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Evaluation of Two Guralp Preamplifiers for GS21 Seismometer Application

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Abstract

Sandia National Laboratories has tested and evaluated two Guralp preamplifiers for use with a GS21 seismometer application. The two preamplifiers have a gain factor of 61.39. The purpose of the preamplifier evaluation was to determine a measured gain factor, transfer function, total harmonic distortion, self-noise, application passband, dynamic range, seismometer calibration pass-through, and to comment on any issues encountered during the evaluation. The test results included in this report were in response to static, tonal, and dynamic input signals. The Guralp GS21 preamplifiers are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear Test-Ban-Treaty Organization (CTBTO).

Test methodologies used were based on IEEE Standards 1057 for Digitizing Waveform Recorders and 1241 for Analog to Digital Converters

ACKNOWLEDGMENTS

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We would like to thank Guralp for providing the GS21 preamplifiers to evaluate.

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NOMENCLATURE

CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
dB	decibel
DOE	Department of Energy
IMS	International Monitoring System
LNM	Low Noise Model
PSD	Power Spectral Density
SNL	Sandia National Laboratories

1 INTRODUCTION

Figure 1 Guralp GS21 Preamplifiers

The evaluation of the two Guralp GS21 preamplifiers, serial numbers G20307 and G20311, was performed by Sandia National Laboratories (SNL) in order to determine their performance for IMS applications. The preamplifiers were developed by Guralp for interfacing between a Geotech GS21 short-period seismometer and a Guralp CMG-DM24S3AM digitizer. A preamplifier is needed in this configuration in order to reduce the quantization and electronic noise of the digitizer and associated amplifiers to a level that is below the local site noise.

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.

2 TESTING OVERVIEW

2.1 Objectives
The objective of this work was to evaluate the overall technical performance of two Guralp preamplifiers. Basic preamplifier characterization includes determining DC gain factor, AC gain factor, noise, dynamic range, transfer function, relative total harmonic distortion, system noise performance, and calibration pass-through. The results of this evaluation were compared to relevant application requirements or specifications of the preamplifier provided by the manufacturer.

2.2 Test and Evaluation Background
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.

2.3 Standardization/Traceability
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).

2.4 Test/Evaluation Process

2.4.1 Preamplifier Testing
Testing of the preamplifiers, serial numbers G20307 and G20311, were performed during March-April 2015, at the Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) Site, Albuquerque, NM.

2.4.2 General Preamplifier Performance Tests
The tests that were conducted on the Guralp Systems GS21 Preamplifier were based on digitizer tests described in the test plan: *Test Definition and Test Procedures for the Evaluation of Digitizing Waveform Recorders* (Kromer, 2007).

The tests selected provide a high level of characterization for IMS when evaluating digitizers and preamplifiers for seismic or acoustic applications.

Preamplifier Configuration

Static Performance Tests
- Preamplifiers DC Gain Factor (PA-DCGF)
- Preamplifier Input Terminated Noise (PA-ITN)
- Maximum Potential Dynamic Range (PA-MPDR)

Tonal Dynamic Performance Tests
- Preamplifier AC Gain Factor (PA-ACGF)
- Preamplifier Relative Total Harmonic Distortion (PA-RTHD)

Broadband Dynamic Performance Tests
    Preamplifier Analog Bandwidth (PA-ABW)
    Preamplifier Relative Transfer Function (PA-RTF)
Application Tests
    Preamplifier Seismic System Noise (PA-SSN)
    Preamplifier Bandwidth Limited Dynamic Range (PA-BLDR)

2.5 Test Configuration and System Specifications

2.5.1 Preamplifier Description and Test Configuration

The GS21 preamplifiers under evaluation were manufactured by Guralp Systems, Inc. The two preamplifiers were designed to accept a differential input from a GS21 seismometer and provide a differential output with a gain of 61.39x. The preamplifiers were also designed to allow for pass-through the calibration signal from the digitizer to the sensor.

Since the Geotech GS21 seismometer is a short-period instrument, this evaluation will focus on the IMS short period pass-band of 0.5 to 16 Hz.

Custom test cables were built to allow the preamplifiers to interface with the FACT site testbed equipment. Two methods were used to collect test data. The Agilent 3458A multimeter provided a calibrated voltage reference for tests that did not require the data to be GPS time stamped. The Guralp CMG-DM24S3AM serial number 2187 was used for tests that did require the data to be GPS time stamped or time synchronized.

Guralp Systems provided notes on the preamplifier:

- Output connector pinout (26-way mil plug)
- Input connector pinout (26 way mil socket)
- Input impedance of the amplifier is 2 meg Ohm
- Input voltage range +/- 0.3 Volts

The input and output connector pin outs are shown in tables below.

Table 2 Preamplifier sensor connector pin outs provide by Guralp Systems

26-pin mil-spec socket MIL-DTL-26482	Description
C	INPUT-
D	GND
N	CAL+
U	INPUT+
V	GND
Z	CAL-

Table 3 Preamplifier recorder connector pin outs provided by Guralp Systems

26-pine mil-spec plug MIL-DTL-26482	Description
A	Output+
B	Output-
N	Signal Ground
P	Calibration Signal
R	Calibration Enable
V	Active-high select
Y	Logic ground
b	+V Power (10-36V)
c	Power Return (Case)

Preamplifier testing was performed at the FACT site.

Figure 2 Guralp preamplifier G20307 and G20311 at FACT

2.6 Test Configuration and System Specifications

The general test configuration was setup consistent with the diagram below. A specific configuration diagram is provided to document each test that is performed.

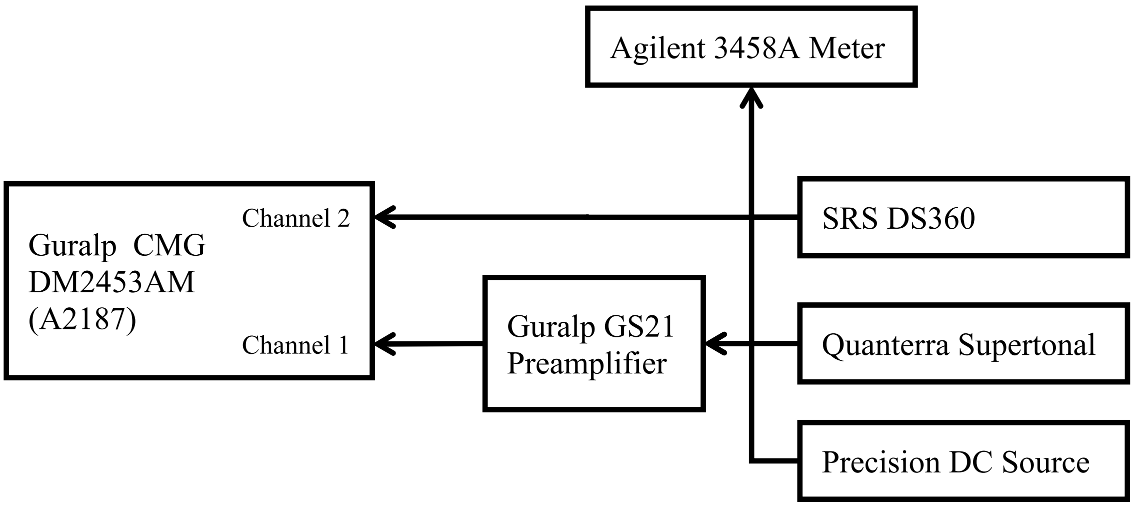


Figure 3 Test Configuration Diagram

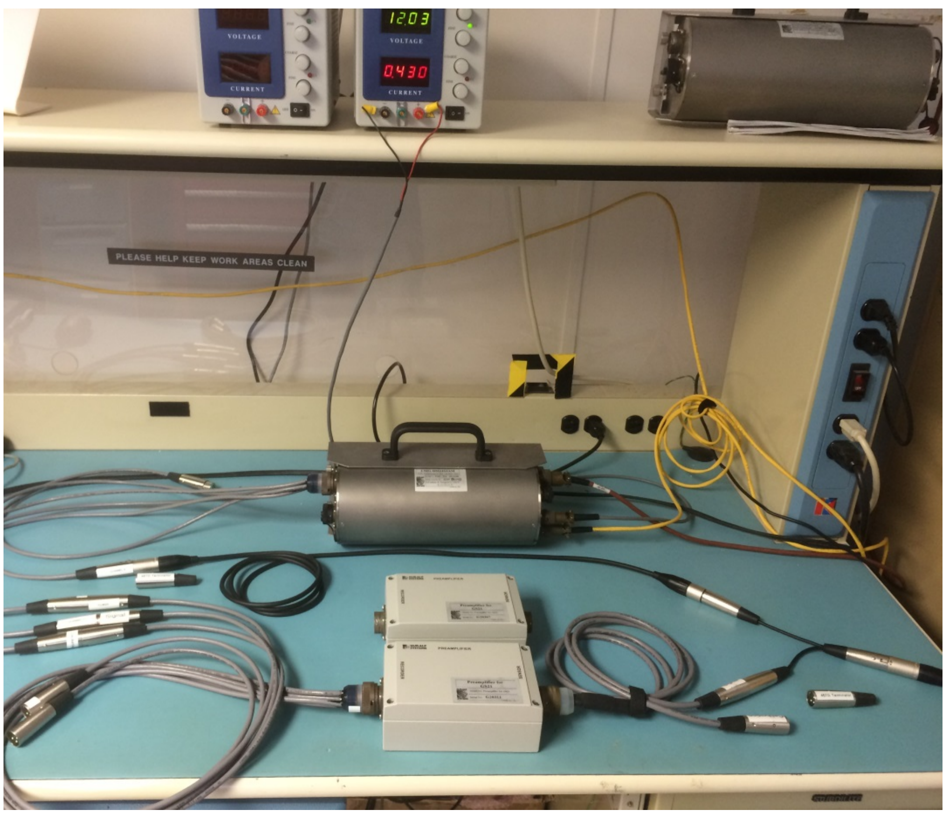


Figure 4 Test Setup

2.6.1 Power

The digitizer within the testbed was powered off of precision laboratory power supplies configured for 12 Volts.

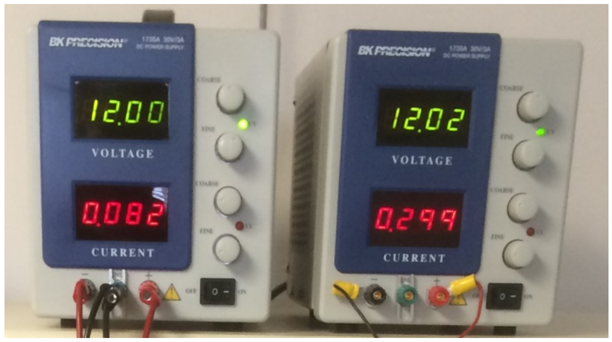


Figure 5 Lab Power Supplies

For the evaluation of the GS21 Preamplifier power consumption, the digitizer and preamplifier were powered independently from their own power supplies. For the remainder of the evaluation, the preamplifier was powered directly from the digitizer.

