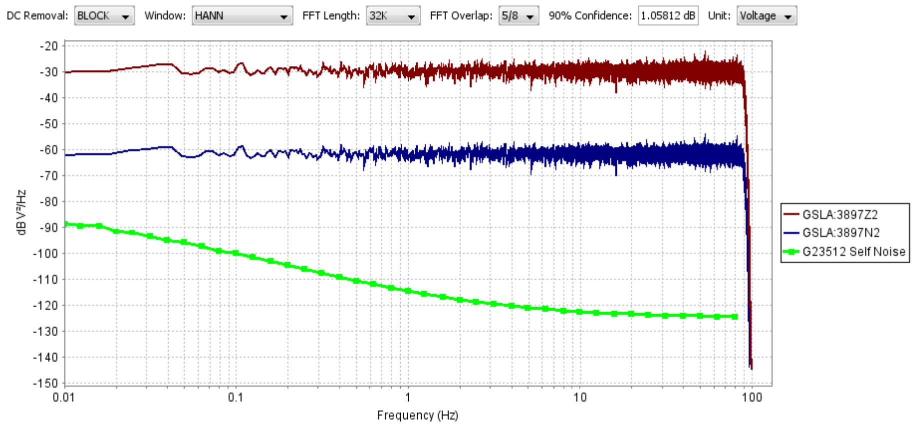

Figure 40 Power Spectra – G23512

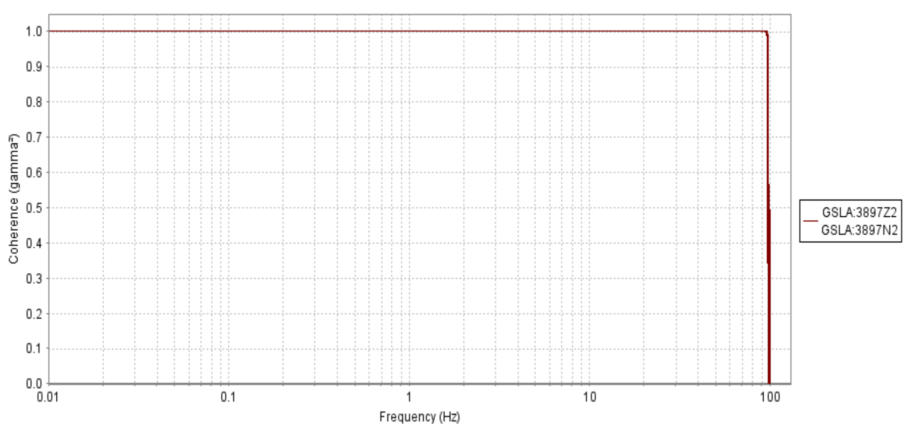

Figure 41 White Noise Coherence – G23511

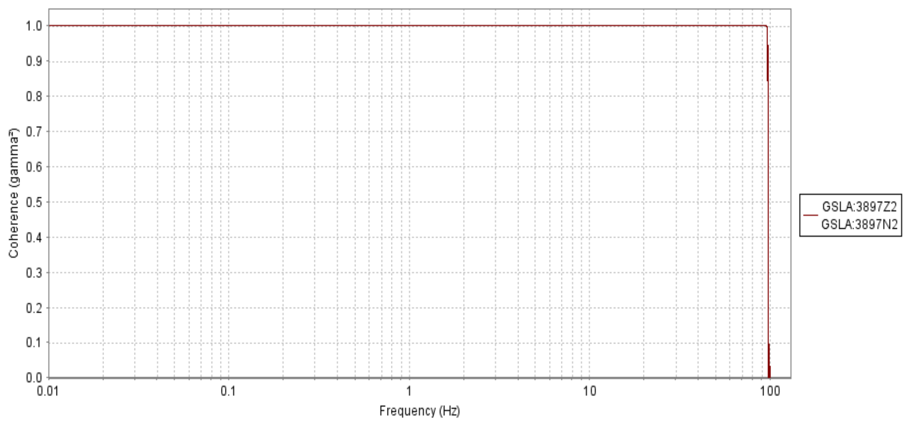

Figure 42 White Noise Coherence – G23512

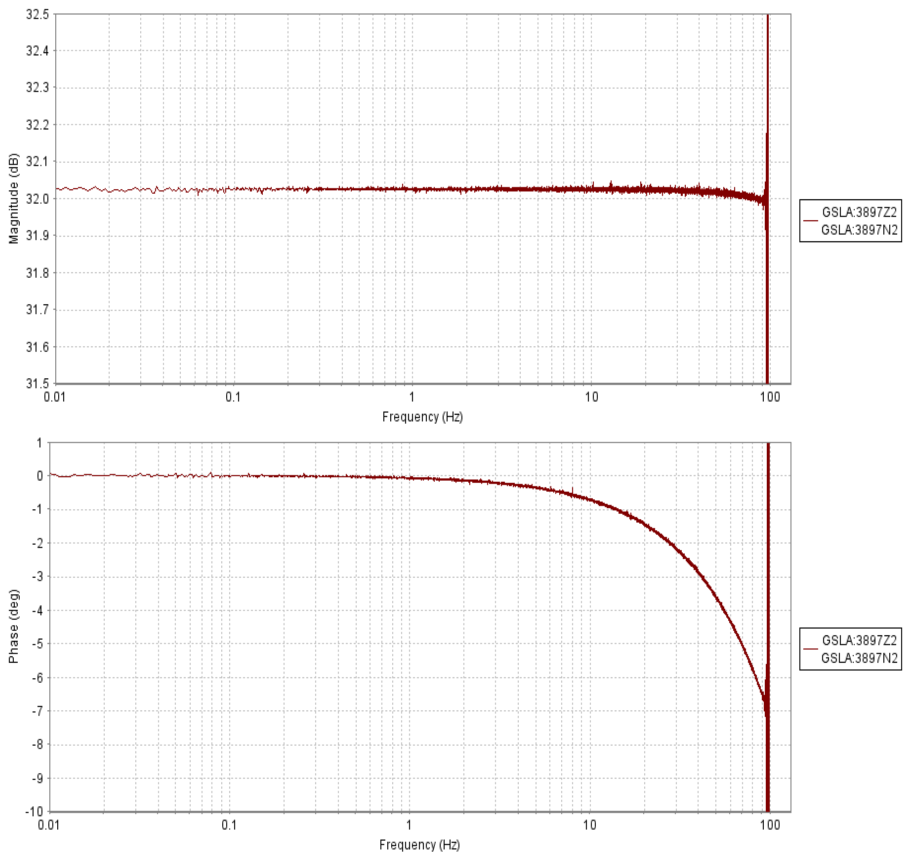

Figure 43 Relative Amplitude and Phase – G23511

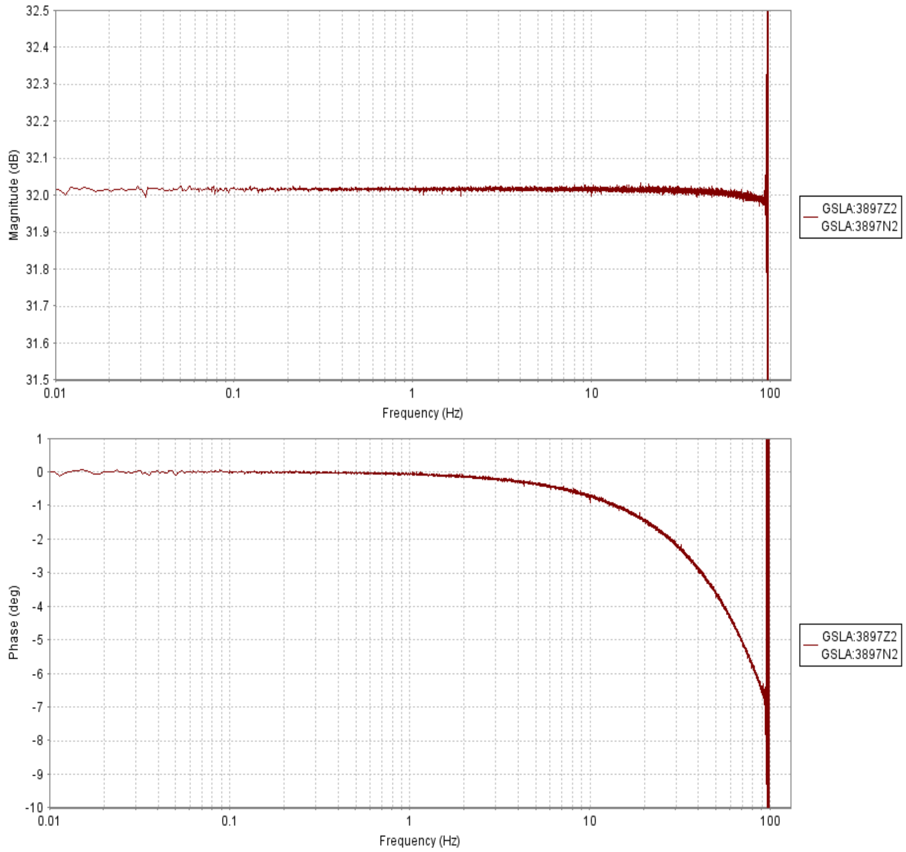

Figure 44 Relative Amplitude and Phase – G23512

The measured gain was approximately 32.025 dB (39.926x) and 32.015 dB (39.880x) for G23511 and G23512, respectively. The amplitude response was effectively flat across the measured pass-band with only a very slightly roll-off of 0.02 dB at 80 Hz.

There were some slight roll-offs in the phase response. However, this phase delay is indicative of a small difference in timing between the channels, as further investigated in section 3.13 Relative Transfer Function.

The table below contains the preamplifier GS13 white noise amplitude and phase response values expressed in dB and degrees.

Table 28 White Noise Amplitude and Phase Response

	G23511		G23512	
Frequency	Amplitude (dB)	Phase (deg)	Amplitude (dB)	Phase (deg)
0.0100 Hz	32.028 dB	-0.0115	32.017 dB	0.0014
0.0125 Hz	32.027 dB	-0.0167	32.016 dB	0.0054
0.0160 Hz	32.026 dB	0.0087	32.016 dB	-0.0064
0.0200 Hz	32.023 dB	0.0140	32.016 dB	-0.0054
0.0250 Hz	32.023 dB	0.0010	32.016 dB	-0.0144
0.0315 Hz	32.023 dB	-0.0010	32.015 dB	-0.0150
0.0400 Hz	32.024 dB	-0.0084	32.015 dB	-0.0095
0.0500 Hz	32.024 dB	-0.0078	32.015 dB	-0.0095
0.0630 Hz	32.024 dB	-0.0062	32.015 dB	-0.0038
0.0800 Hz	32.024 dB	-0.0067	32.015 dB	0.0004
0.1000 Hz	32.025 dB	-0.0077	32.015 dB	-0.0056
0.1250 Hz	32.026 dB	-0.0104	32.015 dB	-0.0098
0.1600 Hz	32.026 dB	-0.0105	32.015 dB	-0.0159
0.2000 Hz	32.026 dB	-0.0141	32.016 dB	-0.0165
0.2500 Hz	32.025 dB	-0.0192	32.016 dB	-0.0196
0.3150 Hz	32.025 dB	-0.0224	32.016 dB	-0.0236
0.4000 Hz	32.025 dB	-0.0297	32.016 dB	-0.0281
0.5000 Hz	32.025 dB	-0.0356	32.016 dB	-0.0350
0.6300 Hz	32.025 dB	-0.0471	32.016 dB	-0.0449
0.8000 Hz	32.025 dB	-0.0585	32.016 dB	-0.0589
1.0000 Hz	32.025 dB	-0.0726	32.016 dB	-0.0707
1.2500 Hz	32.025 dB	-0.0904	32.016 dB	-0.0903
1.6000 Hz	32.025 dB	-0.1145	32.016 dB	-0.1168
2.0000 Hz	32.025 dB	-0.1451	32.016 dB	-0.1445
2.5000 Hz	32.025 dB	-0.1797	32.016 dB	-0.1804
3.1500 Hz	32.025 dB	-0.2266	32.016 dB	-0.2265
4.0000 Hz	32.025 dB	-0.2877	32.016 dB	-0.2897
5.0000 Hz	32.025 dB	-0.3594	32.016 dB	-0.3601
6.3000 Hz	32.025 dB	-0.4536	32.016 dB	-0.4550
8.0000 Hz	32.025 dB	-0.5756	32.015 dB	-0.5781
10.0000 Hz	32.025 dB	-0.7205	32.015 dB	-0.7213
12.5000 Hz	32.025 dB	-0.8999	32.015 dB	-0.9028
16.0000 Hz	32.024 dB	-1.1521	32.015 dB	-1.1553
20.0000 Hz	32.024 dB	-1.4408	32.014 dB	-1.4437
25.0000 Hz	32.023 dB	-1.7984	32.013 dB	-1.8031
31.5000 Hz	32.022 dB	-2.2673	32.012 dB	-2.2737
40.0000 Hz	32.020 dB	-2.8787	32.010 dB	-2.8850
50.0000 Hz	32.016 dB	-3.5976	32.007 dB	-3.6067
63.0000 Hz	32.011 dB	-4.5324	32.001 dB	-4.5441
80.0000 Hz	32.004 dB	-5.7545	31.998 dB	-5.7683

3.13 Relative Transfer Function

The Relative Transfer Function test measures the amount of timing delay present on a preamplifier by measuring the timing skew between the preamplifier output and a reference digitizer channel.

3.13.1 Measurand

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

3.13.2 Configuration

The preamplifier and multiple digitizer channels are connected to a white noise signal source as shown in the diagram below.

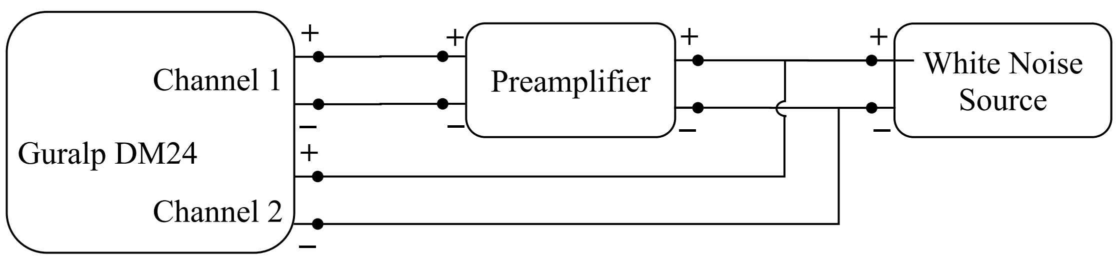

Figure 45 Relative Transfer Function Configuration Diagram

Table 29 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal, +/- 50 mV

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. Two hours of data is recorded.

3.13.3 Analysis

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

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

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

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

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

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

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

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

3.13.4 Result

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

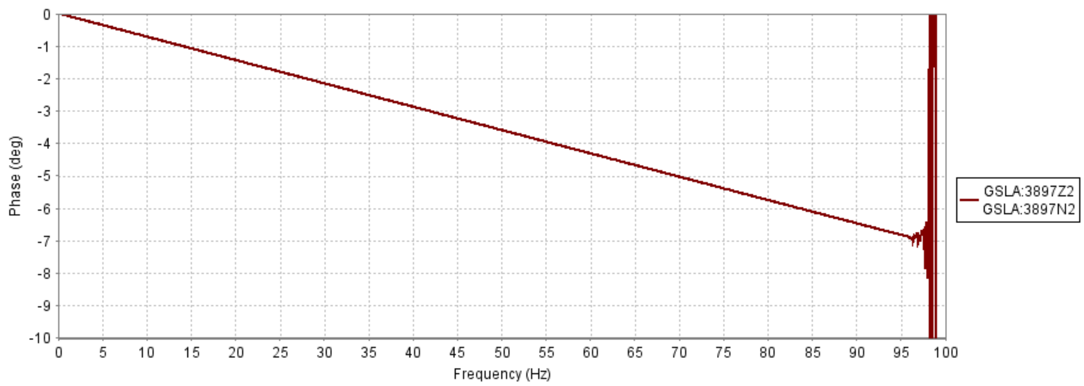

Figure 46 Relative Transfer Function Relative Phase – G23511

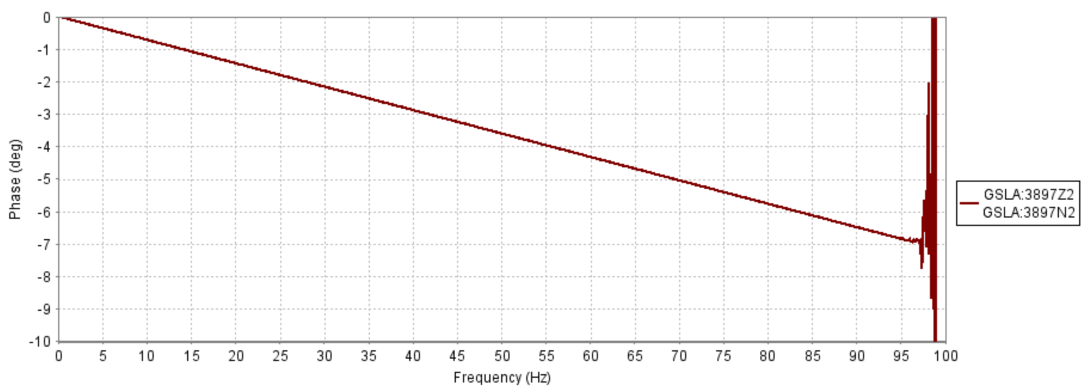

Figure 47 Relative Transfer Function Relative Phase – G23512

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

Table 30 Relative Transfer Function Timing Skew relative to Channel 1

	G23511	G23512
Time Delay (0.01 - 90 Hz)	-199.91 uS	-200.39 uS

Prior to testing the Guralp GS13 preamplifier, the relative transfer function between the Z and the N channels of the Guralp DM24 were independently measured and determined to have a relative timing skew of 0.387 us. This value is significantly less than what was measured using the preamplifier. Therefore, the measured timing delay of 200 us is believed to be attributed to the preamplifier.

3.14 Time Tag Accuracy

The Time Tag Accuracy test was performed on the preamplifier to measures the preamplifier's contribution to timing delay.

3.14.1 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.

3.14.2 Configuration

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

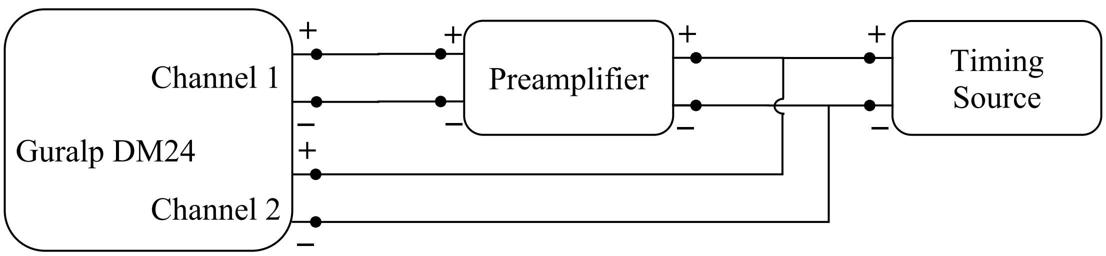

Figure 48 Time Tag Configuration Diagram

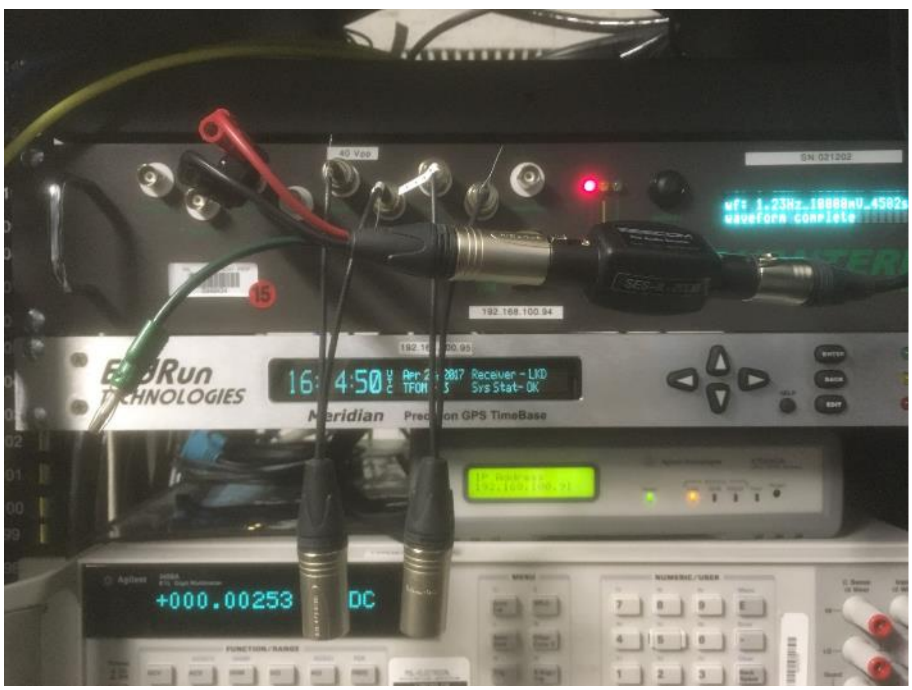

Figure 49 Time Tag Configuration Picture

Table 31 Time Tag Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Timing Source	Quanterra Supertonal	S/N 021202	+5 V PPM
Attenuator	N/A	N/A	20 dB (10x)

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.

Note that the amplitude output of the Quanterra Supertonal was reduced using a 20 dB (10x) attenuator so as not to exceed the full scale limits of the preamplifier.

3.14.3 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.

3.14.4 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.

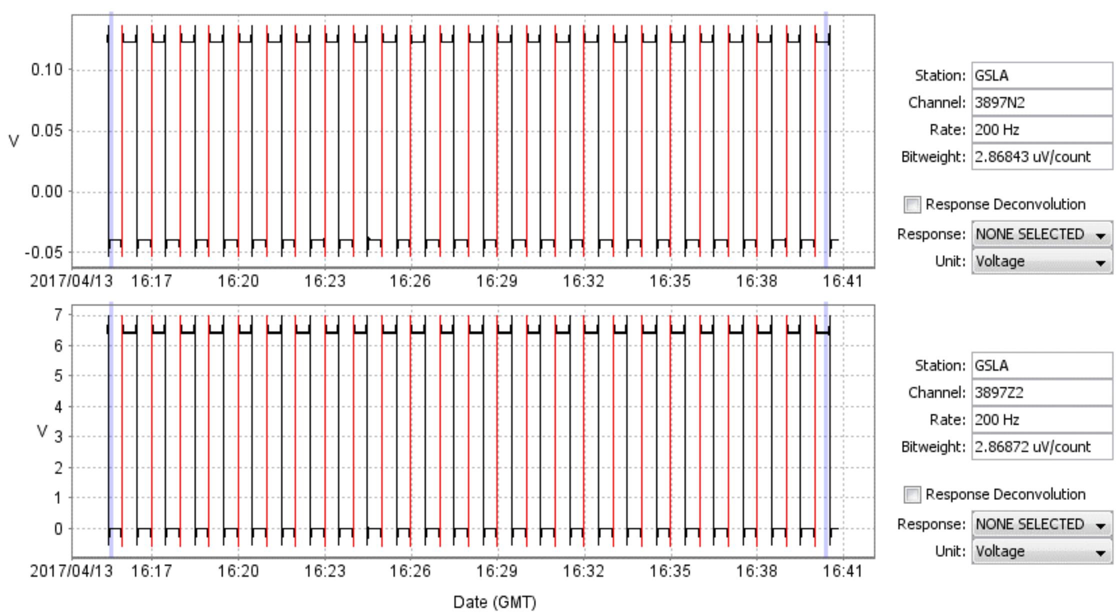

Figure 50 Time Tag Accuracy PPM Time Series

The following table contains the computed timing offsets.

Table 32 Time Tag Accuracy

	G23511	G23512
DM24 CH2 Time Offset	-72.72 uS	-74.02 uS
DM24 CH1 Time Offset	124.71 uS	123.67 uS
Preamp Time Delay	-197.43 uS	-197.69 uS

Prior to testing the Guralp GS13 preamplifier, the Time Tag Accuracy of the Z and the N channels of the Guralp DM24 were independently measured and determined to have a difference in timing accuracy using a PPM signal of 0.4 us.

Therefore, the observed difference in Time Tag Accuracy of 197.5 us is believed to represent the delay of the preamplifier when recording a PPM signal.

3.15 Analog Bandwidth

The Analog Bandwidth test measures the bandwidth of the preamplifier.

3.15.1 Measurand

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

3.15.2 Configuration

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

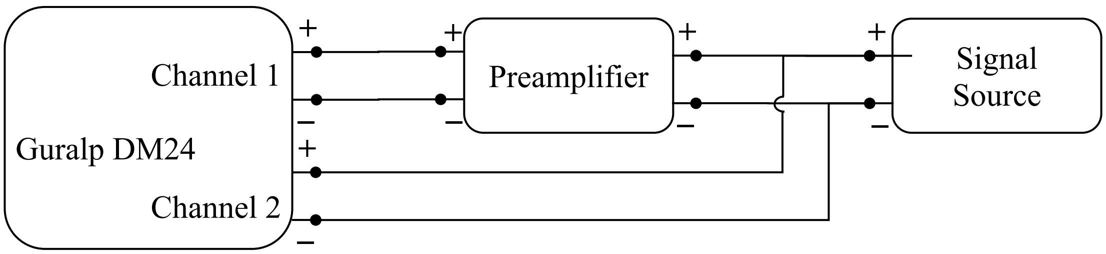

Figure 51 Analog Bandwidth Configuration Diagram

Table 33 Analog Bandwidth Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal, +/- 50 mV

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. Two hours of data is recorded.

3.15.3 Analysis

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

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

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

3.15.4 Result

The power spectra of the white noise signal recorded on the Guralp DM24 digitizer channels are shown in the plot below.

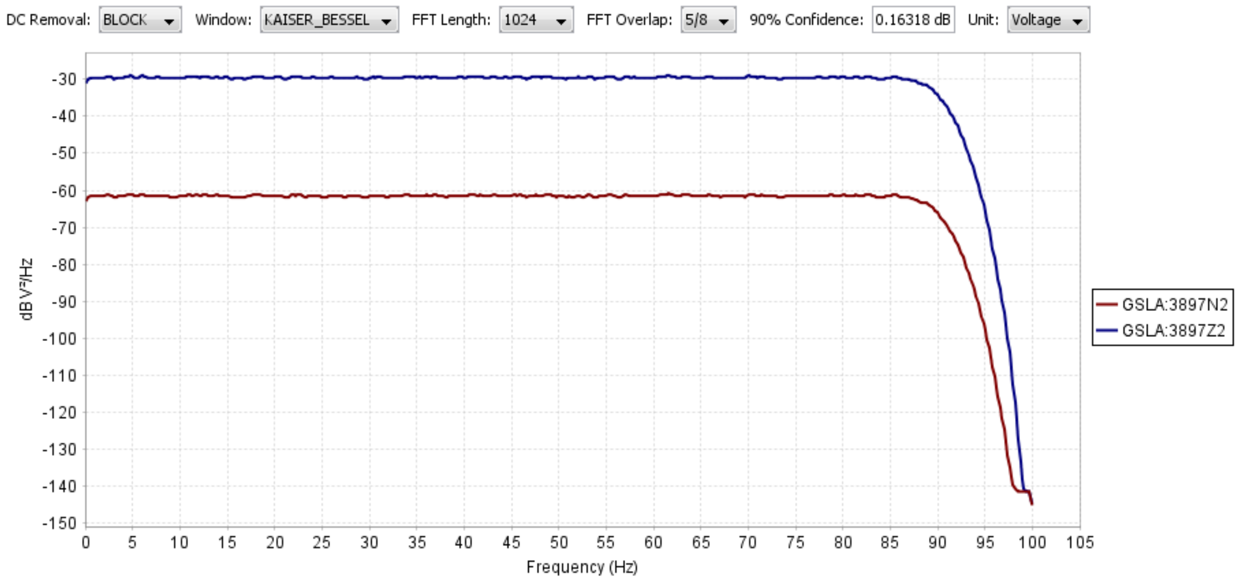

Figure 52 Analog Bandwidth 100 Hz

The table below contains the 3dB point measured from the power spectra.

Table 34 Analog Bandwidth

	G23511	G23512
Preamp channel Z bandwidth	89.453 Hz	89.453 Hz
Reference channel N bandwidth	89.453 Hz	89.453 Hz

Prior to testing the Guralp GS13 preamplifier, the bandwidth of the Z and the N channels of the Guralp DM24 were independently measured and determined to have no significant difference.

The signal recorded on both the Z and N channels of the Guralp DM24 digitizer have identical bandwidths. Therefore, the preamplifier is not believed to be imposing any reduction in the signal bandwidth for this application passband.

3.16 Total Harmonic Distortion

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

3.16.1 Measurand

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

3.16.2 Configuration

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

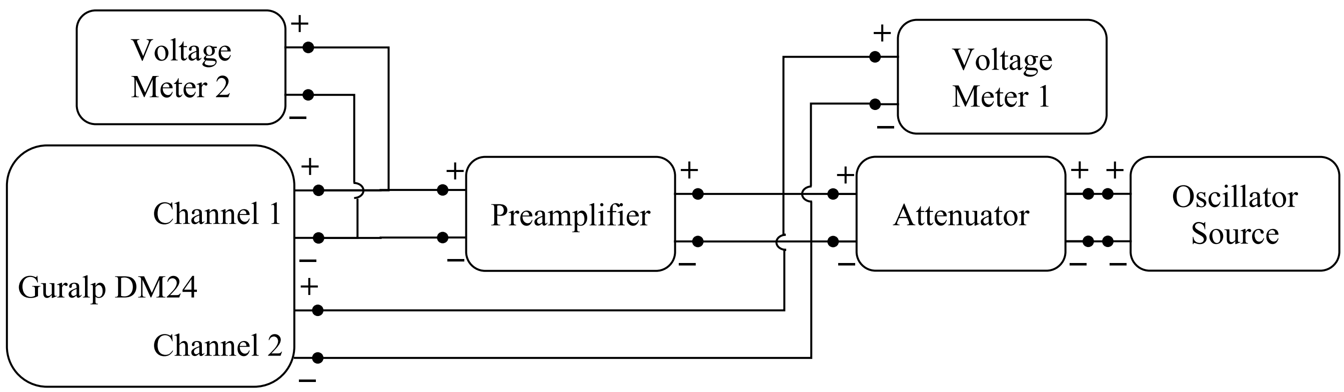

Figure 53 Total Harmonic Distortion Configuration Diagram

Table 35 Total Harmonic Distortion Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Oscillator	Quanterra Supertonal	S/N 021202	1.23 Hz,
Attenuator	N/A	N/A	15 dB (5.62x)
Voltage Meter 1	Agilent 3458A	MY45048372	DC Voltage, 1 V
Voltage Meter 2	Agilent 3458A	MY45048371	DC Voltage, 10 V

In the course of validating the linearity test in this configuration, the Guralp preamplifier was found to have very low levels of signal distortion. One of the challenges associated with measuring harmonic distortion on such a preamplifier comes in matching the capabilities of the oscillator source and each of the meters to be able to fully capture the highest quality signal at both the input and the output levels.

The Quanterra Supertonal is known from earlier characterization to maximize its signal-to-noise ratio and linearity at frequencies between 1.0 Hz and 1.5 Hz and an amplitude approximately 50 % of its full-scale output or 1.25 V peak. This high of a signal amplitude would exceed the full scale of the Guralp preamplifier. Therefore, a passive attenuator was used to bring the signal amplitude down to the desired level.

Selecting the desired level of attenuation was done with care to ensure that the signal amplitudes at both the input and output of the preamplifier would be at levels that the Agilent 3458A reference meter has full resolution of the signal. Briefly, the Agilent 3458A meter has several full-scale modes that it can operate, each with a corresponding noise floor: 0.1 V, 1 V, 10 V, and 100 V. There is very little difference in noise level between the 0.1 V and 1 V modes and the 100 V mode is far too noisy to be useful. In addition, due to a slightly increased noise floor, if using the 10 V mode, it is necessary to utilize as much as the full-scale range as possible to maximum the signal-to-noise ratio.

Therefore, a 1.25 V peak and 1.23 Hz sinusoid was generated by the ultra low distortion oscillator and then passively attenuated using a high quality resistor bridge that provides 15 dB of attenuation (5.62x) to bring the signal amplitude down to approximately 0.2223 V peak. This is very close to the 50 % level of the preamplifier (0.28 V) and allows the meter measuring the input voltage to be in the 1 V mode. The amplitude of the preamplifier output will then be 8.9 V (40x) which is near the top end of the Agilent 3458A 10 V mode. It would have been preferable to have the input signal to be higher in amplitude, however any significant increase in the input amplitude would have pushed the output amplitude beyond 10 V and into the Agilent 3458A 100 V mode.

Not taking such care in setting up the test configuration would have resulted in signal distortion in what was observed at either the preamplifier input or output that would result in the preamplifier appearing to be much noisier or less linear than it actually is.

The meters and the digitizer channels record the described AC voltage signal simultaneously. The recording made on the meters is used as the reference for comparison against the preamplifiers input and output. 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 %.

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.

3.16.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 4k-sample Kaiser-Bessel window. A Kaiser-Bessel window is used to minimize the width of the main lobe and the amplitude of side-lobes. The window length and data duration were chosen to provide sufficient frequency resolution around the primary:

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

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 preamplifier.

3.16.4 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.