2.6.2 Data Recording

The data used in this test were recorded on either an Agilent 3458A meter with a current NIST calibration from Sandia's Primary Standards Laboratory or a Guralp CMG-DM24S3AM #2187 that was evaluated against the same Agilent meter for this test.

Figure 6 Agilent 3458A Serial #MY45048371

The Guralp digitizer is configured with a nominal bitweight of 2.86 uV/count with a 48 V peak-to-peak input range. The digitizer was configured to record each channel of data at both 40 and 80 Hz. The 80 Hz rate data is used to more fully capture the pass band of the preamplifier and the 40 Hz rate data is representative of the intended IMS use.

Figure 7 CMD-DM24S3AM Serial #2187

The digitizer bitweights were verified prior to testing using a precision DC source that was verified against an Agilent 3458A that has been calibrated by the SNL Primary Standards Lab to provide traceability. The measured bitweights, shown in the digitizer configuration tables below, were used for all collected sensor data. In addition, the digitizer input channels were evaluated separately from the amplifier evaluations in order to confirm their performance. Details on the digitizer input channel performance is presented along-side the evaluations of the amplifier for reference.

Table 4 Guralp CMG-DM24S3AM Bitweights

Channel Name	Bitweight
Channel 1 (Z)	2.8684 uV/count
Channel 2 (N)	2.86815 uV/count

2.6.3 Signal Generation

The test signals were generated either from a Stanford Research Systems DS360 Ultra Low Distortion Oscillator, a Quanterra Supertonal Signal Source, or a precision DC voltage calibrator.

Figure 8 Stanford Research Systems DS360 Ultra Low Distortion Oscillator

Figure 9 Quanterra Supertonal Signal Source and GPS

Figure 10 Martel DC Voltage Calibrator

2.6.4 Ambient Conditions

Testing of the Guralp GS21 Preamplifiers was conducted at Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) Site in Albuquerque, NM. The FACT site is at approximately 1830 meters in elevation. Testing was performed at an electronics laboratory at the FACT site in which the ambient temperature was kept at approximately 20 degrees Celsius.

3 EVALUATION

3.1 Power Consumption

Test description: Measure power consumption of the preamplifier. The preamplifier was powered independently on its own lab power supply while connected to the digitizer. Power consumption was recorded with the preamplifiers input terminated with a 467 ohm resistor and while actively driven with a 1 Hz, 0.1 V sinusoid from the SRS DS360.

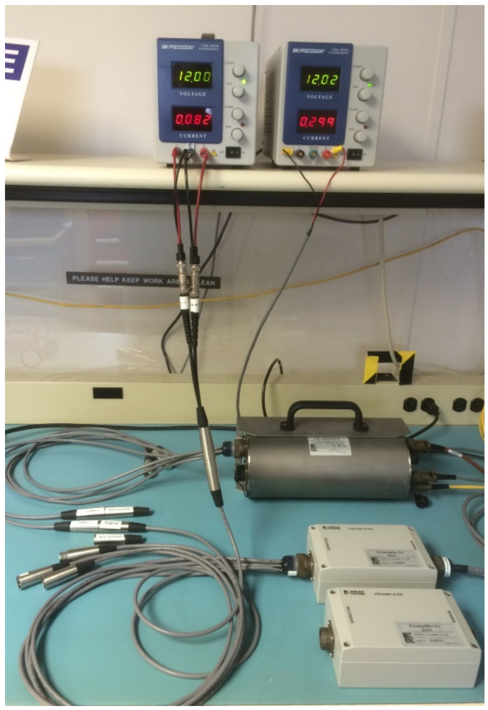


Figure 11 Power Consumption Evaluation

The preamplifiers were measured to have the power consumption in the table below using the lab power supplies:

Sensor	Power Supply Voltage	Current	Power Consumption
G20307 (idle)	12.0 V	82 mA	984 mW
G20307 (active)	12.0 V	83 mA	996 mW
G20311 (idle)	12.0 V	80 mA	960 mW
G20311 (active)	12.0 V	81 mA	972 mW

Figure 12 Guralp GS21 Preamplifier Power Consumption

The observed power consumption of the Guralp GS21 Preamplifier was between 960 and 996 mW at 12.0 V.

3.2 Input Impedance

Test Description: The purpose of the input impedance test is to measure the impedance of the Guralp GS21 Preamplifier sensor input lines. Input impedance was measured using a hand-held Fluke multimeter while the preamplifiers were powered by the digitizer.

Figure 13 G20307 Input Impedance

Figure 14 G20311 Input Impedance

Table 5 Guralp GS21 Preamplifier Input Impedance

Sensor	Input Impedance
G20307	1.468 Mohm
G20311	1.620 Mohm

3.3 Input Terminated Noise

Test Description: The purpose of the input terminated noise test isolation noise test is to evaluate the noise present in the output of the preamplifier without a driven input signal.

The preamplifier input is terminated with a resistor of the approximate output impedance of the application seismometer. Since the application is for GS21 seismometer, we used a 467 ohm resistor that matches the nominal coil impedance of the GS21.

The output of the resistor terminated preamplifier was recorded by digitizer channel 1 (Z). The digitizer channel 2 (N) was also terminated with common resistors for reference. Over 12 hours of input terminated data were collected for each terminated noise test of the preamplifiers.

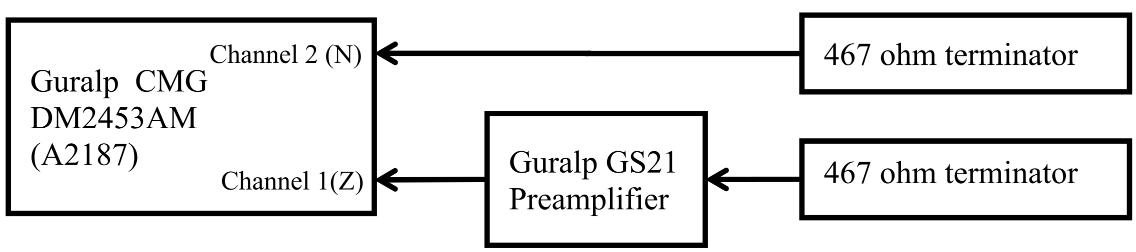


Figure 15 Preamplifier Input Terminated Noise Configuration Diagram

Figure 16 Preamplifier Input Terminated Noise Configuration

The input terminated noise tests were performed for each preamplifier with the digitizer configured with a gain of 1x, 2x, 4x, and 8x. Measurements of input terminated noise were made on the digitizer channel at each of the gain settings as well, without the presence of the preamplifier. The digitizer input terminated noise levels are overlaid on the plots of the preamplifier input terminated noise for comparison.

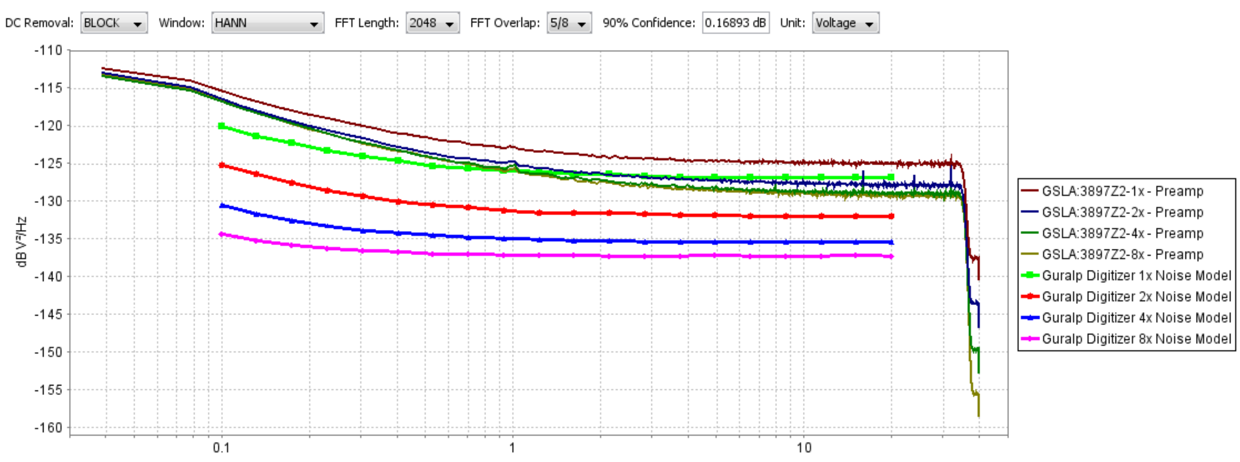


Figure 17 G20307 Preamplifier Input Terminated Noise Power Spectra

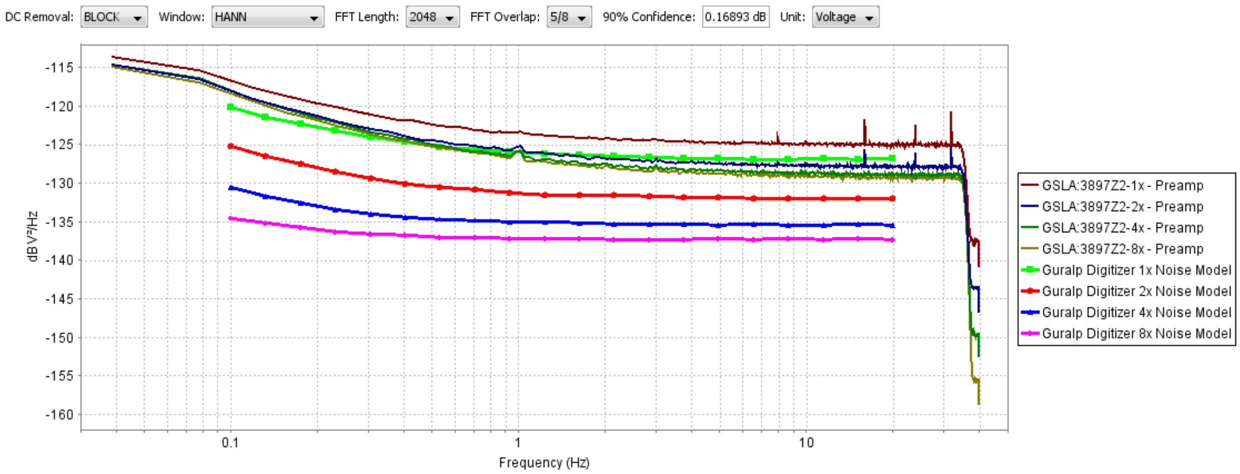


Figure 18 G20311 Preamplifier Input Terminated Noise Power Spectra

We observe that at a digitizer gain of 1x, the input terminated noise of the digitizer and preamplifier are very close to each other. In fact, due to the noise power of the digitizer and preamplifier being additive, the observed noise in the preamplifier at a digitizer gain of 1x is greater than the intrinsic preamplifier noise. At a digitizer gain of 2x, the digitizer is able to better resolve just the preamplifier noise with as much as a 2.5 dB reduction in system noise. At 4x gain, the digitizer appears able to resolve just the preamplifier noise level. At 8x gain, there is minimal improvement in the noise floor suggesting that the observed noise is due solely to the preamplifier.