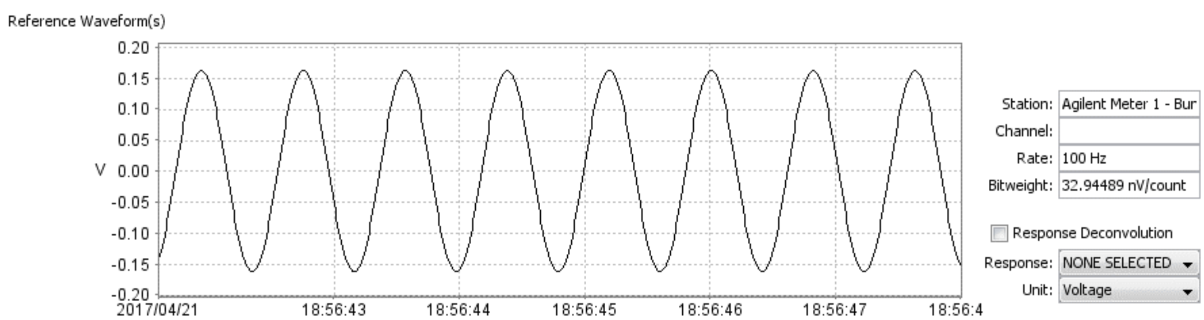

Figure 54 THD Time Series

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

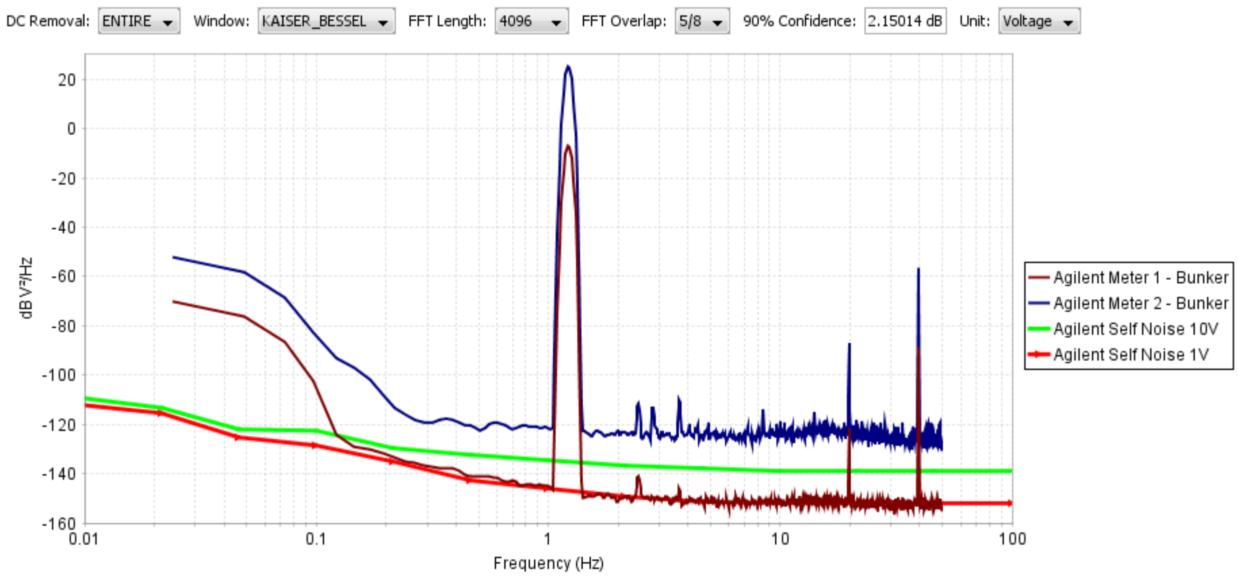

Figure 55 THD Power Spectra – G23511

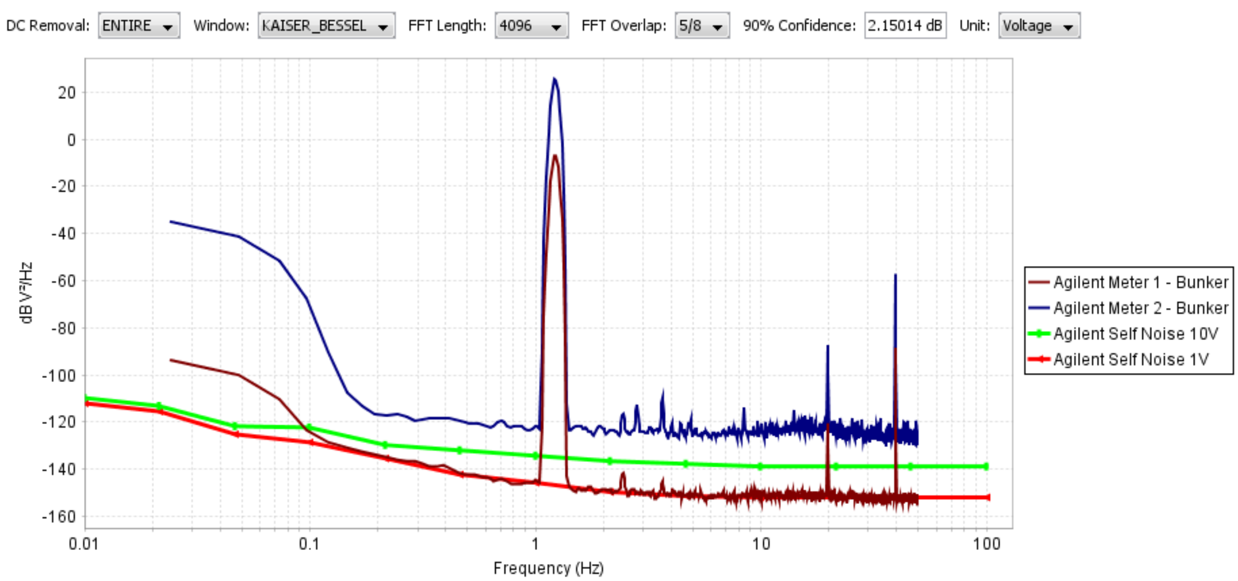

Figure 56 THD Power Spectra – G23512

Table 36 Total Harmonic Distortion

	G23511	G23512
Meter 1 Input THD	-129.80 dB	-131.09 dB
Meter 2 Output THD	-130.01 dB	-130.18 dB

There was no appreciable difference in the measured linearity in the input and output of the preamplifiers. Therefore, the Guralp GS13 preamplifier is determined to have linearity that exceeds the observable limits of -130 dB.

3.17 Modified Noise Power Ratio

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

3.17.1 Measurand

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

3.17.2 Configuration

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

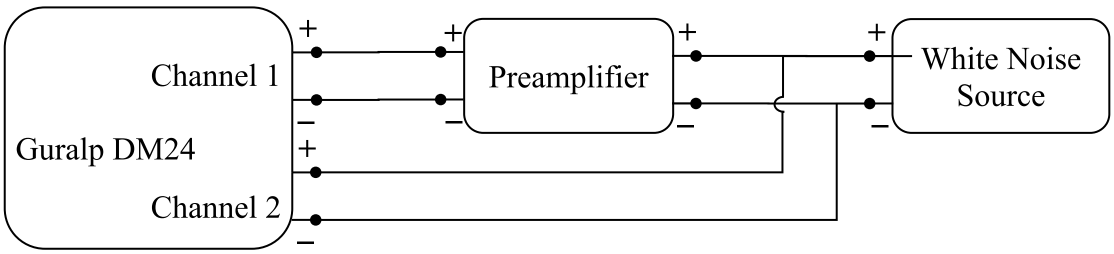

Figure 57 Modified Noise Power Ratio Configuration Diagram

Table 37 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal

As the two Guralp DM24 channels are configured identically with the same sample rate and gain and since the two channels have been calibrated against a reference meter, any difference in the recordings of the channels is assumed to be due to the contribution of the preamplifier.

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

3.17.3 Analysis

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

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

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

3.17.4 Result

Prior to performing the Modified Noise Power Ratio test on the preamplifier, this test was applied to the Z and the N channels without the preamplifier present. The result of this test is represented in the plot and table below:

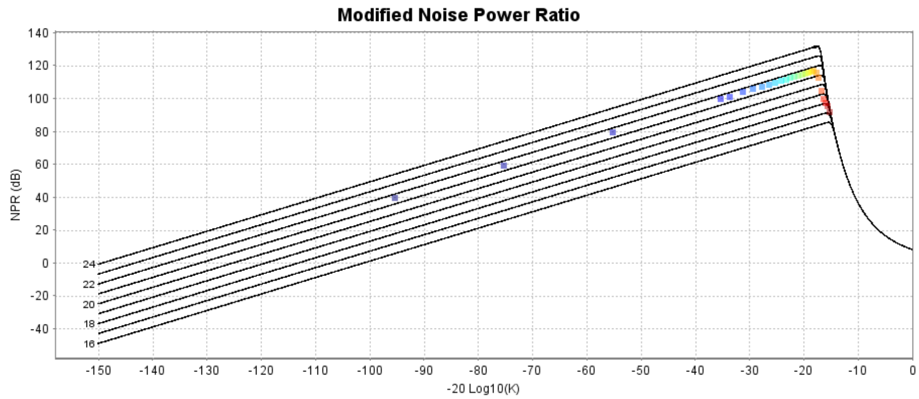

Figure 58 Modified Noise Power Ratio – DM24

Table 38 Modified Noise Power Ratio – DM24

Amplitude	RMS Amplitude	-20 log K	NPR
2.5 mV	0.00029 V rms	-95.29948	39.38789 dB
25 mV	0.00292 V rms	-75.29939	59.3918 dB
0.25 V	0.02914 V rms	-55.30484	79.4009 dB
2.5 V	0.29157 V rms	-35.29921	99.46585 dB
3 V	0.34984 V rms	-33.71655	101.09558 dB
4 V	0.46623 V rms	-31.22198	103.64501 dB
5 V	0.58292 V rms	-29.28173	105.59101 dB
6 V	0.69948 V rms	-27.6984	107.16808 dB
7 V	0.81639 V rms	-26.35597	108.52893 dB
8 V	0.93269 V rms	-25.19918	109.66438 dB
9 V	1.0491 V rms	-24.17761	110.68587 dB
10 V	1.16517 V rms	-23.26614	111.58844 dB
11 V	1.28178 V rms	-22.43764	112.42585 dB
12 V	1.39814 V rms	-21.68289	113.18703 dB
13 V	1.51576 V rms	-20.98131	113.86343 dB
14 V	1.63189 V rms	-20.34011	114.54503 dB
15 V	1.74914 V rms	-19.73746	115.11387 dB
16 V	1.86457 V rms	-19.18234	115.66814 dB
17 V	1.98154 V rms	-18.65387	116.18055 dB
18 V	2.09844 V rms	-18.156	116.63932 dB
19 V	2.21462 V rms	-17.68794	115.31885 dB
20 V	2.33095 V rms	-17.24327	112.53144 dB
21 V	2.44714 V rms	-16.82074	104.34432 dB
22 V	2.56416 V rms	-16.41501	99.56786 dB
23 V	2.68101 V rms	-16.02795	97.2509 dB
24 V	2.79738 V rms	-15.65889	95.10054 dB
25 V	2.91294 V rms	-15.30731	91.61423 dB

The result of this pre-evaluation indicates that the DM24 performed with slightly better than 21.5 effective bits and has a peak noise power ratio with an input signal of approximately 2.1 V rms.

The results of this test performed on the two preamplifiers, with amplitude ranges scaled appropriately, are shown below.

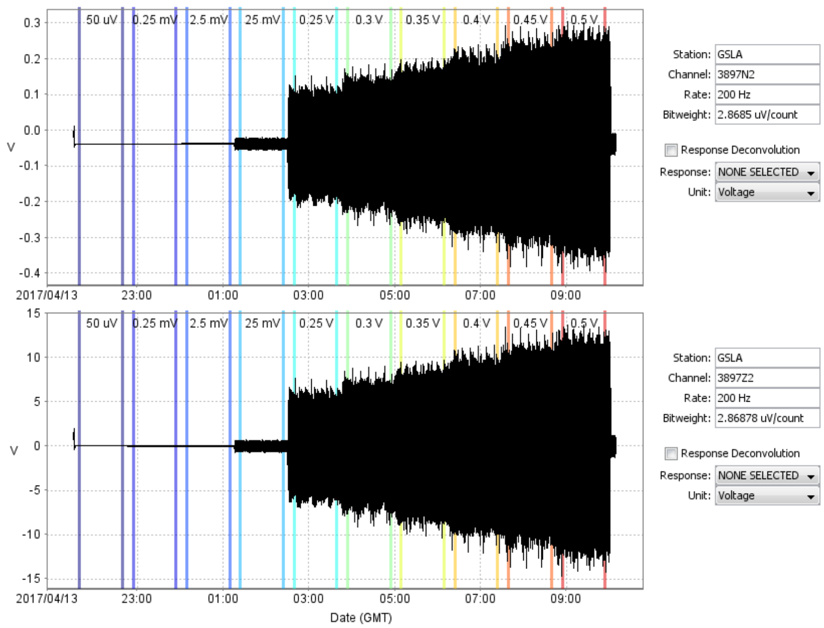

Figure 59 Modified Noise Power Ratio Time Series – G23511

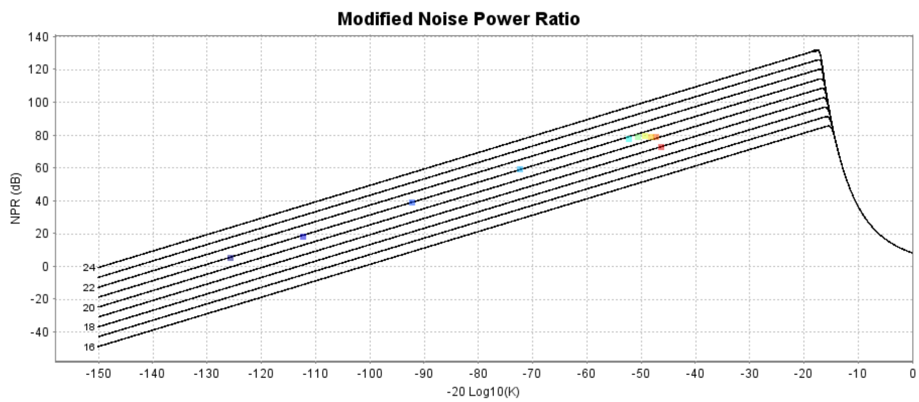

Figure 60 Modified Noise Power Ratio – G23511

Table 39 Modified Noise Power Ratio – G23511

Amplitude	RMS Amplitude	-20 log K	NPR
50 uV	8.2884559E-6 V rms	-125.66388	4.97583 dB
0.25 mV	38.93731E-6 V rms	-112.22603	17.78807 dB
2.5 mV	0.00039 V rms	-92.22494	38.67063 dB
25 mV	0.00389 V rms	-72.22564	59.2587 dB
0.25 V	0.03892 V rms	-52.22898	77.7905 dB
0.3 V	0.04666 V rms	-50.65451	78.86783 dB
0.35 V	0.05446 V rms	-49.31148	79.64943 dB
0.4 V	0.06227 V rms	-48.14734	78.89693 dB
0.45 V	0.07004 V rms	-47.1265	78.84752 dB
0.5 V	0.07786 V rms	-46.20704	72.67917 dB

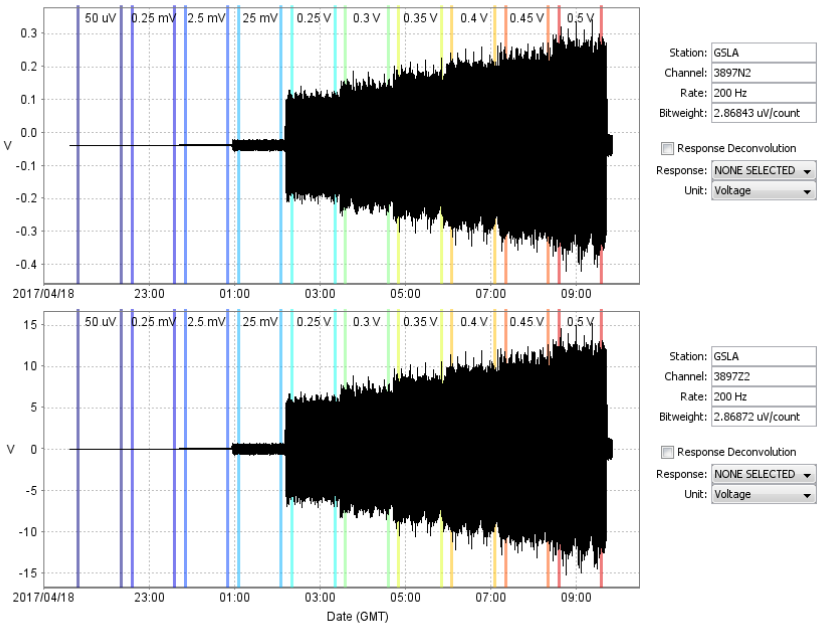

Figure 61 Modified Noise Power Ratio Time Series – G23512

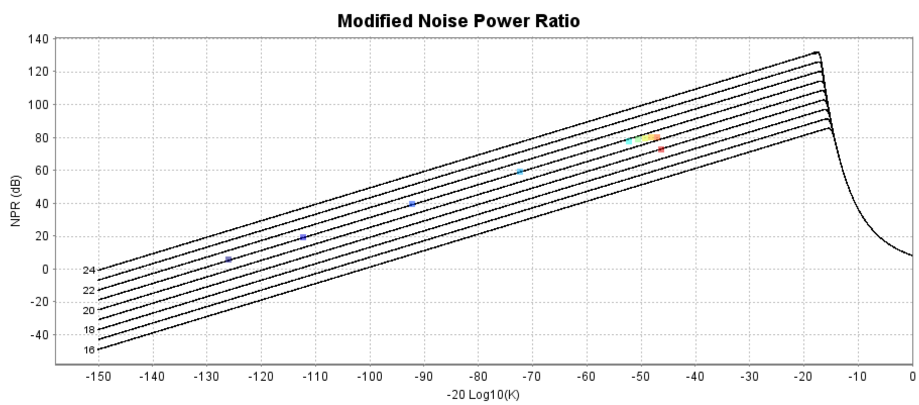

Figure 62 Modified Noise Power Ratio – G23512

Table 40 Modified Noise Power Ratio – G23512

Amplitude	RMS Amplitude	-20 log K	NPR
50 uV	7.8595416E-6 V rms	-126.12541	5.53943 dB
0.25 mV	38.825988E-6 V rms	-112.2509	19.38835 dB
2.5 mV	0.00039 V rms	-92.22517	39.40754 dB
25 mV	0.00389 V rms	-72.22343	59.43624 dB
0.25 V	0.03892 V rms	-52.22976	77.84298 dB
0.3 V	0.04666 V rms	-50.65394	78.87889 dB
0.35 V	0.05446 V rms	-49.31105	79.64888 dB
0.4 V	0.06226 V rms	-48.1489	80.19538 dB
0.45 V	0.07005 V rms	-47.12546	80.20401 dB
0.5 V	0.07784 V rms	-46.20985	72.57616 dB

The results demonstrate that the two preamplifiers perform similarly with approximately 21 effective bits and a peak noise power ratio at between 0.05 and 0.07 V rms.

3.18 Common Mode Rejection

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

3.18.1 Measurand

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

3.18.2 Configuration

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

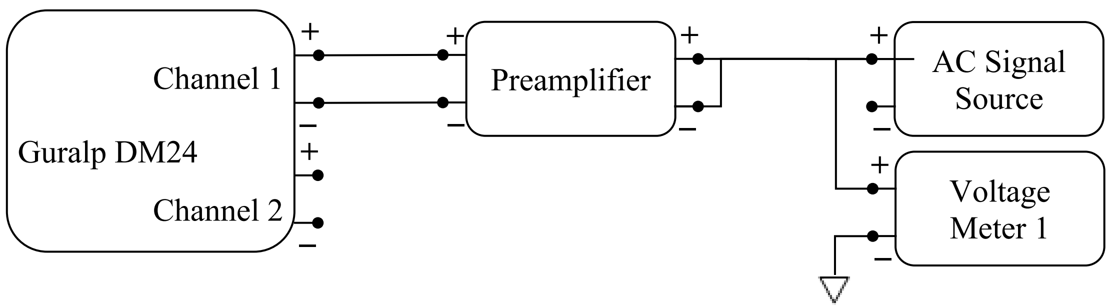

Figure 63 Common Mode Rejection Configuration Diagram

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

Table 41 Common Mode Rejection Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	S/N 123672	50 mV, 1 Hz Sine
Voltage Meter	Agilent 3458A	MY45048372	0.1 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.

3.18.3 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:

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

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

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

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

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

3.18.4 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.

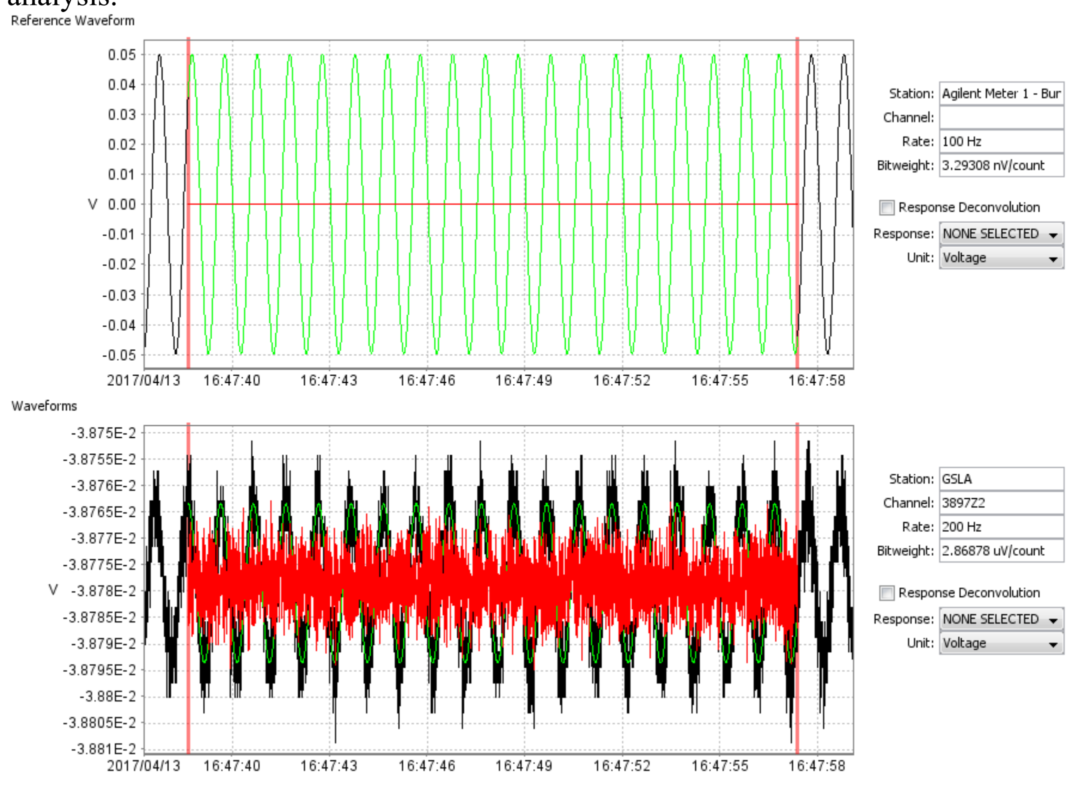

Figure 64 Common Mode Rejection Time Series – G23511

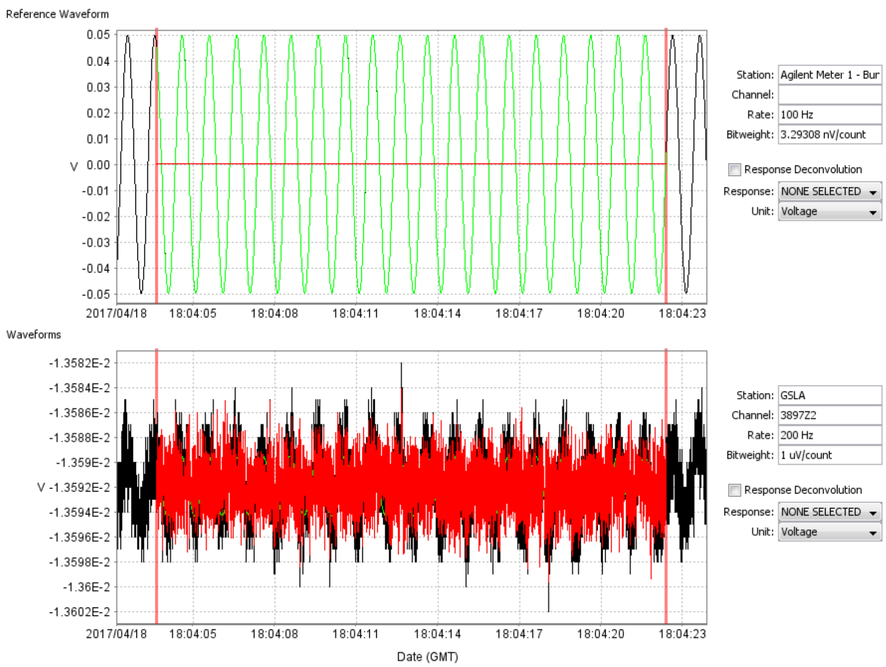

Figure 65 Common Mode Rejection Time Series – G23512

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

Table 42 Common Mode Rejection Ratio

	G23511	G23512
Common Mode Amplitude	0.04973 V	0.04973 V
Signal Amplitude	15.054 uV	2.392 uV
Rejection Gain	70.38 dB	86.36 dB

The observed common mode rejection was typically between 70 and 86 dB.

3.19 Calibrator DC Accuracy

The Calibrator DC Accuracy test is used to measure the gain of a preamplifier calibrator by recording a known positive and negative dc signal at a reference voltage at both the calibrator input and output using a precision voltage source.

3.19.1 Measurand

The quantity being measured is the unitless preamplifier gain at DC.

3.19.2 Configuration

The preamplifier calibrator is connected to a DC signal source and meters are configured to measure voltage as shown in the diagram below.

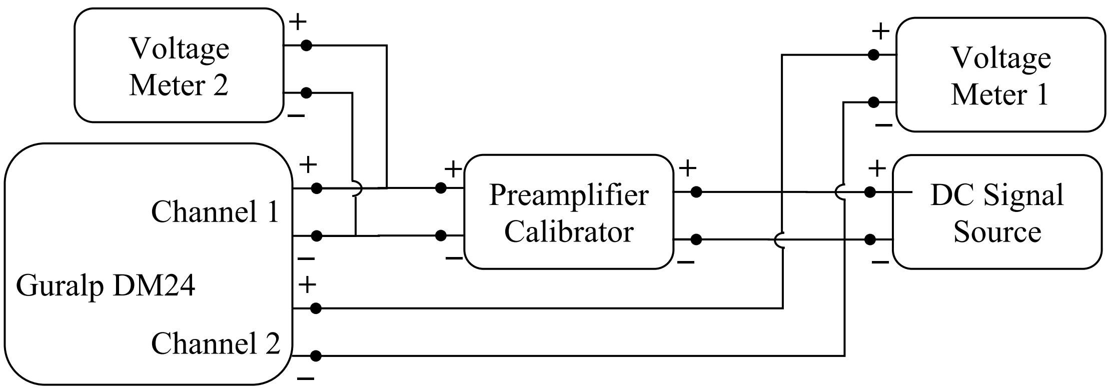

Figure 66 Calibrator DC Accuracy Configuration Diagram

Table 43 Calibrator DC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
DC Signal Source	SRS DS360	S/N 123672	+50 mV / - 50 mV
Voltage Meter 1	Agilent 3458A	MY45048372	0.1 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	10 V Full Scale Mode

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

The meters and the digitizer channels record the described DC voltage signal simultaneously. The recording made on the meters was used as the reference for comparison of the amplifier calibrator input and output. The meters were 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.

3.19.3 Analysis

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

The average of each of the positive and negative segments are computed from the reference meter in volts:
V_{pos} and V_{neg}

The average of each of the positive and negative segments are computed from the digitizer channel in counts:
C_{pos} and C_{neg}

The digitizer bit weight in Volts / count is computed:

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

The digitizer DC offset is computed:

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

3.19.4 Result

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

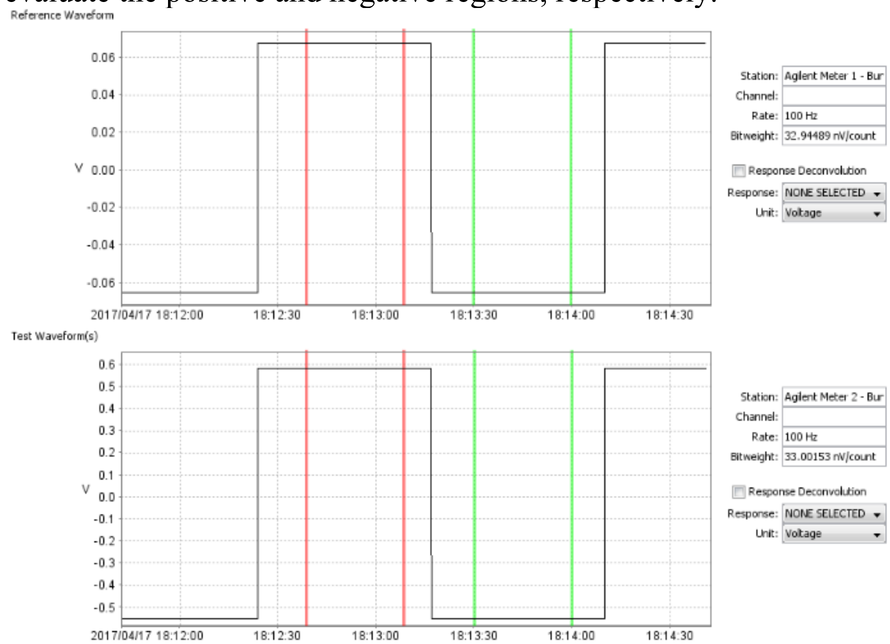

Figure 67 Calibrator DC Accuracy Time Series

The following table contains the recorded amplitudes and gain levels for the two amplifiers.

Table 44 Calibrator DC Accuracy

	G23511	G23512
Output Positive	0.5808 V	0.5723 V
Output Negative	-0.5510 V	-0.5583 V
Output Peak-to-peak	1.1318 V	1.1306 V
Input Peak-to-peak	0.1326 V	0.1329 V
Measured Gain	8.5377	8.5064
Nominal Gain	8.6920	8.6920
Difference	-1.78%	-2.14%

The nominal gain provided by Guralp was specified to be 8.692. The observed DC gain of the two amplifiers differed from nominal by between 1.78 % and 2.14 %.

3.20 Calibrator AC Accuracy

The Calibrator AC Accuracy test is used to measure the gain of a preamplifier calibrator channel by recording a known AC signal at a reference voltage at both the preamplifier calibrator input and output using a precision voltage source.

3.20.1 Measurand

The quantity being measured is the unitless preamplifier gain at 1 Hz.

3.20.2 Configuration

The amplifier is connected to an AC signal source and meters configured to measure voltage as shown in the diagram below.

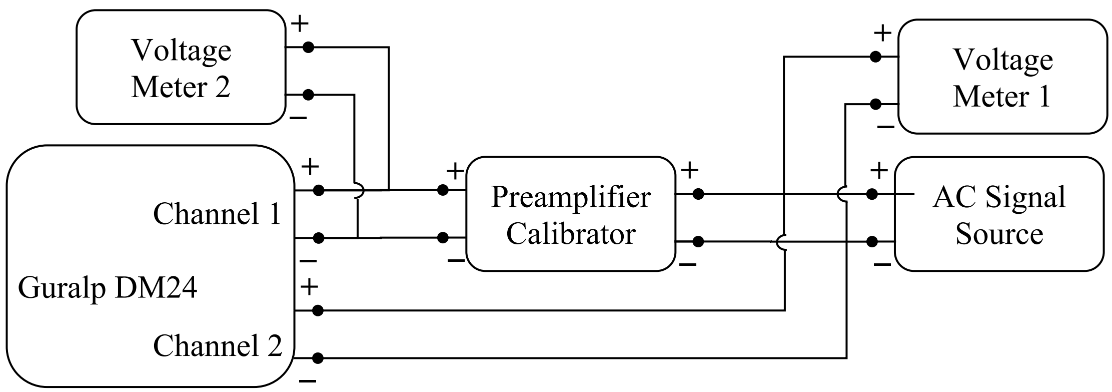

Figure 68 Calibrator AC Accuracy Configuration Diagram

Table 45 Calibrator AC Accuracy Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	SRS DS360	S/N 123672	+50 mV 1.0 Hz Sine
Voltage Meter 1	Agilent 3458A	MY45048372	0.1 V Full Scale Mode
Voltage Meter 2	Agilent 3458A	MY45048371	10 V Full Scale Mode

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

The meters and the digitizer channels record the described AC voltage signal simultaneously. The recording made on the meters is used as the reference for comparison of the amplifier input and output. The meters are 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.

3.20.3 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:

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

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

The digitizer bit weight in Volts / count is computed:

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

3.20.4 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.

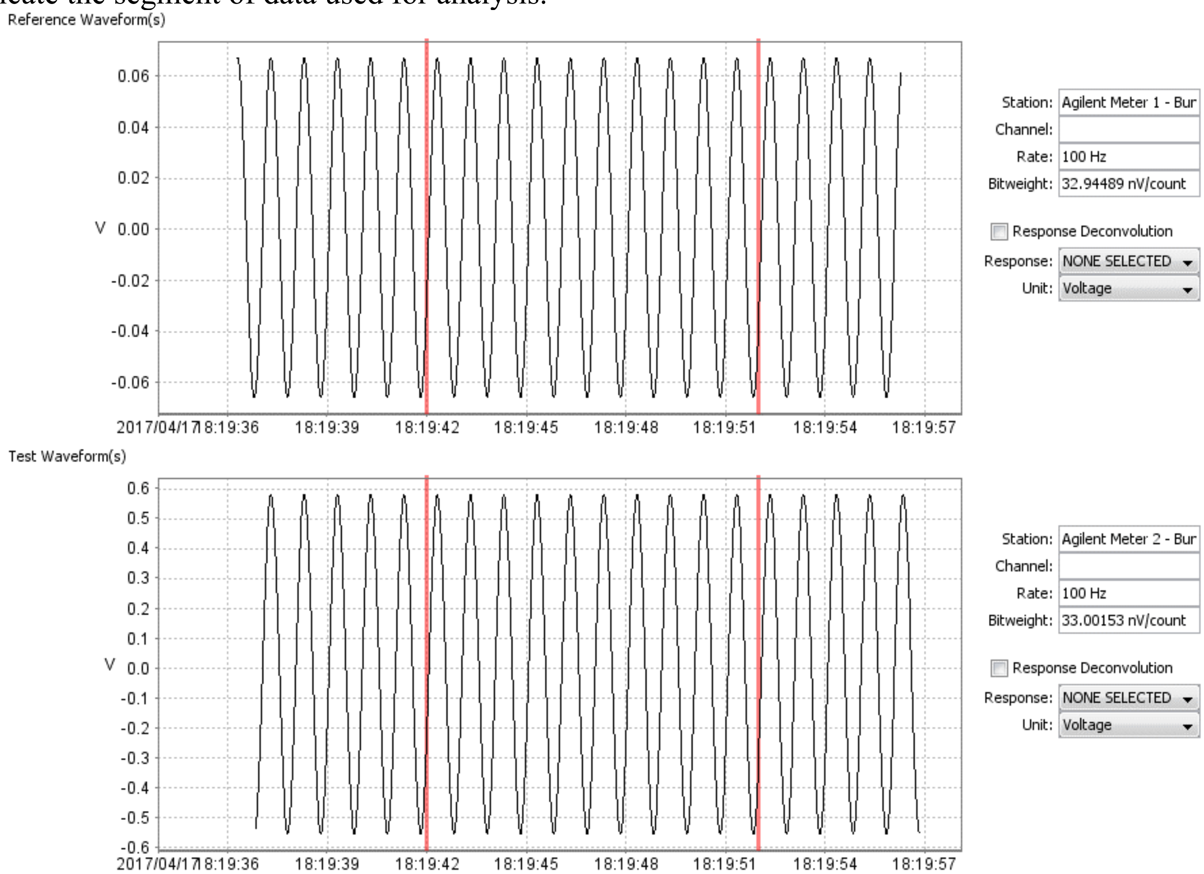

Figure 69 Calibrator AC Accuracy Time Series

The following table contains the recorded amplitudes and gain levels for the two amplifiers.