The preamplifier could be operated with a digitizer gain of between 1x and 4x depending upon the requirements for noise level and dynamic range. Gain levels beyond 4x will only serve to reduce dynamic range without any significant improvement in noise level.

Measurements of the RMS noise level across 0.5 to 16 Hz were calculated for the power spectra at each gain level for the two preamplifiers.

	1x Gain	2x Gain	4x Gain	8x Gain
G20307	2.28062 uV rms	1.71114 uV rms	1.52518 uV rms	1.47571 uV rms
G20311	2.27935 uV rms	1.66947 uV rms	1.49986 uV rms	1.44004 uV rms

Figure 19 Preamplifier Input Terminated RMS Noise

Note that this analysis uses the digitizer bit weight for channel 1 and so does not take into account the gain of the preamplifier, which would serve to reduce the noise level in volts by a factor equal to the preamplifiers gain (61.39x or 35.76 dB). The reported terminated noise values should be interpreted as being voltage amplitudes on the output of the preamplifier.

3.4 AC Clip

Test Description: The purpose of the ac clip test is to evaluate the voltage at which the preamplifier's output will clip.

Prior to this evaluation, the clip levels of channels 1 and 2 of the Guralp digitizer were evaluated with a 30 V peak input sinusoid whose amplitude was verified on the Agilent meter:

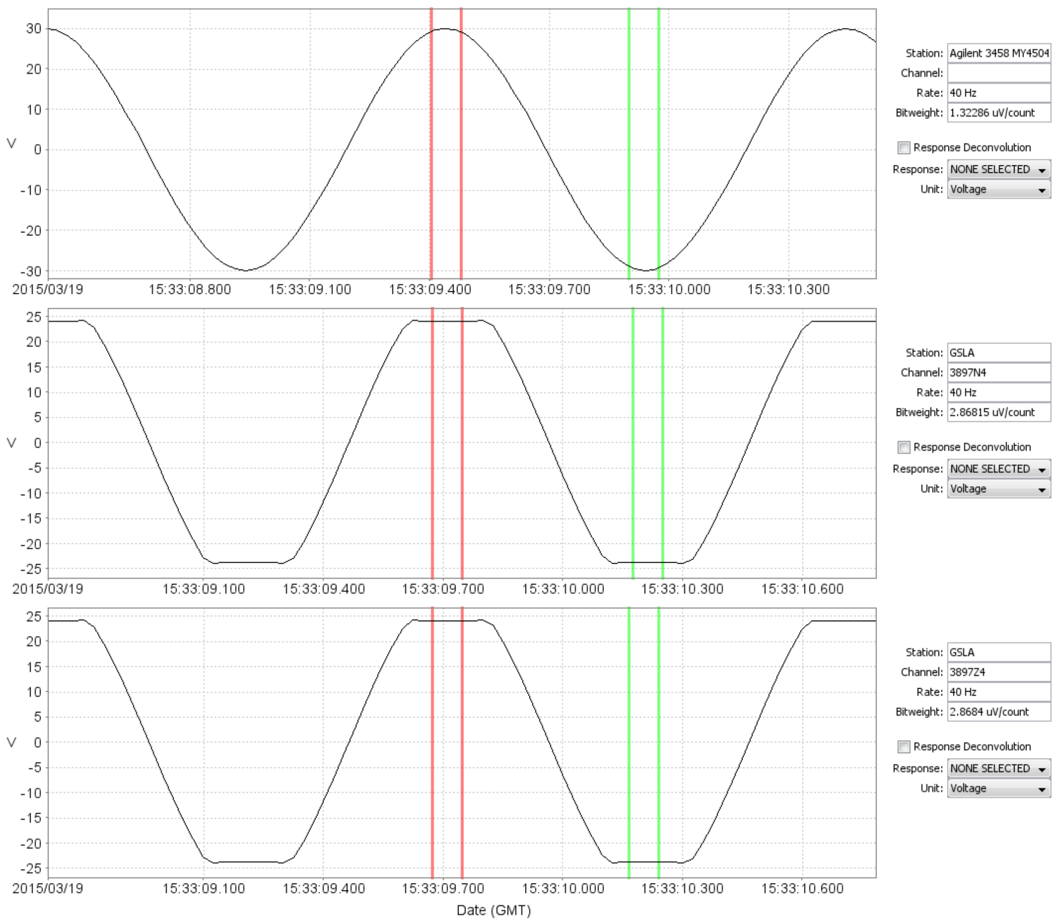


Figure 20 Guralp Digitizer Clip

Table 6 Guralp Digitizer Clip Levels

Waveform	Positive mean	Negative mean
Agilent 3458 MY45048371	29.73054 V	-29.72299 V
GSLA:3897N4	24.06165 V	-23.84857 V
GSLA:3897Z4	24.06373 V	-23.85059 V

The Guralp digitizer was verified to have a maximum input voltage of +/- 24 Vp (48 Vpp). Based upon this determination, the test bed configuration was modified to record the output of the preamplifier on both the Guralp digitizer and the reference Agilent 3458A meter. This would allow a measurement of the preamplifier output to be made regardless of whether the digitizer clipped.

The SRS DS360 is used to generate a 1 Hz sinusoid with an amplitude that is increased until the output of the Guralp GS21 Preamplifier is observed to clip. The output of the DS360 is fed into the input of the preamplifier and channel 2 of the digitizer. The output of the preamplifier is connected to both channel 1 of the digitizer and to the reference Agilent 3458A meter.

Note that the durations of the signals used for performing clip testing are kept as short as possible so as to minimize any possible damage to the equipment.

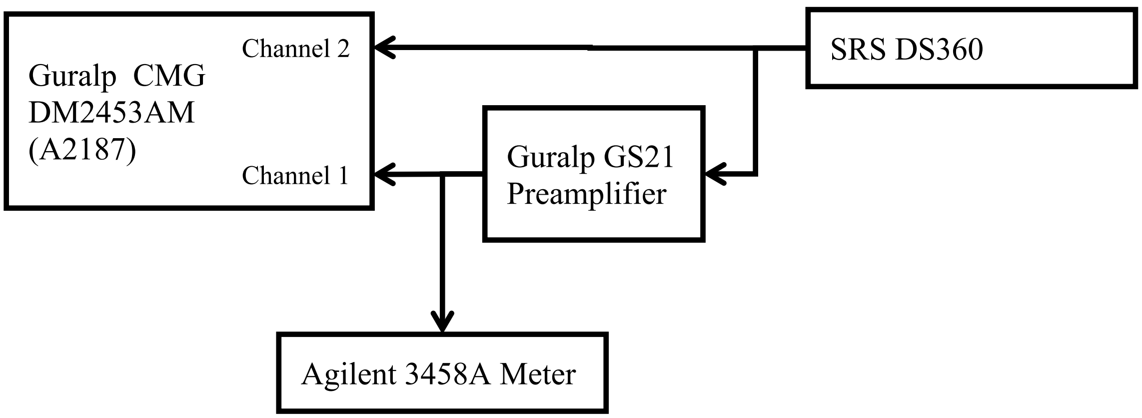


Figure 21 Preamplifier AC Clip Configuration Diagram

Figure 22 Preamplifier AC Clip Configuration

Clipping of the preamplifier output was observed with an input of a 1.0 Hz, 0.4 V sinusoid.

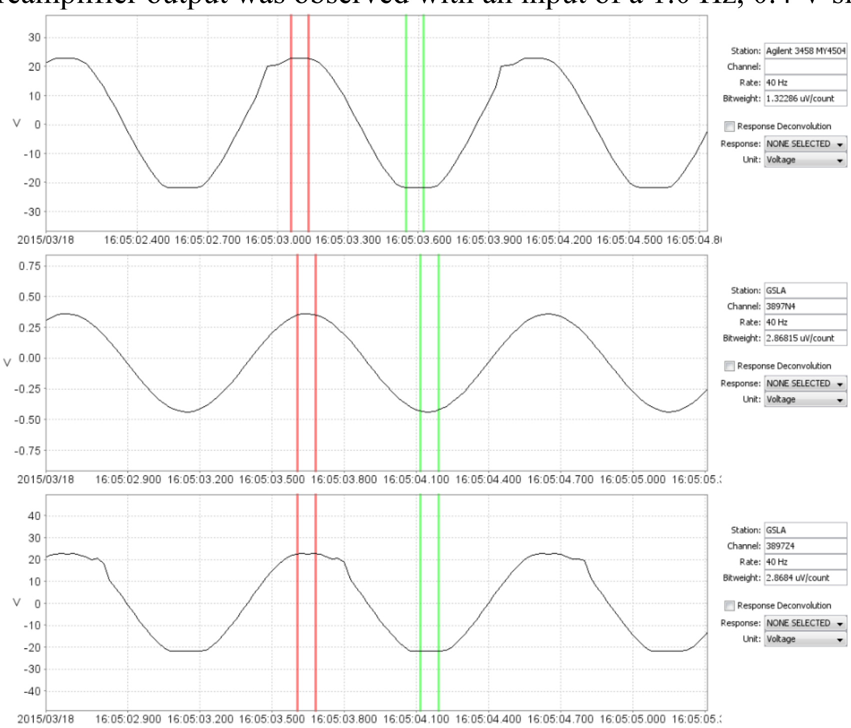


Figure 23 G20307 Clip Waveforms

Table 7 G20307 Clip Levels

Waveform	Positive	Negative
Agilent 3458 MY45048371	22.64714 V	-21.78202 V
GSLA:3897N4	0.35749 V	-0.43577 V
GSLA:3897Z4	22.66293 V	-21.795 V

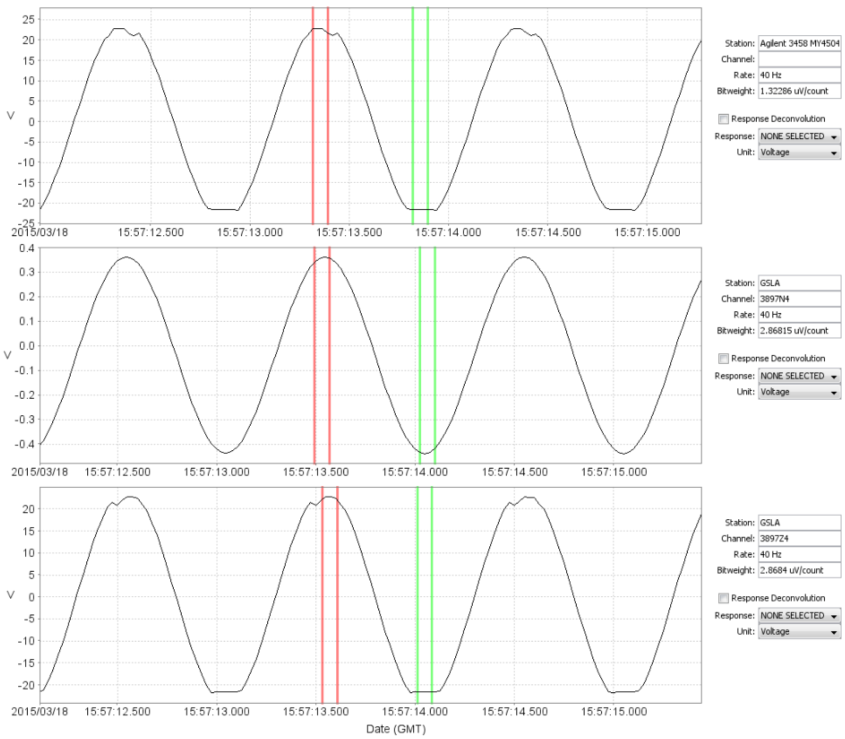


Figure 24 G20311 Clip Waveforms

Table 8 G20311 Clip Levels

Waveform	Positive	Negative
Agilent 3458 MY45048371	22.35357 V	-21.65059 V
GSLA:3897N4	0.35748 V	-0.43577 V
GSLA:3897Z4	22.60836 V	-21.68021 V

Based upon the measurements made on the reference meter, the preamplifier outputs were observed to clip at the following levels:

Table 9 Preamplifier Clip Levels

	Positive clip	Negative clip	Range (peak-peak)
G20307	22.64714 V	-21.78202 V	44.4292 V
G20311	22.35357 V	-21.65059 V	44.0042 V

Based upon these results, the preamplifier clip levels appears to be well matched to the Guralp CMG-DM24's clip level so as to maximize the available dynamic range.

3.5 Dynamic Range

Test Description: The purpose of the dynamic range test is to determine the ratio between the largest and smallest possible signals that may be observed on the sensor. SNL defines dynamic range as the ratio between the RMS of a full-scale sinusoid at the calibration frequency, typically 1 Hz, and the RMS noise present in the self-noise across the application pass band, in this case 0.5 to 16 Hz.

The full scale values at a gain of 1x were obtained from the observed clip level of the preamplifier output. The full scale values at gain setting of 2x, 4x, and 8x were obtained from the theoretical 48 V full scale of the Guralp digitizer scaled by the gain setting.

Using the self-noise estimates obtained from section 3.3 Input Terminated Noise, which are believed to be the best estimate of self-noise available, the preamplifier dynamic ranges are:

Table 10 Preamplifier G20307 Dynamic Range

	Full Scale (peak-peak)	Noise	Dynamic Range
1x Gain	44.4292 V	2.28062 uV rms	136.76 dB
2x Gain	24 V	1.71114 uV rms	133.91 dB
4x Gain	12 V	1.52518 uV rms	128.89 dB
8x Gain	6 V	1.47571 uV rms	123.15 dB

Table 10 Preamplifier G20311 Dynamic Range

	Full Scale (peak-peak)	Noise	Dynamic Range
1x Gain	44.0042 V	2.27935 uV rms	136.68 dB
2x Gain	24 V	1.66947 uV rms	134.12 dB
4x Gain	12 V	1.49986 uV rms	129.03 dB
8x Gain	6 V	1.44004 uV rms	123.36 dB

Both the G20307 and G20311 preamplifiers have a measured dynamic range in excess of 136 dB at a gain of 1x. In the quietest configuration of the preamplifier and digitizer at a gain setting of 8x, the combination still has a dynamic range better than 123 dB.

3.6 Seismic System Noise

Test Description: The purpose of the seismic system noise to evaluate the noise present in the output of the preamplifier without a driven input signal, shaped by the intended seismometer response.

We treat the preamplifier as if it was part of the digitizer input channel, and use the data obtained from section 3.3 Input Terminated Noise shaped by the GS21 response. The bitweight of the digitizer channel recording the preamplifier is adjusted to reflect the 61.39x gain. The response model of the GS21 is applied to shape the noise spectra and the compared to the Low Noise Model and the Geotech GS21 noise model in the plots below.

The terminated noise data from each of the 1x, 2x, 4x, and 8x gain levels are shown below scaled by the GS21 response with and without the Guralp preamplifier.

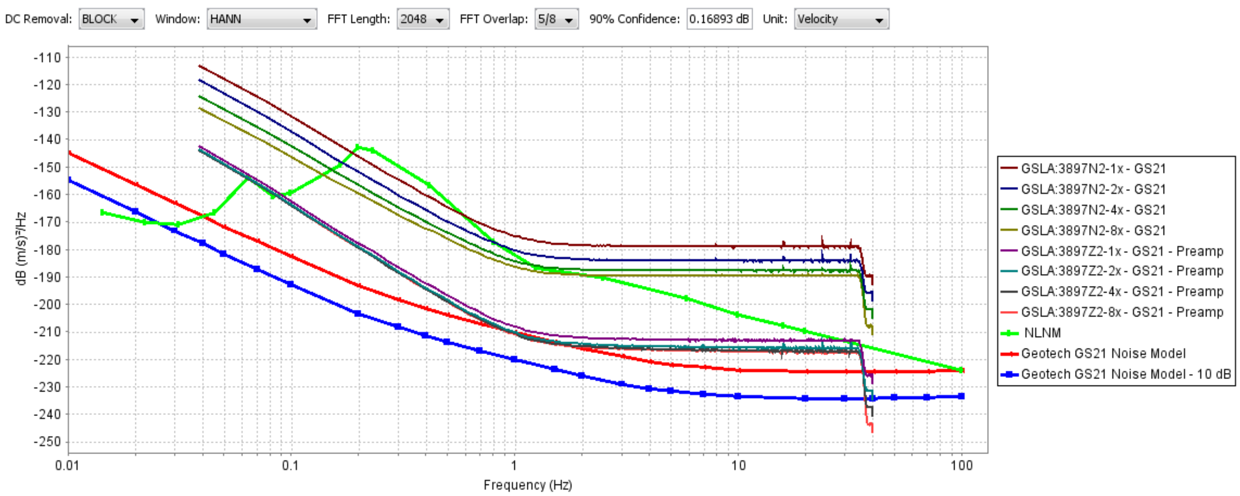


Figure 25 G20307 Preamplifier Seismic System Noise Power Spectra

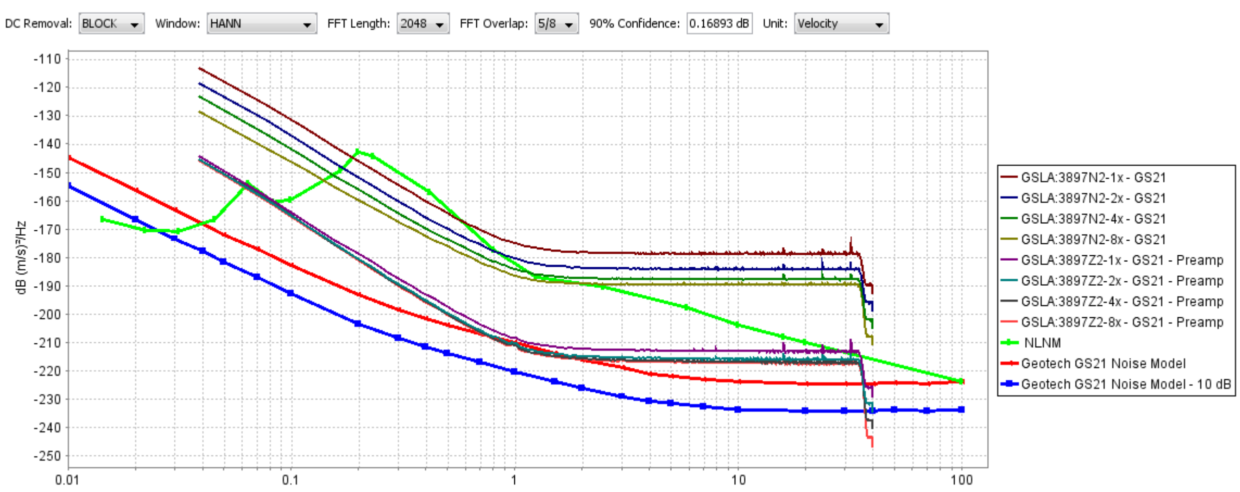


Figure 26 G20311 Preamplifier Seismic System Noise Power Spectra

We observe that introducing the preamplifier greatly decreases the ground motion equivalent noise due to the digitizer and preamplifier as compared to using a GS21 without a preamplifier. The seismic system noise of both preamplifiers, when paired with a Guralp CMG-DM24S3AM with a bitweight 2.86 uV/count, is entirely below the seismic low noise model over 0.5 to 16 Hz. Even with the digitizer gain at 4x or 8x, which minimizes total system noise, the noise is not entirely below the Geotech GS21 noise mode. Increasing the digitizer gain further will not result in any additional reduction in the equivalent seismic system noise.

3.7 DC Accuracy

Test description: The purpose of the DC Accuracy test is to evaluate the gain of the preamplifier for a constant DC voltage.

A precision DC calibration voltage source is used to generate a positive and negative DC voltage. The output of the DC voltage source is fed into the input of the preamplifier, channel 2 of the digitizer, and a reference Agilent 3458A meter. The output of the preamplifier is connected to channel 1 of the digitizer. The resulting amplitudes from the output of the preamplifier will then be compared to the reference meter. The preamplifier gains levels are evaluated at two DC voltage levels: 0.01V and 0.1V.