Table 46 Calibrator AC Accuracy Bitweight

	G23511	G23512
Output Peak-to-peak	1.1328 V	1.1316 V
Input Peak-to-peak	0.1327 V	0.1330 V
Measured Gain	8.5376	8.5063
Nominal Gain	8.6920	8.6920
Difference	-1.78%	-2.14%

The nominal gain provided by Guralp was specified to be 8.692. The observed AC gain of the two amplifiers differed from nominal by between 1.78 % and 2.14 %.

3.21 Calibrator Response Verification

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

3.21.1 Measurand

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

3.21.2 Configuration

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

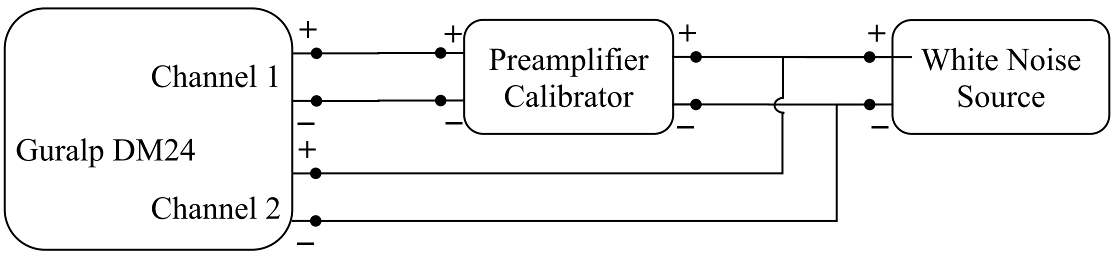

Figure 70 Response Verification Configuration Diagram

Table 47 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal, +/- 50 mV

As the two Guralp DM24 channels are configured identically with the same sample rate and gain and since the two channels have been calibrated against a reference meter, any difference in the recordings of the channels is assumed to be due to the contribution of the preamplifier.

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.

3.21.3 Analysis

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

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

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

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

3.21.4 Result

The coherence and relative amplitude and phase response were computed between the preamplifier calibrator recording channel and the reference recording channel. In all cases, the coherence was identically 1.0 across the entire pass-band. The power spectra, coherence, relative amplitude, and relative phase are shown in the plots below.

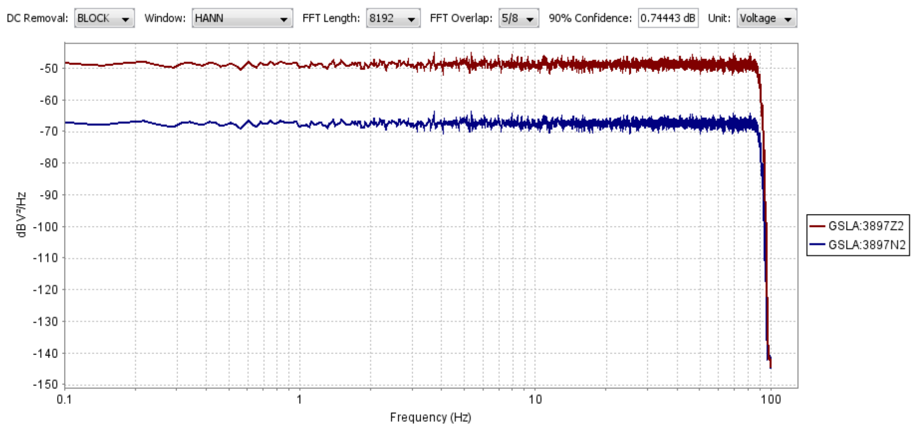

Figure 71 Power Spectra – G23511 Calibrator

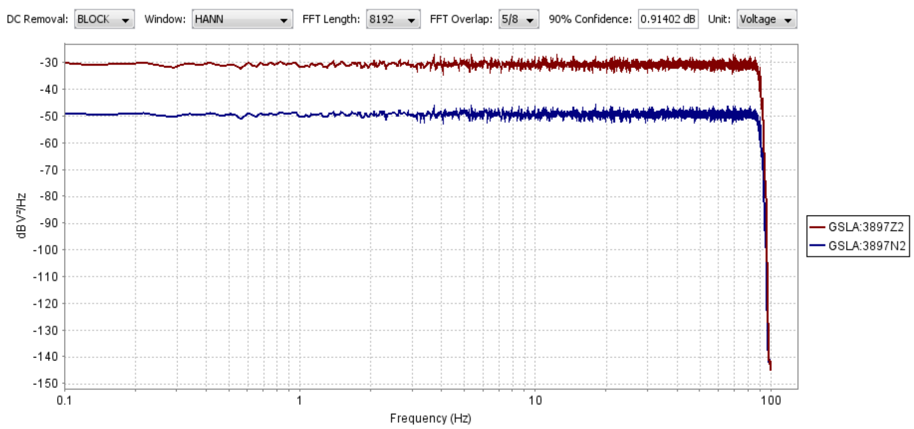

Figure 72 Power Spectra – G23512 Calibrator

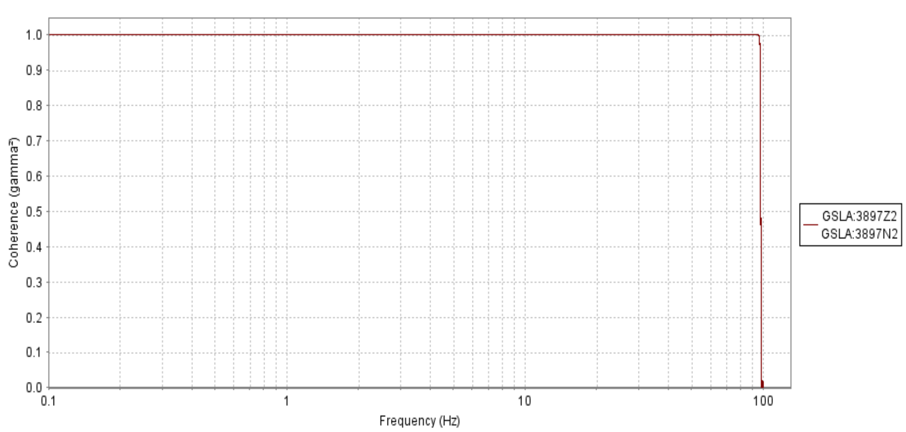

Figure 73 White Noise Coherence – G23511 Calibrator

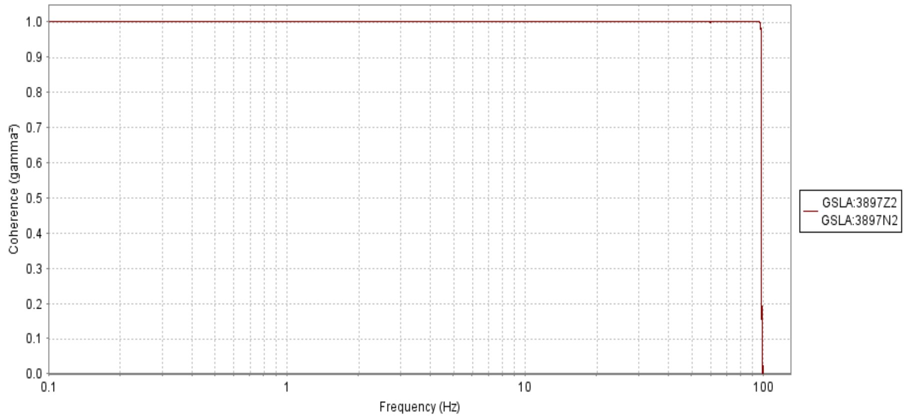

Figure 74 White Noise Coherence – G23512 Calibrator

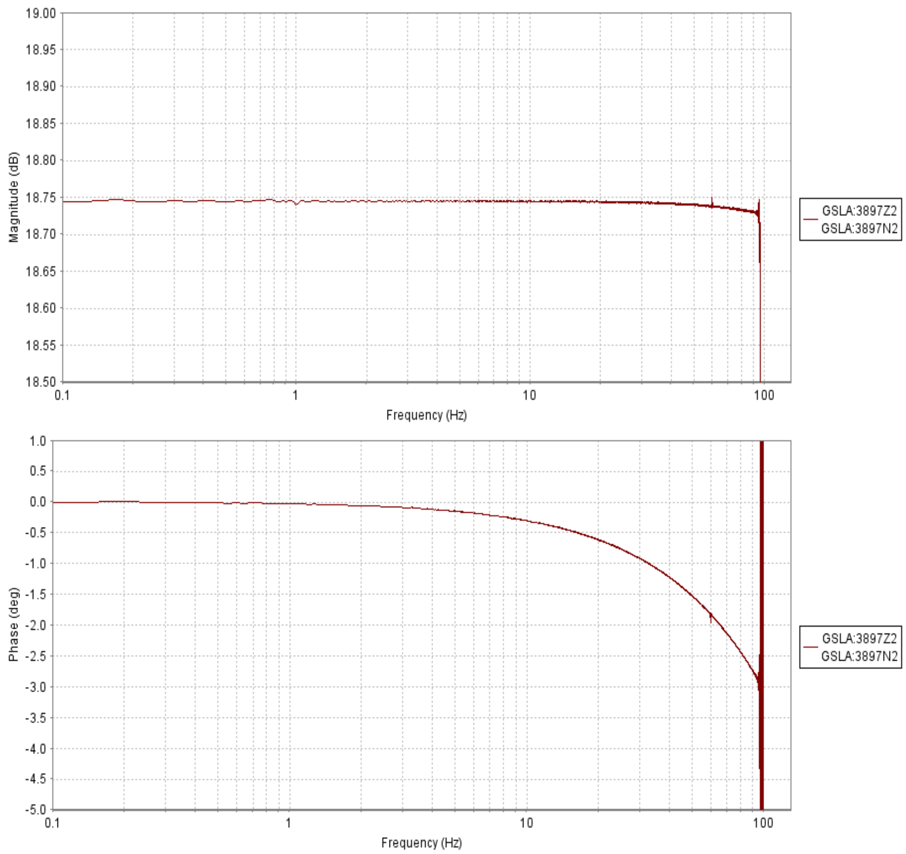

Figure 75 Relative Amplitude and Phase – G23511 Calibrator

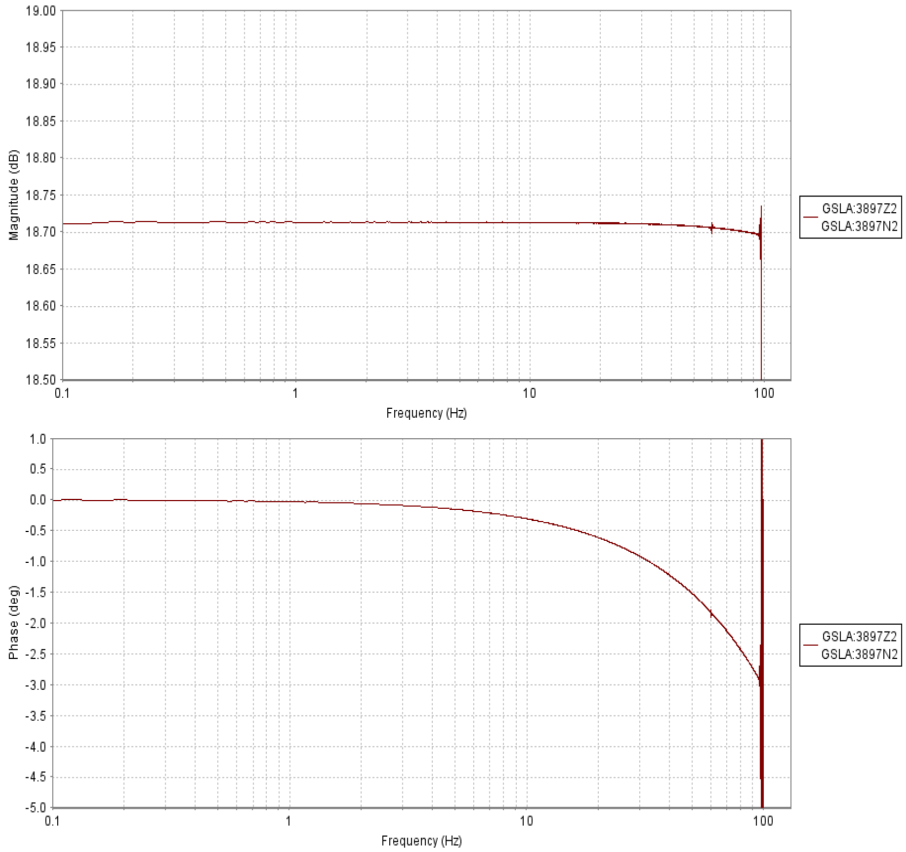

Figure 76 Relative Amplitude and Phase – G23512 Calibrator

The measured gain was approximately 18.745 dB (8.655x) and 18.713 dB (8.623x) for G23511 and G23512, respectively. The amplitude response was effectively flat across the measured pass-band with only a very slightly roll-off of 0.01 dB at 80 Hz.

There were some slight roll-offs in the phase response. However, this phase delay is indicative of a small difference in timing between the channels, as further investigated in section 3.22 Calibrator Relative Transfer Function.

The table below contains the preamplifier calibrator white noise amplitude and phase response values expressed in dB and degrees.

Table 48 White Noise Amplitude and Phase Response

	G23511		G23512	
Frequency	Amplitude (dB)	Phase (deg)	Amplitude (dB)	Phase (deg)
0.100 Hz	18.743 dB	-0.0002	18.711 dB	-0.0016
0.125 Hz	18.745 dB	-0.0013	18.712 dB	0.0006
0.160 Hz	18.747 dB	-0.0002	18.713 dB	-0.0029
0.200 Hz	18.745 dB	-0.0065	18.714 dB	-0.0050
0.250 Hz	18.745 dB	-0.0132	18.713 dB	-0.0080
0.315 Hz	18.745 dB	-0.0151	18.713 dB	-0.0088
0.400 Hz	18.745 dB	-0.0105	18.713 dB	-0.0114
0.500 Hz	18.745 dB	-0.0138	18.713 dB	-0.0150
0.630 Hz	18.745 dB	-0.0216	18.713 dB	-0.0208
0.800 Hz	18.745 dB	-0.0260	18.713 dB	-0.0263
1.000 Hz	18.745 dB	-0.0318	18.713 dB	-0.0333
1.250 Hz	18.744 dB	-0.0387	18.713 dB	-0.0389
1.600 Hz	18.745 dB	-0.0507	18.713 dB	-0.0481
2.000 Hz	18.745 dB	-0.0609	18.713 dB	-0.0605
2.500 Hz	18.745 dB	-0.0780	18.713 dB	-0.0777
3.150 Hz	18.745 dB	-0.0977	18.713 dB	-0.0963
4.000 Hz	18.745 dB	-0.1237	18.713 dB	-0.1230
5.000 Hz	18.745 dB	-0.1535	18.713 dB	-0.1536
6.300 Hz	18.745 dB	-0.1946	18.713 dB	-0.1928
8.000 Hz	18.745 dB	-0.2455	18.713 dB	-0.2449
10.000 Hz	18.744 dB	-0.3077	18.713 dB	-0.3068
12.500 Hz	18.744 dB	-0.3831	18.713 dB	-0.3827
16.000 Hz	18.744 dB	-0.4897	18.712 dB	-0.4908
20.000 Hz	18.744 dB	-0.6145	18.712 dB	-0.6107
25.000 Hz	18.743 dB	-0.7663	18.711 dB	-0.7641
31.500 Hz	18.742 dB	-0.9637	18.711 dB	-0.9605
40.000 Hz	18.741 dB	-1.2228	18.710 dB	-1.2181
50.000 Hz	18.740 dB	-1.5274	18.708 dB	-1.5231
63.000 Hz	18.737 dB	-1.9229	18.705 dB	-1.9183
80.000 Hz	18.734 dB	-2.4304	18.701 dB	-2.4293

3.22 Calibrator Relative Transfer Function

The Calibrator Relative Transfer Function test measures the amount of timing delay present on a preamplifier calibrator by measuring the timing skew between the preamplifier calibrator output and a reference digitizer channel.

3.22.1 Measurand

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

3.22.2 Configuration

The preamplifier and multiple digitizer channels are connected to a white noise signal source as shown in the diagram below.

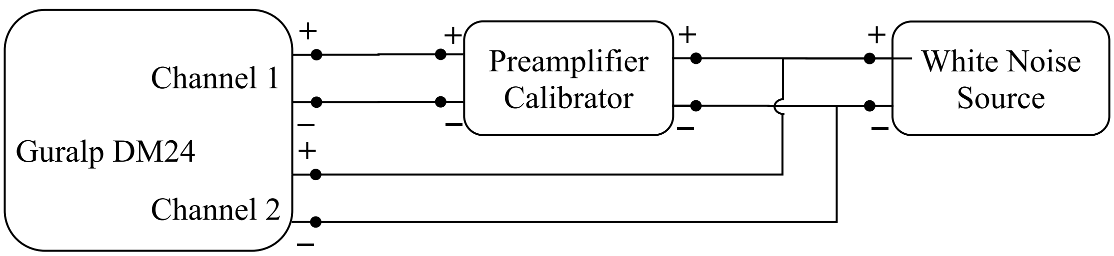

Figure 77 Relative Transfer Function Configuration Diagram

Table 49 Relative Transfer Function Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal, +/- 50 mV

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.

3.22.3 Analysis

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

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

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

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

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

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

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

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

3.22.4 Result

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

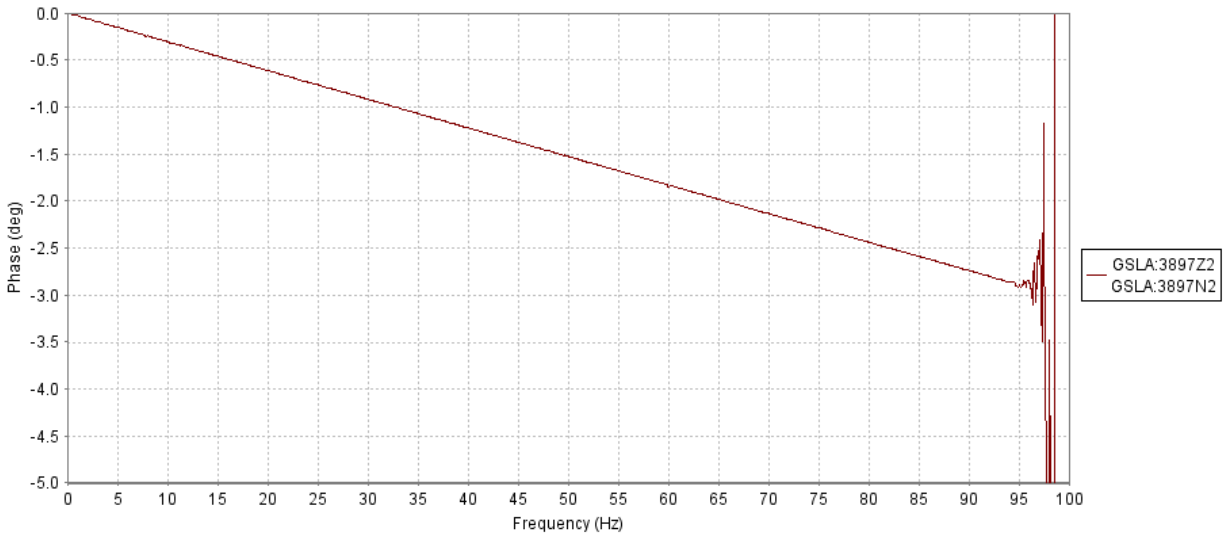

Figure 78 Relative Transfer Function Relative Phase – G23511 Calibrator

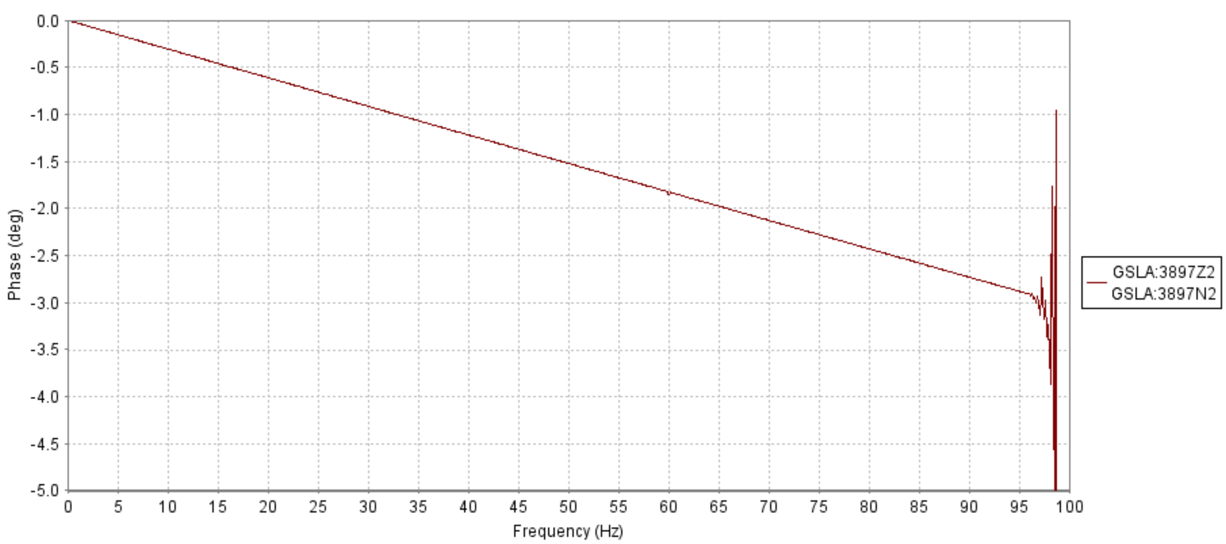

Figure 79 Relative Transfer Function Relative Phase – G23512 Calibrator

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

Table 50 Calibrator Relative Transfer Function Timing Skew relative to Channel 1

	G23511	G23512
Time Delay (0.01 - 90 Hz)	-85.41 uS	-85.13 uS

Prior to testing the Guralp GS13 preamplifier, the relative transfer function between the Z and the N channels of the Guralp DM24 were independently measured and determined to have a relative timing skew of 0.387 us. This value is significantly less than what was measured using the preamplifier calibrator. Therefore, the measured timing delay of 85 us is believed to be attributed to the preamplifier calibrator.

3.23 Calibrator Analog Bandwidth

The Calibrator Analog Bandwidth test measures the bandwidth of the preamplifier calibrator.

3.23.1 Measurand

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

3.23.2 Configuration

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

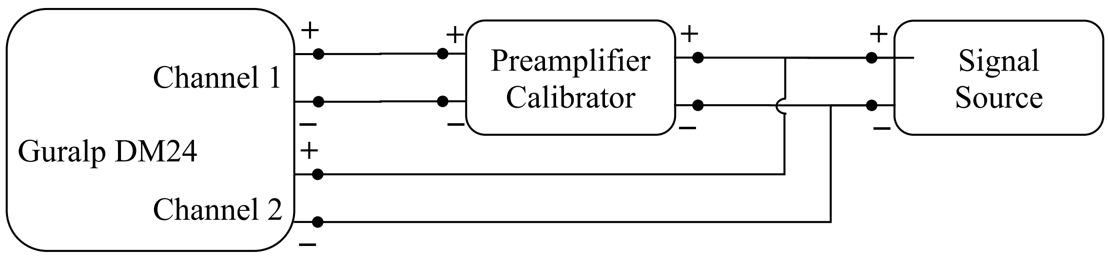

Figure 80 Calibrator Analog Bandwidth Configuration Diagram

Table 51 Calibrator Analog Bandwidth Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
White Noise Source	SRS DS360	S/N 123672	White Signal, +/- 50 mV

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.

3.23.3 Analysis

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

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

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

3.23.4 Result

The power spectra of the white noise signal recorded on the Guralp DM24 digitizer channels are shown in the plot below.

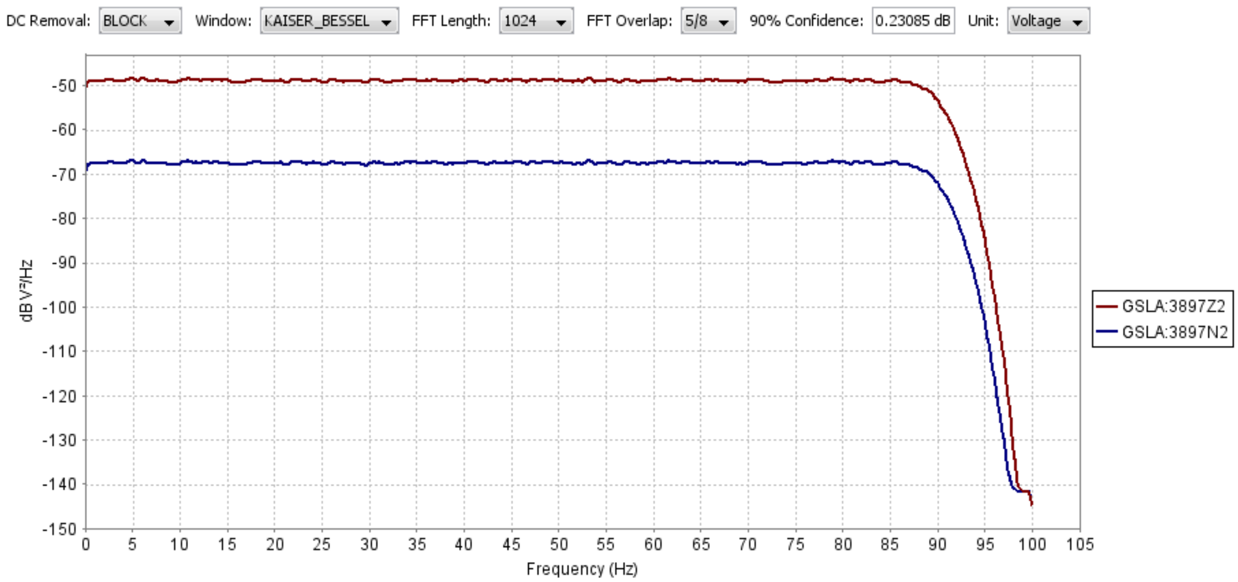

Figure 81 Calibrator Analog Bandwidth 100 Hz

The table below contains the 3dB point measured from the power spectra.

Table 52 Calibrator Analog Bandwidth

	G23511	G23512
Preamp channel Z bandwidth	89.453 Hz	89.453 Hz
Reference channel N bandwidth	89.453 Hz	89.453 Hz

Prior to testing the Guralp GS13 preamplifier, the bandwidth of the Z and the N channels of the Guralp DM24 were independently measured and determined to have no significant difference.

The signal recorded on both the Z and N channels of the Guralp DM24 digitizer have identical bandwidths. Therefore, the preamplifier calibrator is not believed to be imposing any reduction in the signal bandwidth for this application passband.

3.24 Calibrator Crosstalk

The Calibrator Crosstalk test measures how much of a calibration signal is present on the signal input channel as noise.

3.24.1 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.

3.24.2 Configuration

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

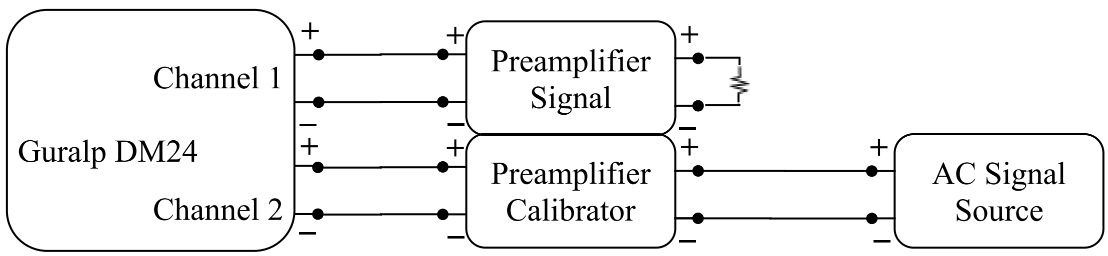

Figure 82 Crosstalk Configuration Diagram

The signal input to the preamplifier is terminated with a resistor while an AC signal is fed into the calibrator and the calibrator is enabled. Both the signal output and the calibrator output are recorded on the input channels of the DM24. The signal output is examined for evidence of the calibration signal

Table 53 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
AC Signal Source	Guralp DM24 Calibrator	S/N 3897	1 Hz Sine
Resistor	N/A	N/A	10k (5k x 2) ohm

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

3.24.3 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 1k-sample Hann window and 5/8 overlap of the input terminated channel and all of the tonal channels:

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

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

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

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

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

3.24.4 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.

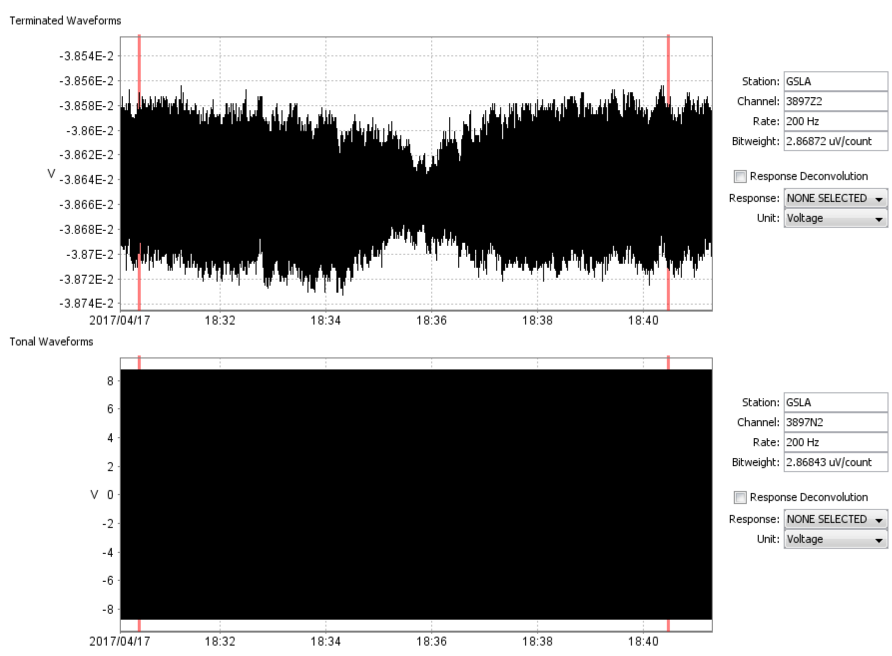

Figure 83 Crosstalk Time Series

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

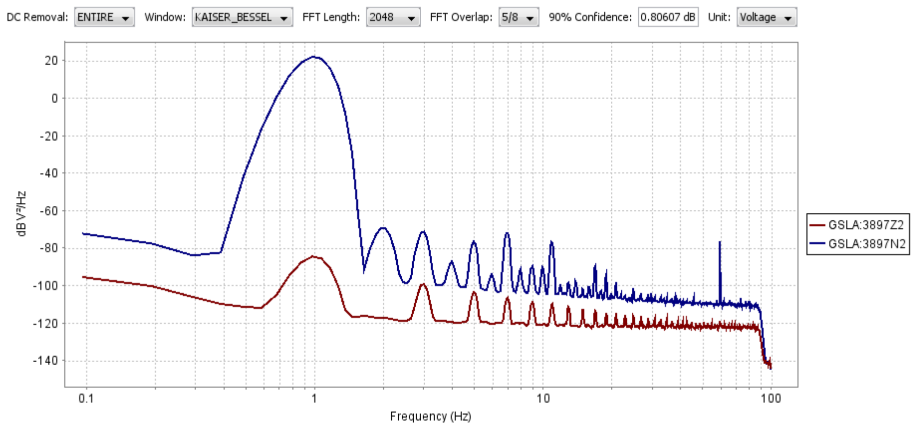

Figure 84 Crosstalk Power Spectra

The following table contains the computed crosstalk ratios.

Table 54 Calibrator Crosstalk

	G23511	G23512
Terminated Amplitude	28.99 uV rms	45.71 uV rms
Tonal Amplitude	6.167 V rms	6.131 V rms
Rejection	-106.56 dB	-102.55 dB

The observed levels of crosstalk were all between -106.56 and -102.55 dB.

3.25 GS13 Seismometer Calibrator

The GS13 Seismometer Calibration test is performed to validate the performance of the preamplifier at calibrating a GS13 Seismometer.

3.25.1 Measurand

The quantity being measured is a comparison between the expected and actual recorded output of the seismometer.

3.25.2 Configuration

The preamplifier and its calibration line are connected to a Guralp DM24 Digitizer and a Geotech GS13 Seismometer as shown in the diagram below.

Figure 85 GS13 Seismometer Calibrator Configuration Diagram

Figure 86 GS13 Seismometer Calibrator Picture

The seismometer signal output from the preamplifier was recorded on channel 1 (Z). The calibration signal input to the preamplifier was externally looped back to channel 2 (N).

Table 55 Crosstalk Testbed Equipment

	Manufacturer / Model	Serial Number
Digitizer	Guralp DM24	S/N 3897
Seismometer	Geotech GS13	S/N 884

A 1 Hz sinusoid and broadband white noise were generated from the DM24 to perform a calibration.

3.25.3 Analysis

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

$x[n]$

The recorded calibration input amplitude is scaled to determine the amount of acceleration imparted to the seismometer through its calibration coil:

$$A_{gs13} = \frac{V_{cal} * \ G_{preamp\ cal}}{R_{preamp} + R_{gs13\ calcoil}} * \ \frac{G_{cal\ coil}}{M}$$

Where

A_{gs13}	Acceleration imparted to the GS13 Seismometer Mass
V_{cal}	Calibration voltage input to the preamplifier
$G_{preamp\ cal}$	Calibration gain factor of the preamplifier, nominally 8.692x
R_{preamp}	Output impedance of the preamplifier calibration line, nominally 200 ohm
$R_{gs13\ calcoil}$	GS13 calibration coil impedance, 28.8 ohm from S/N 884 datasheet
$G_{cal\ coil}$	GS13 coil motor constant, 5.392 N/Ampere from S/N 884 datasheet
M	GS13 mass, 5 kg

That acceleration is then determined to impart an expected voltage output recorded on the data recorder:

$$V_{out} = A_{gs13} * \frac{1}{2\pi f} * G_{gs13} * G_{preamp}$$

Where

V_{out}	Voltage measured on the data recorder
A_{gs13}	Acceleration imparted to the GS13 Seismometer Mass
$2\pi f$	Frequency, in Hz, dependent scaling term to convert from acceleration to velocity.
G_{gs13}	GS13 Seismometer sensitivity, nominally 2000 V/m/s at 10 Hz or 1413 V/m/s at 1 Hz.
G_{preamp}	Preamplifier gain, nominally 40x.