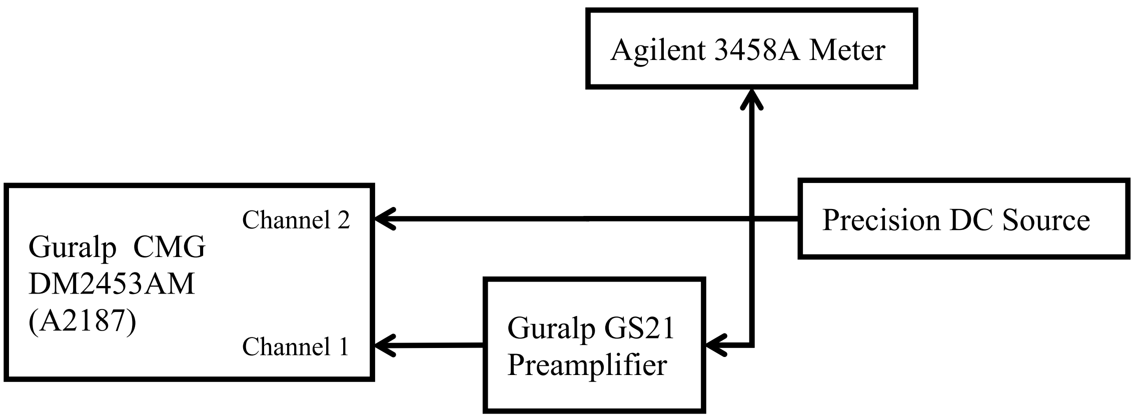


Figure 27 Preamplifier DC Accuracy Configuration Diagram

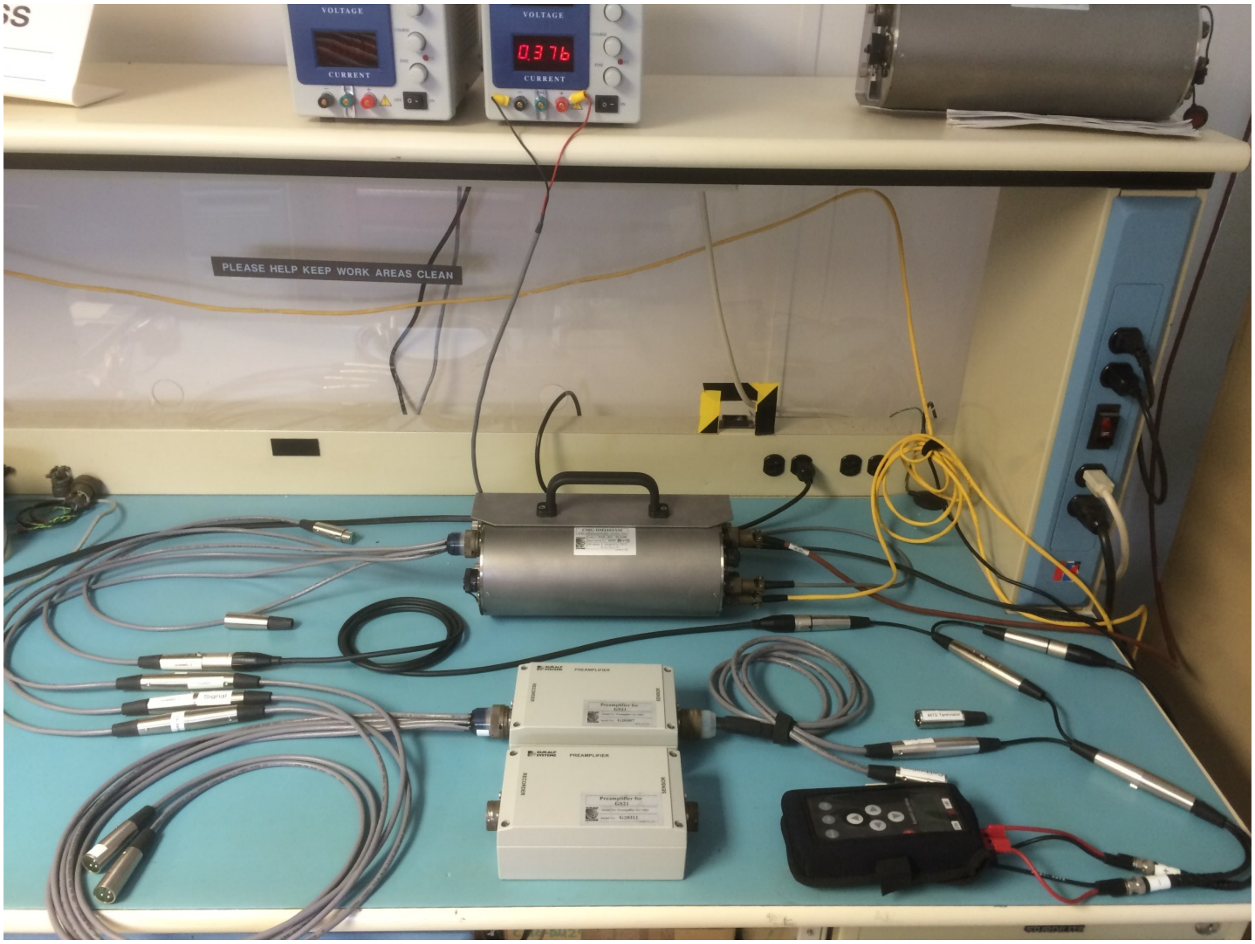


Figure 28 Preamplifier DC Accuracy Configuration

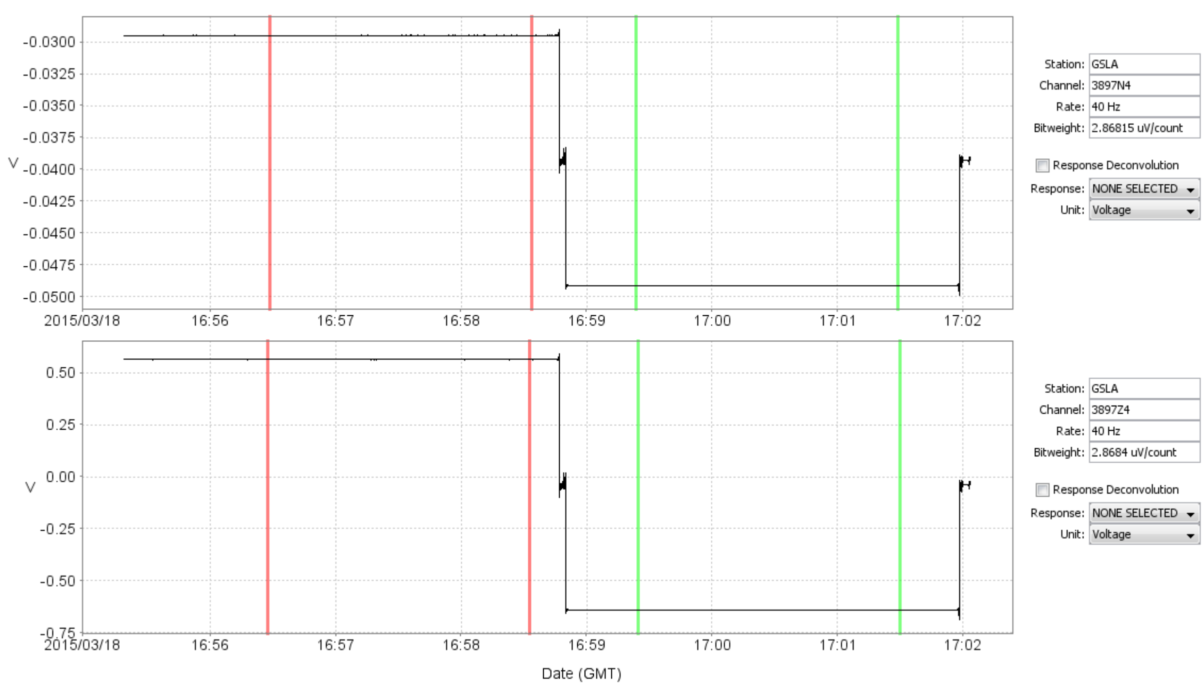


Figure 29 DC Accuracy Waveform

Table 12 DC Accuracy Results

	Input Range	Output Range	Gain	Percent Difference (from 61.39)
G20307 (0.01 V)	19.65258 mV	1.204390 V	61.2841	0.1725 %
G20307 (0.1 V)	0.20018 V	12.26631 V	61.2764	0.1850 %
G20311 (0.01 V)	19.65342 mV	1.205490 V	61.3374	0.0857 %
G20311 (0.1 V)	0.20017 V	12.27462 V	61.3210	0.1124 %

G20307 was observed to have a DC gain of approximately 61.28 and G20311 was observed to have a DC gain of 61.33. The preamplifiers deviated from their nominal gain of 61.39 by less than 0.2%.

3.8 AC Accuracy

Test description: The purpose of the AC Accuracy test is to evaluate the gain of the preamplifier for AC voltages across a range of frequencies and amplitudes.

A sequence of tones covering the combination of frequencies and amplitudes below were generated by the SRS DS360.

Table 13 Tone Amplitudes

Amplitudes
0.001 V
0.005 V
0.01 V
0.05 V
0.1 V
0.2 V

Table 14 Tone Frequencies

Frequencies
0.1 Hz
0.2 Hz
0.4 Hz
0.8 Hz
1 Hz
2 Hz
4 Hz
8 Hz
10 - 20 Hz in 1 Hz increments

The output of the DS360 is fed into the input of the preamplifier, channel 2 of the digitizer, and a reference Agilent 3458A meter. The output of the preamplifier is connected to channel 1 of the digitizer. The resulting amplitudes from the output of the preamplifier will then be compared to the reference meter.

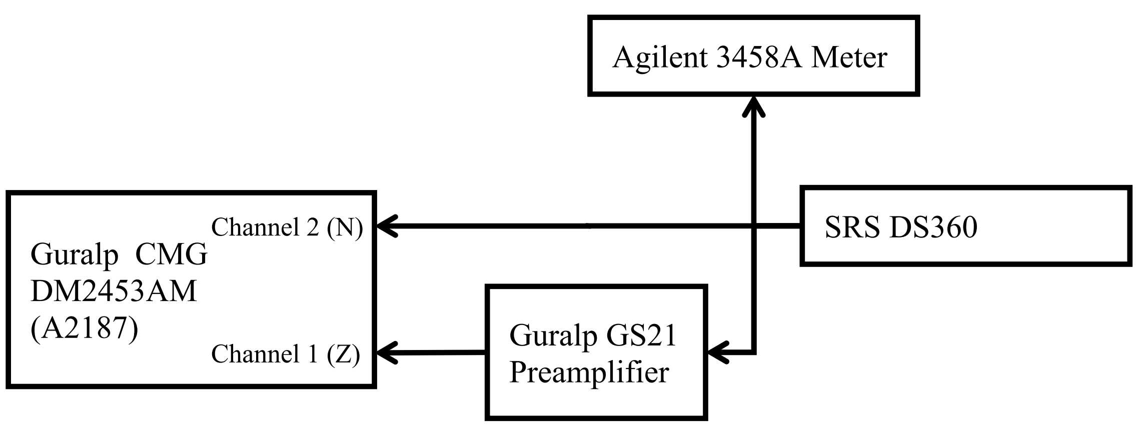


Figure 30 Preamplifier AC Accuracy Configuration Diagram

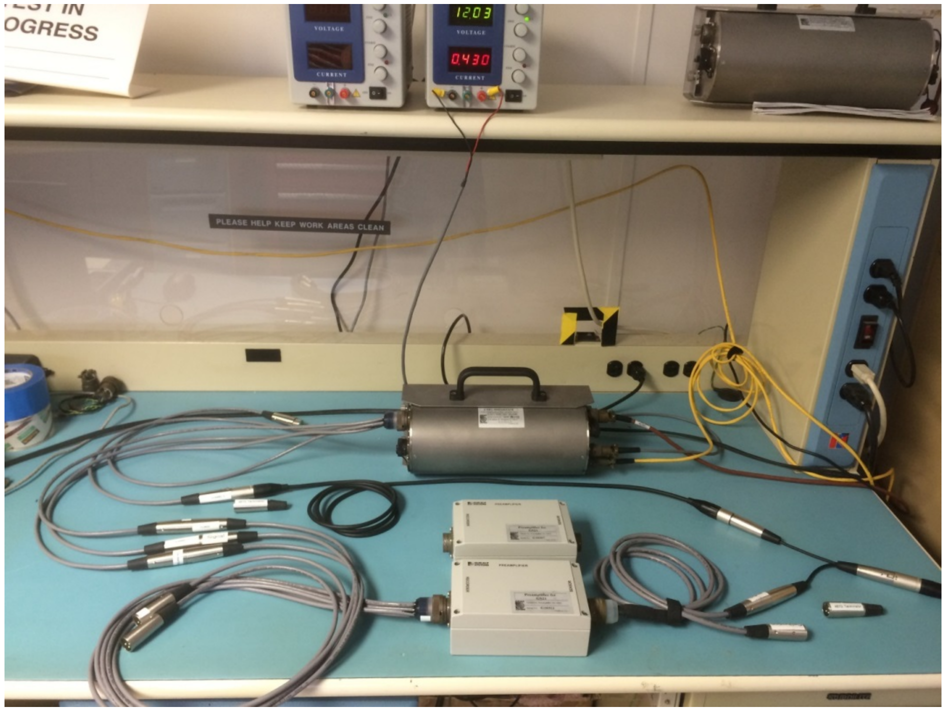


Figure 31 Preamplifier AC Accuracy Configuration

Although the Agilent 3458A meter was used to acquire a reference measurement, comparison of the input and output amplitudes of the preamplifiers was performed using the data collected on the two channels of the Guralp digitizer. This was done so that both measurements of input and output would have the same roll-off characteristics versus frequency. Any digitizer roll-off present in the Guralp will cancel out when the ratios between input and output amplitudes are computed to get the preamplifier gain.

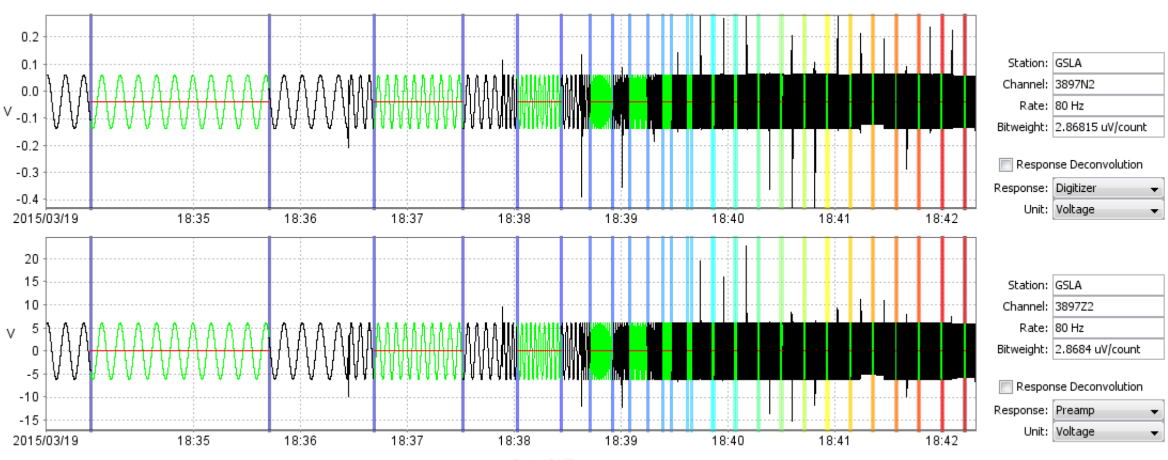


Figure 32 AC Accuracy Tone Time Series for 0.1 V and a sweep of frequencies

The observed gain between the output and input of the preamplifiers are shown in the tables below. No processing of the waveform time series was required to obtain stable sine fits.

Table 15 G20307 AC Accuracy gain levels

	Input Amplitude					
Frequency	0.001 V	0.005 V	0.01 V	0.05 V	0.1 V	0.2 V
0.1 Hz	61.26568	61.27510	61.27757	61.27660	61.27620	61.27593
0.2 Hz	61.26129	61.27610	61.27576	61.27616	61.27616	61.27581
0.4 Hz	61.27944	61.27737	61.27692	61.27665	61.27610	61.27578
0.8 Hz	61.27977	61.27646	61.27503	61.27611	61.27634	61.27577
1 Hz	61.28315	61.27318	61.27740	61.27608	61.27612	61.27574
2 Hz	61.28288	61.27905	61.27541	61.27593	61.27584	61.27564
4 Hz	61.27629	61.27043	61.27466	61.27492	61.27576	61.27537
8 Hz	61.31566	61.26819	61.27634	61.27434	61.27455	61.27414
10 Hz	61.28165	61.27459	61.27829	61.27389	61.27414	61.27306
11 Hz	61.22394	61.26168	61.27299	61.27356	61.27290	61.27272
12 Hz	61.26107	61.27151	61.27273	61.27278	61.27286	61.27220
13 Hz	61.28061	61.26639	61.26643	61.27194	61.27229	61.27150
14 Hz	61.27990	61.25944	61.27491	61.27180	61.27144	61.27066
15 Hz	61.30712	61.26651	61.26763	61.27056	61.27052	61.26998
16 Hz	61.24318	61.25983	61.27087	61.26979	61.26911	61.26927
17 Hz	61.32906	61.28362	61.26507	61.26993	61.26816	61.26814
18 Hz	61.24555	61.25975	61.26695	61.26789	61.26782	61.26756
19 Hz	61.24425	61.26121	61.26731	61.26734	61.26608	61.26684
20 Hz	61.25588	61.23681	61.27042	61.26505	61.26698	61.26577

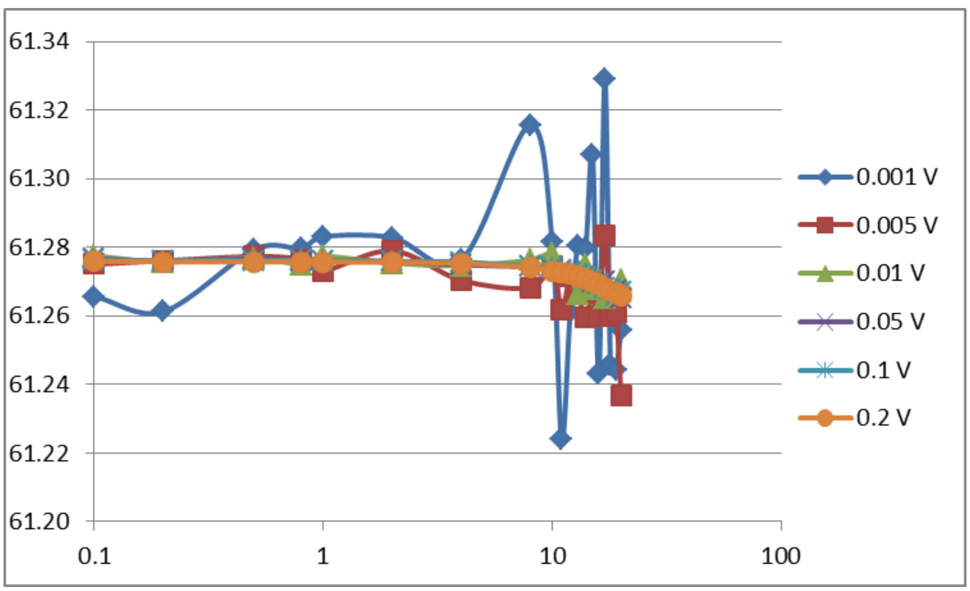


Figure 33 G20307 AC Accuracy gain levels

Table 16 G20311 AC Accuracy gain levels

	Input Amplitude					
Frequency	0.001 V	0.005 V	0.01 V	0.05 V	0.1 V	0.2 V
0.1 Hz	61.33860	61.31749	61.31883	61.31888	61.31879	61.31890
0.2 Hz	61.32777	61.31689	61.31833	61.31870	61.31879	61.31894
0.4 Hz	61.32059	61.31764	61.32102	61.31871	61.31889	61.31897
0.8 Hz	61.32434	61.31815	61.31851	61.31893	61.31888	61.31897
1 Hz	61.31499	61.32150	61.31735	61.31853	61.31890	61.31907
2 Hz	61.31751	61.31708	61.31775	61.31874	61.31879	61.31894
4 Hz	61.30635	61.31903	61.31956	61.31798	61.31784	61.31880
8 Hz	61.28787	61.32258	61.31823	61.31778	61.31733	61.31746
10 Hz	61.35979	61.30916	61.31654	61.31630	61.31622	61.31637
11 Hz	61.34159	61.31573	61.31276	61.31498	61.31578	61.31605
12 Hz	61.32299	61.32264	61.31546	61.31503	61.31497	61.31532
13 Hz	61.36281	61.30206	61.31839	61.31393	61.31491	61.31462
14 Hz	61.33238	61.31801	61.31782	61.31436	61.31485	61.31399
15 Hz	61.36450	61.30562	61.31802	61.31324	61.31330	61.31324
16 Hz	61.31921	61.31591	61.31060	61.31206	61.31278	61.31269
17 Hz	61.28263	61.32254	61.30614	61.31333	61.31159	61.31156
18 Hz	61.25896	61.31418	61.31306	61.31024	61.31098	61.31098
19 Hz	61.35212	61.30348	61.30358	61.30934	61.30934	61.30991
20 Hz	61.28327	61.30350	61.31662	61.30828	61.30858	61.30901

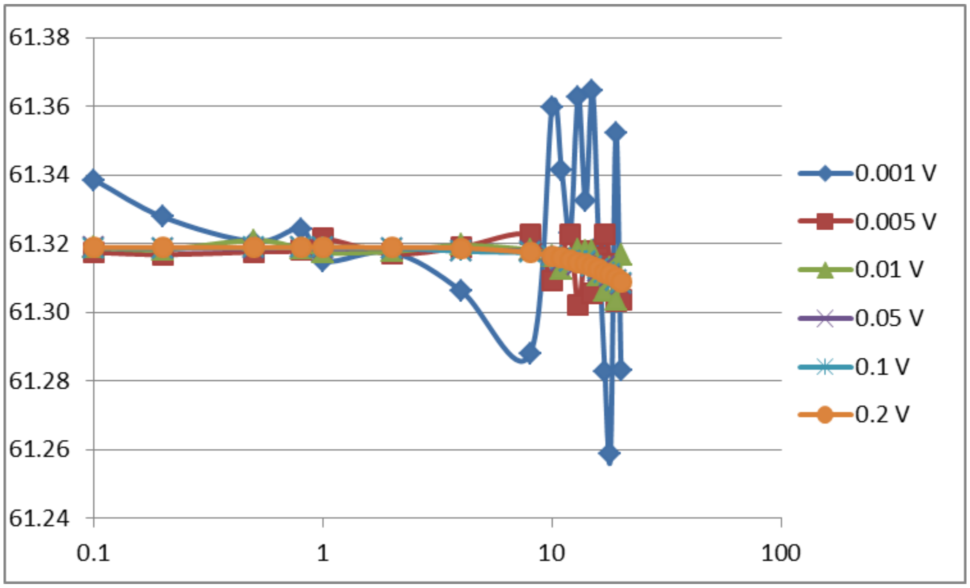


Figure 34 G20311 AC Accuracy gain levels

The gain in both preamplifiers is very consistent across the input amplitude range of the preamplifier. There is a greater distribution of gain values at low input amplitudes, likely due to a lower signal-to-noise ratio reducing the accuracy of the sine-fit. A very slight decrease in gain is observed with increasing frequency.