The expected output and measured output are then compared and either the percent or dB difference between them is calculated.

3.25.4 Result

The figures below show the waveform time series for the recording made of the calibration input signal and the seismometer output signal. The window regions bounded by the blue lines indicate the segment of data used to evaluate the results.

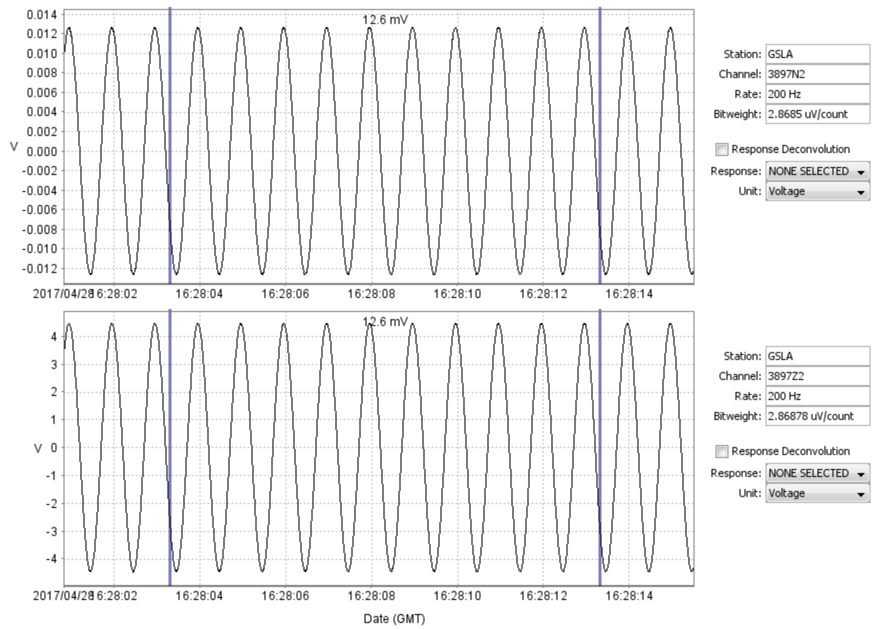

Figure 87 GS13 Seismometer Calibration Time Series – G23511 1 Hz Sine

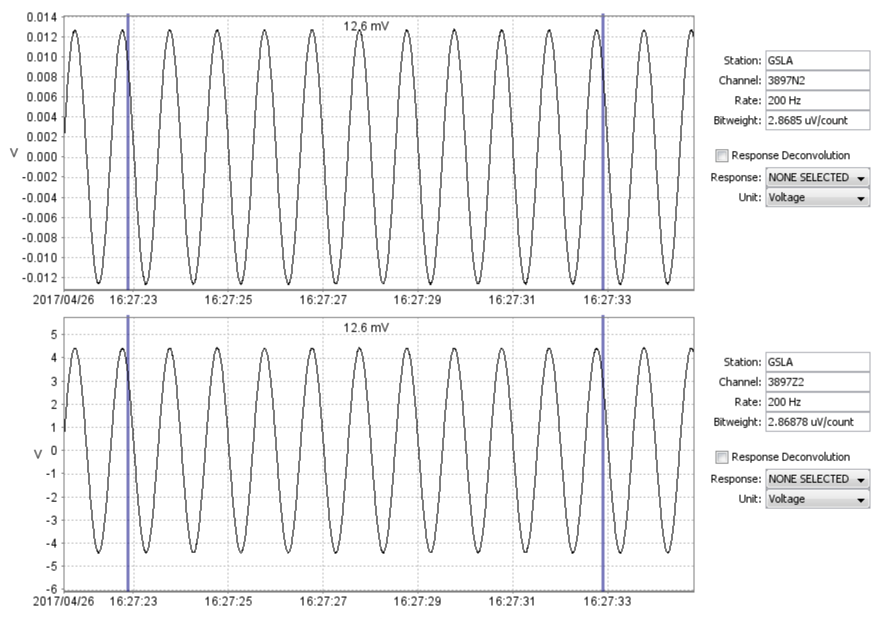

Figure 88 GS13 Seismometer Calibration Time Series – G23512 1 Hz Sine

The results of the calibration are shown in the table below.

Table 56 GS13 Seismometer Calibration Results – 1 Hz Sine

	G23511	G23512
Input Amplitude	0.01264 V	0.01263 V
Preamplifier Calibrator Gain	8.5376	8.5063
Preamplifier Calibration Impedance	200	200
GS13 Calibration Coil Impedance	28.8	28.8
GS13 Coil motor constant	5.392	5.392
GS13 Mass	5	5
Frequency	1	1
GS13 Sensitivity at 1 Hz	1413	1413
Preamplifier Gain	40	40
Expected Output Amplitude	4.5756 V	4.5566 V
Measured Output Amplitude	4.4552 V	4.4168 V
Percent Difference	-2.63%	-3.07%

The resulting seismometer outputs are within between 2.6% and 3.1% of the expected outputs.

A similar calibration was performed using one hour of white noise for each of the preamplifiers. The raw power spectra and relative amplitude response between the calibration signal and the seismometers are shown in the plots below. Note that the calibration signal was corrected for the preamplifer calibration gain, the calibration resistance, and the GS13 motor constant before being converted from acceleration to velocity for display. The GS13 signal output was corrected for the preamplifier signal gain and the GS13 sensitivity but not the nominal poles and zeros of a GS13. So, any shape in the amplitude response should reflect the GS13 response curve.

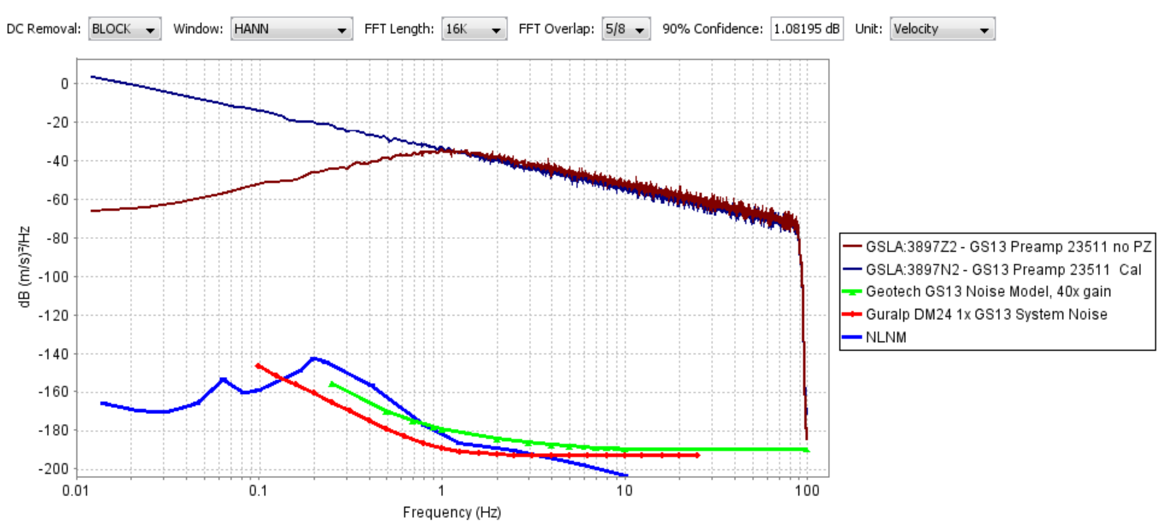

Figure 89 GS13 Seismometer Calibration Power Spectra – G23511 White

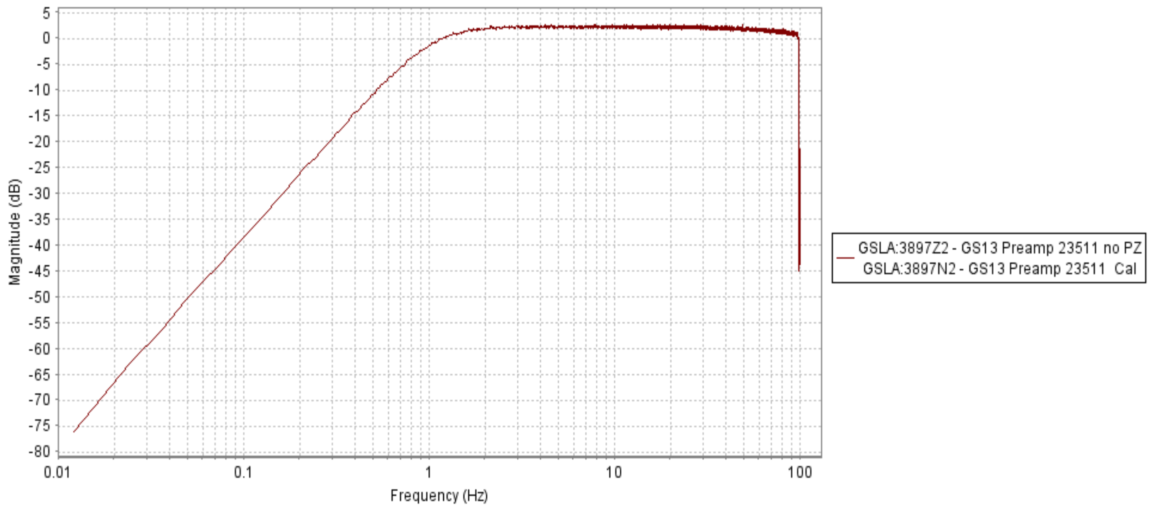

Figure 90 GS13 Seismometer Calibration Amplitude Response – G23511 White

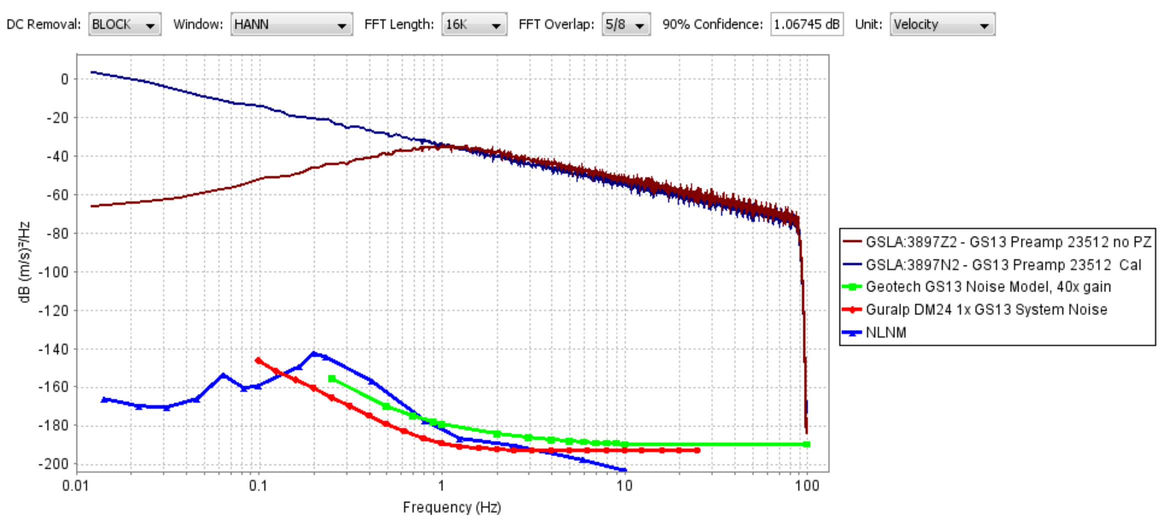

Figure 91 GS13 Seismometer Calibration Power Spectra – G23512 White

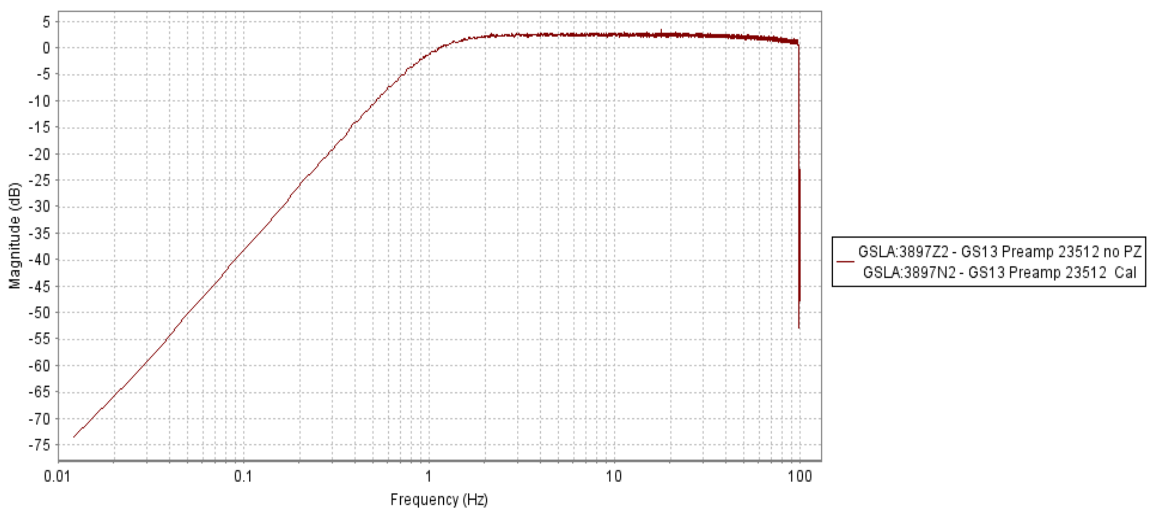

Figure 92 GS13 Seismometer Calibration Amplitude Response – G23512 White

Examining the amplitude response curves, the GS13's do appear to be down 3 dB at 1 Hz, as expected. However, the absolute level of the GS13 output appears to be approximately 2.5 dB higher than otherwise expected. There is no explanation for this at this time.

4 SUMMARY

Power Consumption
Both preamplifiers were found to consume approximately 0.98 W of power at 12.9 V with no input. While amplifying a full-scale sinusoid, power consumption increased to 1.07 W.

Impedance
The measured line impedances were found to be consistent with the specified signal input impedance of 47 kOhms and the calibration output impedance of 200 ohms. Impedance measurements confirm that the calibration line is controlled by a relay that is open when calibration is not enabled.

DC Accuracy
The preamplifiers were found to have DC gains of 39.9274x and 39.8819x for G23511 and G23512, respectively. Both of these values are within 0.3 % of the nominal 40x gain.

AC Accuracy
The preamplifiers were found to have DC gains of 39.9267x and 39.8820x for G23511 and G23512, respectively. Both of these values are within 0.29 % of the nominal 40x gain.

AC Full Scale
Both preamplifiers were found to correctly amplify an input sinusoid approximately 0.5 V peak and generate an output sinusoid of 20 V peak without any evidence of clipping.

AC Over Scale
Both preamplifiers were found to clip at an output amplitude of 45 V peak-to-peak (22.5 V peak) which would correspond to an input amplitude of 1.125 V peak-to-peak (0.5625 V peak)

Input Shorted Offset
The output of the preamplifiers were found to have a shorted offset on the output of -4.1084 mV and -3.8621 mV for G23511 and G23512, respectively.

Self-Noise
Both preamplifiers were found to have nearly identical self-noise that was a minimum of 5 dB above the Guralp DM24 1x self-noise at 16 Hz and 10 dB above the Guralp DM24 2x self-noise at 16 Hz.

Dynamic Range
The preamplifiers were found to have a dynamic range across 0.5 – 16 Hz of 133.17 dB and 132.47 dB for G23511 and G23512, respectively, assuming the digitizer is configured with a gain of 1x. For digitizer gains of 2x, 4x, and 8x, the dynamic ranges would be better than 127 dB, 121 dB, and 115 dB, respectively.

System Noise
The evaluation of system noise has demonstrated that the preamplifiers have a self-noise that is equivalent with the GS13 Seismometer self-noise. Due to the noise being additive, this will result in a combined self-noise that is 6 dB higher. This higher combined self-noise should be

taken into account when selecting the maximum acceptable level of digitizer self-noise. The noise for the lumped combination of GS13 Seismometer and Guralp preamplifier is well positioned against the IMS short-period requirements being better than 10 dB below the GERES Low Noise Model and 10 dB above the Guralp DM24 digitizer self-noise.

Tonal Response Verification
Using discrete sinusoidal tones, both preamplifiers were found to be flat across the evaluation pass-band of 0.01 Hz – 80 Hz with gain factors of 39.93x and 39.88x for G23511 and G23512, respectively. There was a slight roll-off in amplitude of 0.25 % (0.02 dB) evidence at 80 Hz. The phase response was linear, indicating a constant time delay.

Response Verification
Using white noise, both preamplifiers were found to be flat across the evaluation pass-band of 0.01 Hz – 80 Hz with gain factors of 39.926x and 39.880x for G23511 and G23512, respectively. There was a slight roll-off in amplitude of 0.25 % (0.02 dB) evidence at 80 Hz. The phase response was linear, indicating a constant time delay.