Table 17 Preamplifier AC gain

	Average Gain at 1 Hz	Difference between 1 Hz average and nominal gain of 61.39	Difference between 1 Hz average and gain at 16 Hz and 0.2 V
G20307	61.277	0.18 % (0.008 dB)	-0.0126 % (-0.00055 dB)
G20311	61.318	0.12 % (0.005 dB)	-0.0147 % (-0.00064 dB)

G20307 and G20311 were observed to have gains of 61.277 and 61.318, respectively, at 1 Hz. The preamplifiers deviated from their nominal gain of 61.39 by less than 0.18% (0.008 dB) and 0.12% (0.005 dB), respectively. The preamplifiers exhibited a very small roll-off in gain at higher frequencies for a maximum of -0.0126 % (-0.00055 dB) and -0.0147 % (-0.00064 dB), respectively.

3.9 Harmonic Distortion

Test description: The purpose of the harmonic distortion test is to verify the linearity of the preamplifier. A Quanterra Supertonal ultra-low-distortion oscillator is used to generate a very pure sinusoid with a frequency of 1.23 Hz and amplitude of 0.2 V. The output of the Quanterra Supertonal is fed into the input of the preamplifier, channel 2 of the digitizer, and a reference Agilent 3458A meter. The output of the preamplifier is connected to channel 1 of the digitizer. The resulting harmonic distortion in the output of the preamplifier will then be compared to the reference meter.

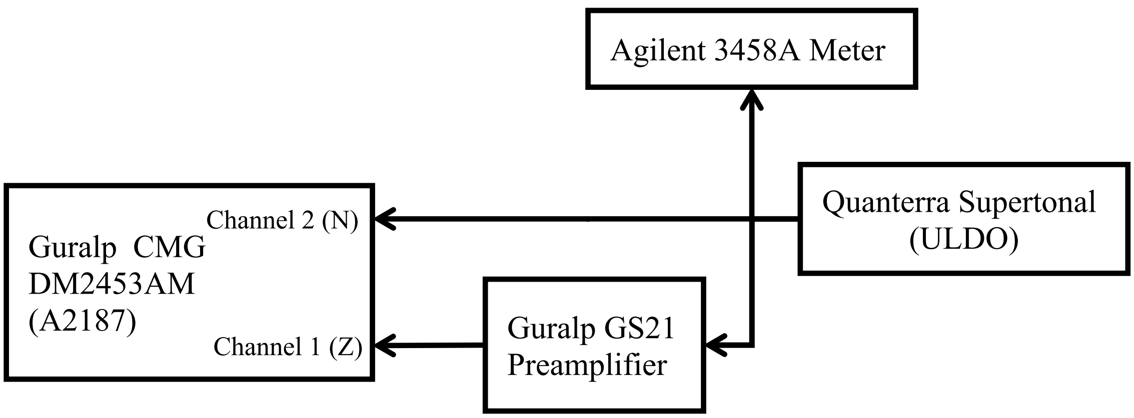


Figure 35 Preamplifier Harmonic Distortion Configuration Diagram

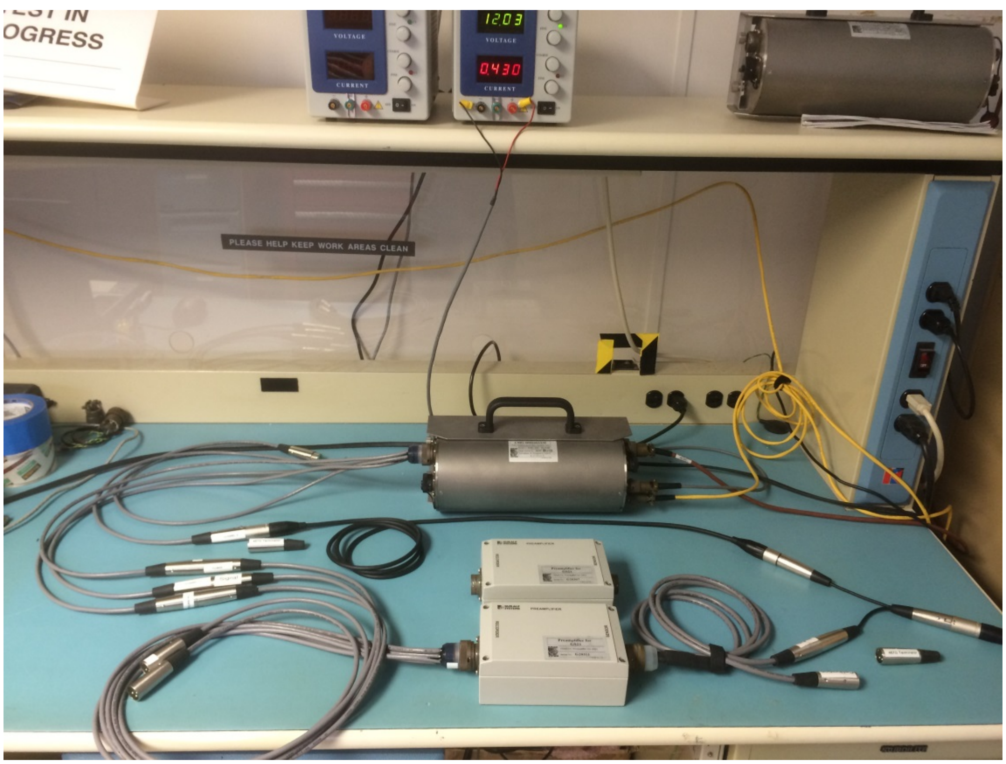


Figure 36 Preamplifier Harmonic Distortion Configuration

Prior to evaluating the harmonic distortion of the preamplifier, harmonic distortion tests of both the digitizer channels were performed at 0.2 V and 10 V without the preamplifier. This was done to account for the contributions of the digitizer channel versus the preamplifier to the total amount of measured harmonic distortion.

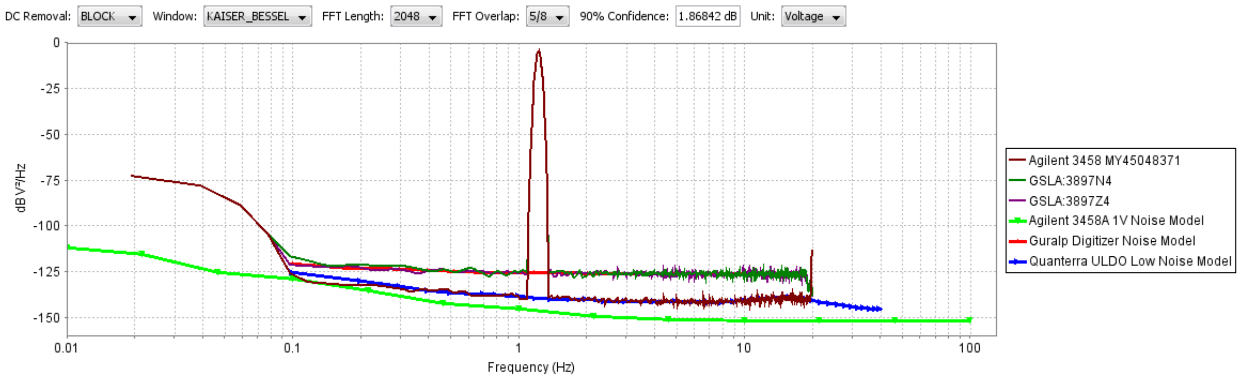


Figure 37 Guralp Digitizer 0.2 V Harmonic Distortion

Table 18 Guralp Digitizer 0.2 V Harmonic Distortion

Waveform	Peak Count	Peak Frequency	Peak RMS	Secondary RMS	THD
Agilent 3458 MY45048371	2	1.23015 Hz	0.13976 V rms	23.42435 nV rms	-135.51456 dB
GSLA:3897N4	2	1.23014 Hz	0.13993 V rms	0.14358 uV rms	-119.77607 dB
GSLA:3897Z4	2	1.23014 Hz	0.13992 V rms	0.15744 uV rms	-118.97567 dB

At 0.2 V, there are no visible harmonics in the signal that was generated by the Quanterra Supertonal or the recordings made on channels 1 and 2 of the digitizer. The resulting estimate of harmonic distortion is bounded by the noise floor of each device at the predicted location of the first harmonic. For the Agilent 3458A, this corresponds to better than -135.5 dB. For the digitizer input channels 1 and 2, this corresponds to better than -118.9 and -119.7, respectively.

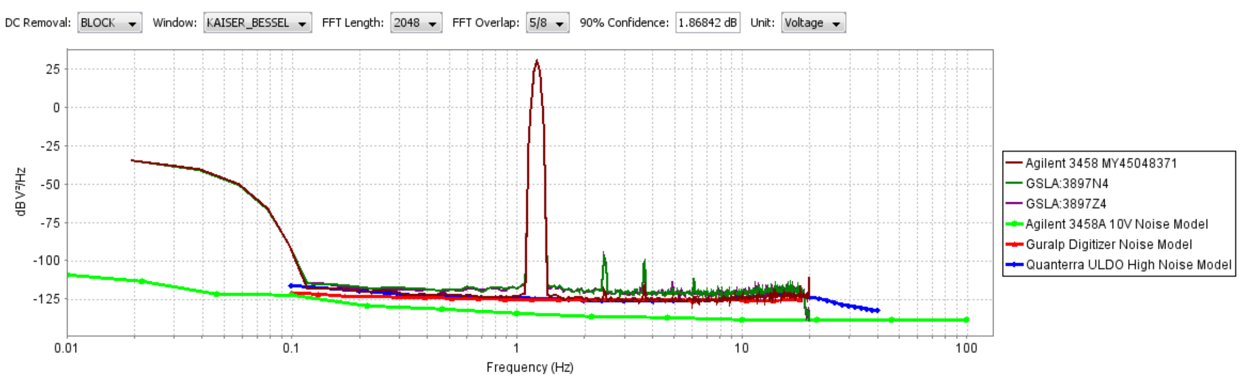


Figure 38 Guralp Digitizer 10 V Harmonic Distortion

Table 19 Guralp Digitizer 10 V Harmonic Distortion

Waveform	Peak Count	Peak Frequency	Peak RMS	Secondary RMS	THD
Agilent 3458 MY45048371	4	1.22995 Hz	6.98851 V rms	0.30333 uV rms	-142.35065 dB
GSLA:3897N4	6	1.22995 Hz	6.99642 V rms	2.84569 uV rms	-125.45763 dB
GSLA:3897Z4	5	1.22995 Hz	6.99634 V rms	3.07508 uV rms	-125.485 dB

At 10.0 V, there are visible harmonics in the signal that was generated by the Quanterra Supertonal and the recordings made on channels 1 and 2 of the digitizer, allowing for a more accurate estimate of harmonic distortion. For the Agilent 3458A reference measurement of the generated sinusoid, harmonic distortion is estimated at better than -142.3 dB. Both digitizer input channels 1 and 2 had measured harmonic distortion better than -125.4 dB. It is also worth pointing out that the Guralp digitizer self-noise levels are greater than the self-noise of the Quanterra ULDO, which is in turn greater than the self-noise of the Agilent 3458A meter.

Knowing the harmonic distortion present in the digitizer input channels at these two signal levels as a baseline, the results of the preamplifier harmonic distortion evaluation may be interpreted.

An ultra-low distortion sinusoid with a frequency of 1.23 Hz and amplitude of 0.2 V is inputted to each of the preamplifiers. With the preamplifiers nominal gain of 61.39, this should result in an output voltage of 12.278 V. This is approximately one-half of the measured full scale of both the preamplifier output and the digitizer channels.