Relative Transfer Function
The preamplifiers were found to have a timing delay of approximately 200 uS when examining the linear phase delay using white noise.

Time Tag Accuracy
The preamplifiers were found to have a timing delay of approximately 197.5 uS when examining the delay of a PPM timing pulse.

Analog Bandwidth
Examining the roll-off of a white noise signal, the 3dB roll-off point of the recorded signal was limited by the digitizer FIR filter. The preamplifiers are not shown to impose any reduction in the signal passband for the seismic monitoring application.

Total Harmonic Distortion
The harmonic distortion of both preamplifiers was found to be better than -130 dB, which represents the limit of the signal that could be generated.

Modified Noise Power Ratio
Evaluating the modified noise power ratio indicates that both preamplifiers perform consistently with 21 effective bits and have limits on distortion at their full-scale range that are consistent with their clip levels.

Common Mode Rejection
The preamplifiers were found to have a common mode rejection ratio of 70 dB and 86 dB for G23511 and G23512, respectively.

Calibrator DC Accuracy
The preamplifier calibrators were found to have DC gains of 8.5377x and 8.5064x for G23511 and G23512, respectively. Both of these values are within 2.14 % of the nominal 8.692x gain.

Calibrator AC Accuracy
The preamplifier calibrators were found to have AC gains of 8.5376x and 8.5063x for G23511 and G23512, respectively. Both of these values are within 2.14 % of the nominal 8.692x gain.

Calibrator Response Verification
Using white noise, both preamplifier calibrators were found to be flat across the evaluation pass-band of 0.01 Hz – 80 Hz with gain factors of 8.655x and 8.623x for G23511 and G23512, respectively. There was a slight roll-off in amplitude of 0.12 % (0.01 dB) evident at 80 Hz. The phase response was linear, indicating a constant time delay.

Calibrator Relative Transfer Function
The preamplifier calibrators were found to have a timing delay of approximately 85uS when examining the linear phase delay using white noise.

Calibrator Analog Bandwidth
Examining the roll-off of a white noise signal, the 3dB roll-off point of the recorded calibration signal was limited by the digitizer FIR filter. The preamplifier calibrators are not shown to impose any reduction in the signal passband for the seismic monitoring application.

Calibrator Crosstalk
The calibrators were found to have a crosstalk of -106.56 dB and -102.55 dB for G23511 and G23512, respectively, between the calibration input line and the signal output line when calibration was not enabled.

GS13 Seismometer Calibration Demonstration
The preamplifiers were demonstrated to function with a GS13 seismometer and perform sinusoidal tone and white noise calibrations. The accuracy of the recorded calibrations were within 3.07 % for the sinusoidal tones and 2.5 dB for the white noise. No explanation for the difference in the two methods is available.

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

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

APPENDIX A: RESPONSE MODELS

Geotech GS13 Response

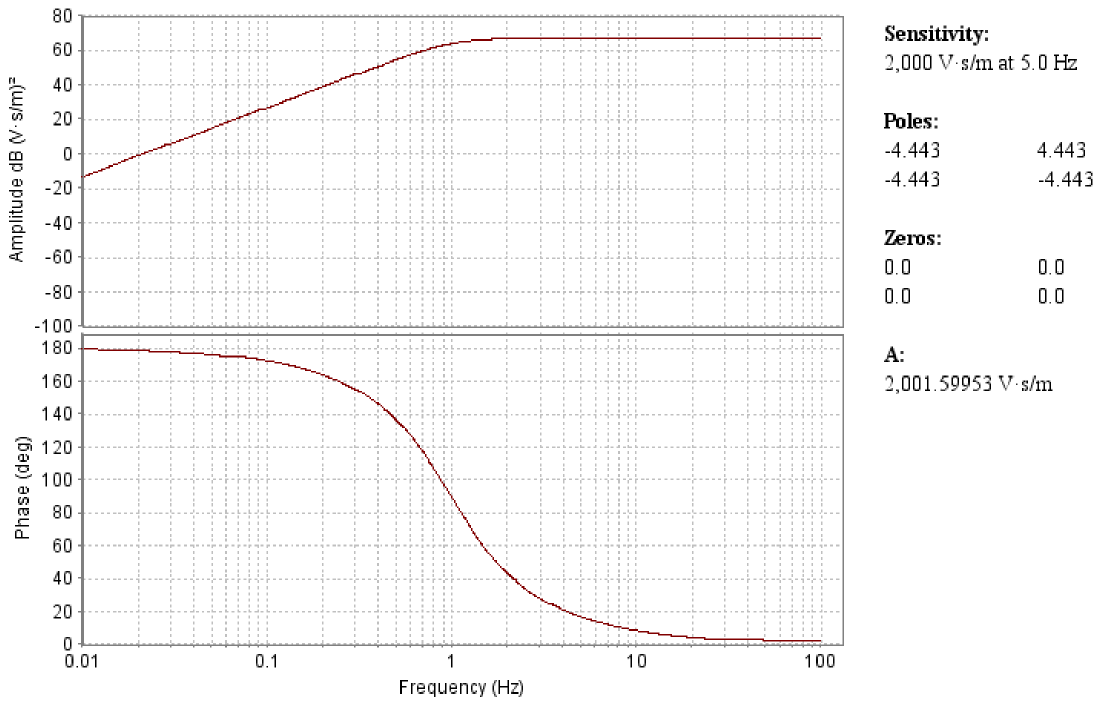
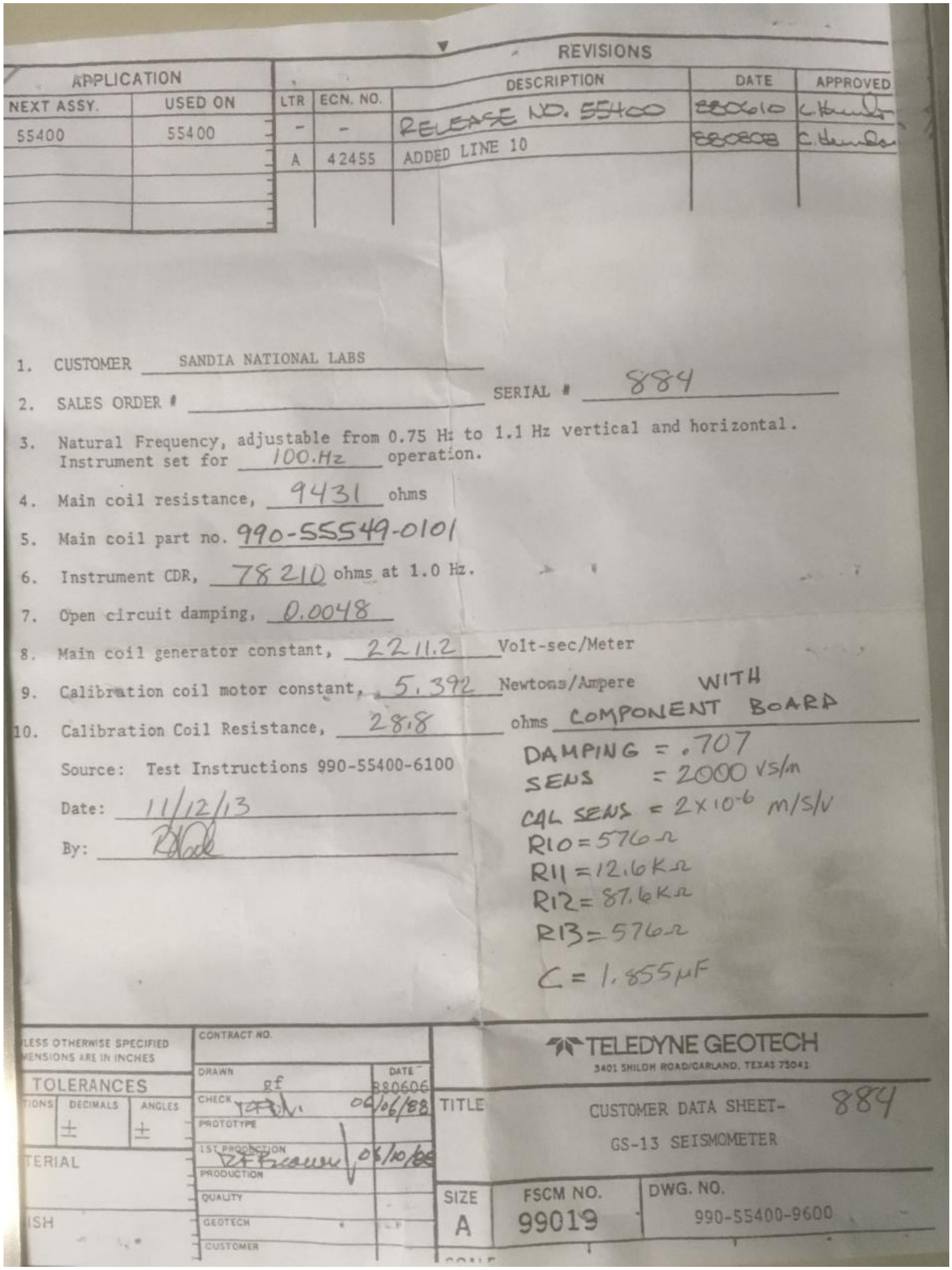


Figure 93 Geotech GS13 Generic Response Model



REVISIONS

APPLICATION	
NEXT ASSY.	USED ON
55400	55400

LTR	ECN. NO.	DESCRIPTION	DATE	APPROVED
-	-	RELEASE NO. 55400	880610	C.Hamilton
A	42455	ADDED LINE 10	880808	C.Hamilton

1. CUSTOMER SANDIA NATIONAL LABS
2. SALES ORDER # ______ SERIAL # 884
3. Natural Frequency, adjustable from 0.75 Hz to 1.1 Hz vertical and horizontal. Instrument set for 1.00 Hz operation.
4. Main coil resistance, 9431 ohms
5. Main coil part no. 990-55549-0101
6. Instrument CDR, 78210 ohms at 1.0 Hz.
7. Open circuit damping, 0.0048
8. Main coil generator constant, 2211.2 Volt-sec/Meter
9. Calibration coil motor constant, 5.392 Newtons/Ampere
10. Calibration Coil Resistance, 28.8 ohms WITH COMPONENT BOARD

DAMPING = .707
SENS = 2000 Vs/m
CAL SENS = 2x10-6 m/s/v
R10 = 576 Ω
R11 = 12.6 KΩ
R12 = 87.6 KΩ
R13 = 576 Ω
C = 1.855 μF

Source: Test Instructions 990-55400-6100

Date: 11/12/13

By: [signature]

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES
FRACTIONS ± DECIMALS ± ANGLES ±
MATERIAL
FINISH

CONTRACT NO.
DRAWN gf DATE 880606
CHECK 06/06/88
PROTOTYPE
1ST PRODUCTION R.F.Brauer 06/10/88
PRODUCTION
QUALITY
GEOTECH
CUSTOMER

TELEDYNE GEOTECH
3401 SHILOH ROAD/GARLAND, TEXAS 75041

TITLE CUSTOMER DATA SHEET- 884
GS-13 SEISMOMETER

SIZE A FSCM NO. 99019 DWG. NO. 990-55400-9600

Figure 94 Geotech GS13 #884 Calibration Data Sheet

APPENDIX B: TESTBED CALIBRATIONS

Agilent 3458A # MY45048371

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate
Document #: 6652541_11682157

Item Identification

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

Calibration Description

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

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

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

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

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

Test Results

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

```
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
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 36.2 deg.C
DC Volts
```

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	10.000220	9.99552	10.00043	10.00492	V	>10	4	
10.00000 V @ 20 kHz	10.000190	9.99549	9.99959	10.00489	V	>10	13	
10.00000 V @ 50 kHz	10.000207	9.99001	10.00030	10.01041	V	>10	1	
10.00000 V @ 100 kHz	9.999795	9.97960	9.99935	10.01999	V	>10	2	
10.00000 V @ 300 kHz	10.001654	9.90064	9.99865	10.10267	V	>10	3	
100.0000 V @ 10 Hz	100.00266	99.8007	100.0055	100.2047	V	>10	1	
100.0000 V @ 40 Hz	100.00218	99.9552	100.0044	100.0492	V	>10	5	
100.0000 V @ 20 kHz	100.00295	99.9559	100.0003	100.0500	V	>10	6	
100.0000 V @ 50 kHz	100.00901	99.9070	100.0129	100.1110	V	>10	4	
100.0000 V @ 100 kHz	100.01336	99.8113	100.0096	100.2154	V	>10	2	
100.0000 V @ 200 kHz	100.06044	99.0498	100.0300	101.0710	V	>10	3	
700.0000 V @ 40 Hz	700.01590	699.4359	700.0061	700.5959	V	>10	2	
700.0000 V @ 20 kHz	700.02470	699.4447	699.7808	700.6047	V	>10	42	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000039	10.005000	Hz	>10	2	
40.00000 Hz @ 1 V		39.996000	40.000415	40.004000	Hz	>10	10	
100.00000 Hz @ 1 V		99.990000	100.000600	100.010000	Hz	>10	6	
1000.0000 Hz @ 1 V		999.90000	1000.00696	1000.10000	Hz	>10	7	
10000.0000 Hz @ 1 V		9999.00000	10000.06962	10001.00000	Hz	>10	7	
20000.0000 Hz @ 1 V		19998.00000	20000.13923	20002.00000	Hz	>10	7	
50000.0000 Hz @ 1 V		49995.00000	50000.35285	50005.00000	Hz	>10	7	
100.00000 kHz @ 1 V		99.990000	100.000696	100.010000	kHz	>10	7	
500.00000 kHz @ 1 V		499.950000	500.003481	500.050000	kHz	>10	7	
1.000000 MHz @ 1 V		0.9999000	1.0000071	1.0001000	MHz	>10	7	
2.000000 MHz @ 1 V		1.9998000	2.0000139	2.0002000	MHz	>10	7	
4.000000 MHz @ 1 V		3.9996000	4.0000278	4.0004000	MHz	>10	7	
6.000000 MHz @ 1 V		5.9994000	6.0000422	6.0006000	MHz	>10	7	
8.000000 MHz @ 1 V		7.9992000	8.0000566	8.0008000	MHz	>10	7	
10.000000 MHz @ 1 V		9.9990000	10.0000696	10.0010000	MHz	>10	7	

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

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

Equipment (Standard) Used

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Traceability

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

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

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

Authorization

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

End-of-Document

Agilent 3458A # MY45048372

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Limited Calibration Certificate

Document #: 6652539_11669844

Item Identification

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

Calibration Description

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

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6652539_11669844

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

Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

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

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

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

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

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

Test Results

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

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

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Test Results

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

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Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	9.999940	9.99524	10.00044	10.00464	V	>10	11	
10.00000 V @ 20 kHz	10.000035	9.99533	9.99981	10.00474	V	>10	5	
10.00000 V @ 50 kHz	10.000073	9.98987	10.00033	10.01027	V	>10	3	
10.00000 V @ 100 kHz	10.000197	9.98000	9.99859	10.02040	V	>10	8	
10.00000 V @ 300 kHz	10.000297	9.89929	9.99356	10.10130	V	>10	7	
100.0000 V @ 10 Hz	99.99889	99.7969	100.0082	100.2009	V	>10	5	
100.0000 V @ 40 Hz	99.99940	99.9524	100.0070	100.0464	V	>10	16	
100.0000 V @ 20 kHz	100.00103	99.9540	100.0023	100.0480	V	>10	3	
100.0000 V @ 50 kHz	100.00567	99.9037	100.0131	100.1077	V	>10	7	
100.0000 V @ 100 kHz	100.00786	99.8058	100.0083	100.2099	V	>10	0	
100.0000 V @ 200 kHz	100.04847	99.0380	100.0279	101.0590	V	>10	2	
700.0000 V @ 40 Hz	700.01380	699.4330	699.9477	700.5930	V	>10	11	
700.0000 V @ 20 kHz	700.03500	699.4550	699.6812	700.6150	V	>10	61	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000029	10.005000	Hz	>10	1	
40.00000 Hz @ 1 V		39.996000	40.000000	40.004000	Hz	>10	0	
100.00000 Hz @ 1 V		99.990000	100.000085	100.010000	Hz	>10	1	
1000.0000 Hz @ 1 V		999.90000	1000.00152	1000.10000	Hz	>10	2	
10000.0000 Hz @ 1 V		9999.00000	10000.01335	10001.00000	Hz	>10	1	
20000.0000 Hz @ 1 V		19998.00000	20000.02479	20002.00000	Hz	>10	1	
50000.0000 Hz @ 1 V		49995.00000	50000.06675	50005.00000	Hz	>10	1	
100.00000 kHz @ 1 V		99.990000	100.000133	100.010000	kHz	>10	1	
500.00000 kHz @ 1 V		499.950000	500.000668	500.050000	kHz	>10	1	
1.000000 MHz @ 1 V		0.9999000	1.0000012	1.0001000	MHz	>10	1	
2.000000 MHz @ 1 V		1.9998000	2.0000027	2.0002000	MHz	>10	1	
4.000000 MHz @ 1 V		3.9996000	4.0000053	4.0004000	MHz	>10	1	
6.000000 MHz @ 1 V		5.9994000	6.0000078	6.0006000	MHz	>10	1	
8.000000 MHz @ 1 V		7.9992000	8.0000101	8.0008000	MHz	>10	1	
10.000000 MHz @ 1 V		9.9990000	10.0000134	10.0010000	MHz	>10	1	

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

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Limitations

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

Equipment (Standard) Used

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

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