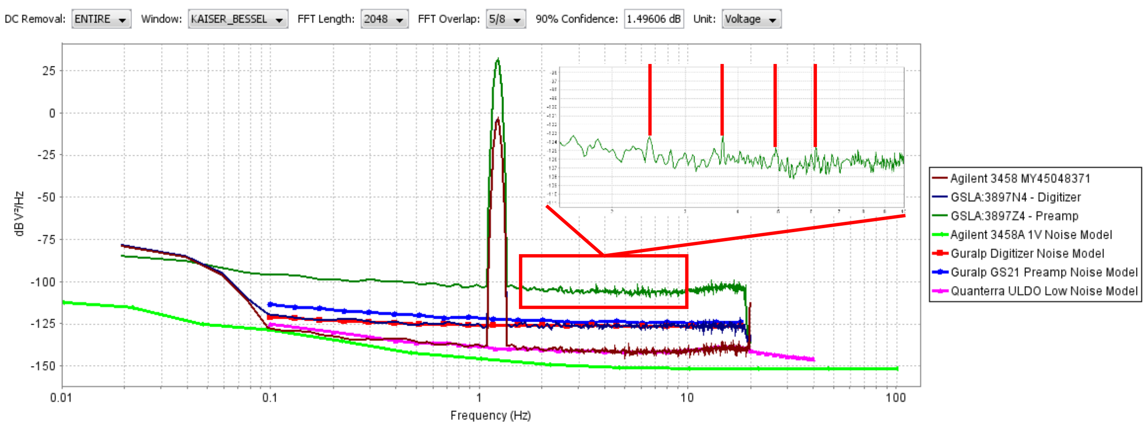


Figure 39 G20307 0.2V Harmonic Distortion

Table 20 G20307 0.2V Harmonic Distortion

Waveform	Peak Count	Peak Frequency	Peak RMS	Secondary RMS	THD
Agilent 3458 MY45048371	2	1.22995 Hz	0.13988 V rms	27.84865 nV rms	-134.01885 dB
GSLA:3897N4 - Digitizer	4	1.22995 Hz	0.14003 V rms	0.26206 uV rms	-111.46205 dB
GSLA:3897Z4 - Preamp	5	1.22995 Hz	8.58036 V rms	2.26634 uV rms	-126.66074 dB

At 0.2 V input to the G20307 (~ 12 V output), there were visible harmonics on the output of the preamplifier. The harmonic distortion is estimated to be -126.7 dB, which was approximately equal to the earlier evaluation of this digitizer channel at 10 V of -125.4 dB.

It is likely the harmonic distortion using the preamplifier appears improved because fewer harmonics were able to be identified because of the elevated baseline noise in the output of the preamplifier as compared to the digitizer. Note that this elevated baseline noise is not the self-noise of preamplifier output, it is the self-noise of the Quanterra ULDO that has been amplified 61.39x (35.76 dB) by the preamplifier.

The harmonic distortion of the G20307 appears to be better than the Guralp digitizer.

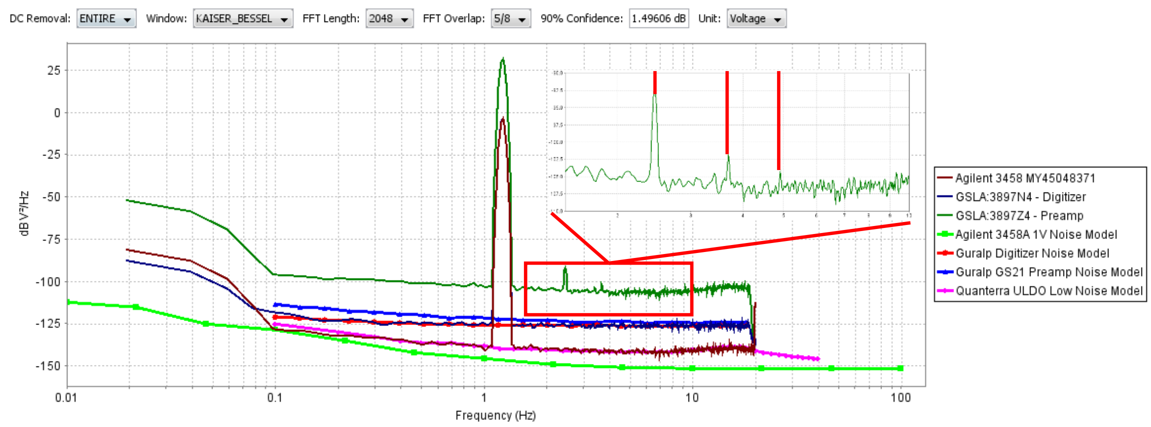


Figure 40 G20311 0.2V Harmonic Distortion

Table 21 G20311 0.2V Harmonic Distortion

Waveform	Peak Count	Peak Frequency	Peak RMS	Secondary RMS	THD
Agilent 3458 MY45048371	2	1.22995 Hz	0.13988 V rms	26.58984 nV rms	-134.42058 dB
GSLA:3897N4 - Digitizer	3	1.22995 Hz	0.14003 V rms	0.18339 uV rms	-113.5176 dB
GSLA:3897Z4 - Preamp	6	1.22995 Hz	8.5864 V rms	6.14458 uV rms	-120.91495 dB

At 0.2 V input to the G20311 (~ 12 V output), there were visible harmonics on the output of the preamplifier. The harmonic distortion is estimated to be -120.9 dB, which is greater than the earlier evaluation of this digitizer channel at 10 V of -125.4 dB.

3.10 Time Tag

Test description: The purpose of the Time Tag test is to evaluate the accuracy of the digitizer time tag characteristics using a synchronous timing signal. Analysis of the recorded signal is able to identify the time difference between an observed signal transition and the digitizer time tag. For the purpose of evaluating the preamplifier, the time tag test will serve to identify any timing delay introduced by the preamplifier.

Prior to testing either of the preamplifiers, a test was run on just the two digitizers channels in which a 1 pulse-per-minute (PPM) timing signal was used to evaluate the channels. Verifying that the two channels have consistent timing accuracy will establish confidence when comparing the timing results from the preamplifier with the other digitizer channel. This estimate of time tag error was made using the same attenuator as was used in the evaluation of the preamplifier.

The measured timing accuracy of the digitizer channels, averaged over 30 minutes, is as follows:

Table 21 Guralp Digitizer Time Tag Accuracy

	Timing Accuracy
Channel 1	5.62 microseconds
Channel 2	6.09 microseconds

Both of the Guralp digitizer channels have similar timing results with less than 0.5 microseconds of timing skew between them.

A 1 PPM synchronous signal was generated using the Quanterra ULDO. An attenuator was used in order to keep the 5 V PPM signal from clipping the preamplifier. The output of the Quanterra ULDO is fed into the input of the preamplifier and channel 2 of the digitizer. The output of the preamplifier is connected to channel 1 of the digitizer. The resulting recorded signals will then be compared to each other to determine the characteristics of the preamplifier.

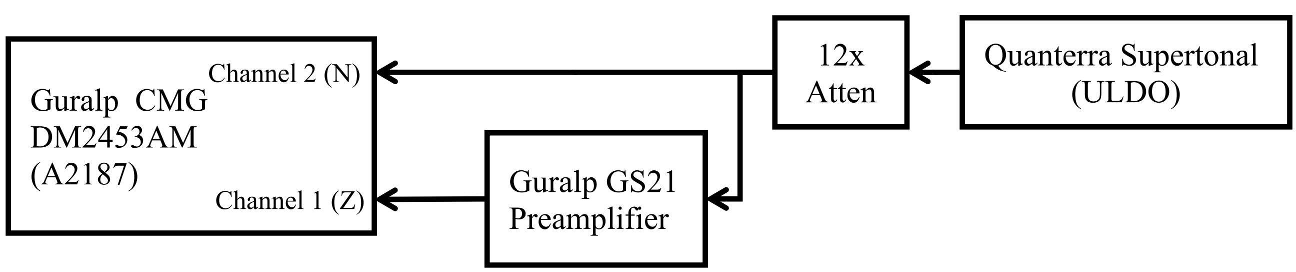


Figure 41 Preamplifier Time Tag Configuration Diagram

Figure 42 Preamplifier Time Tag Configuration

The measured timing accuracy of the preamplifier and digitizer channels, for each preamplifier averaged over 30 minutes, are as follows:

Table 21 Preamplifier Timing Accuracy

	Channel 1 (preamplifier)	Channel 2 (digitizer)
G20307	-185.9 microseconds	-16.5 microseconds
G20311	-191.9 microseconds	-15.4 microseconds

The difference between the observed timing error on the preamplifier and just the digitizer channel is 169.4 and 176.5 microseconds for G20307 and G20311, respectively.

3.11 Response Verification

Test description: The purpose of the Response Verification test is to evaluate the response characteristics of the preamplifier using a broadband signal.

Prior to testing either of the preamplifiers, a test was run on just the two digitizers channels in which a band-limited white noise signal was used to evaluate the channels. One of the channels was attenuated to approximate the difference in amplitudes in order to evaluate the performance of the digitizer.

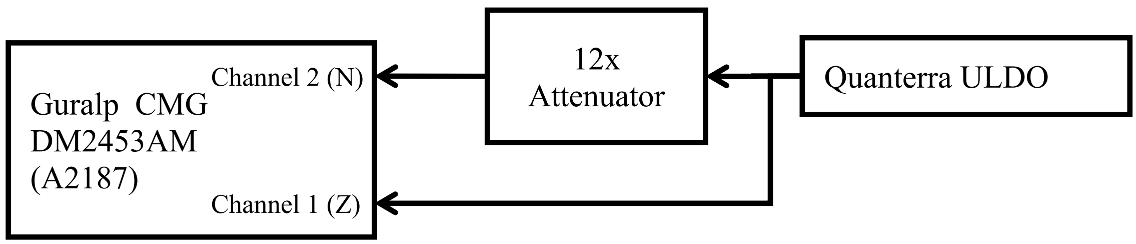


Figure 43 Guralp Digitizer Response Verification Configuration Diagram

The white noise signals recorded on the two channels were analyzed using 2-channel coherence (Holcomb, 1989). The following determinations were made across the 0.5 to 16 Hz passband for the two digitizer channels:

- Coherence was above 0.99995.
- Incoherent noise was consistent with the digitizer input terminated noise.
- Relative magnitude response was flat to within 0.005 dB.
- Relative phase response was linear with a change across the pass-band less than 0.01 degrees, corresponding to a 0.6 microsecond channel-to-channel delay.

Having determined the broadband performance of these two channels, testing may proceed to evaluating the preamplifiers.

Band-limited white noise was generated with an RMS amplitude of approximately 0.1 V using the Quanterra ULDO. The output of the Quanterra ULDO is fed into the input of the preamplifier and channel 2 of the digitizer. The output of the preamplifier is connected to channel 1 of the digitizer. The resulting recorded signals will then be compared to each other to determine the characteristics of the preamplifier. An hour of data was recorded for analysis.

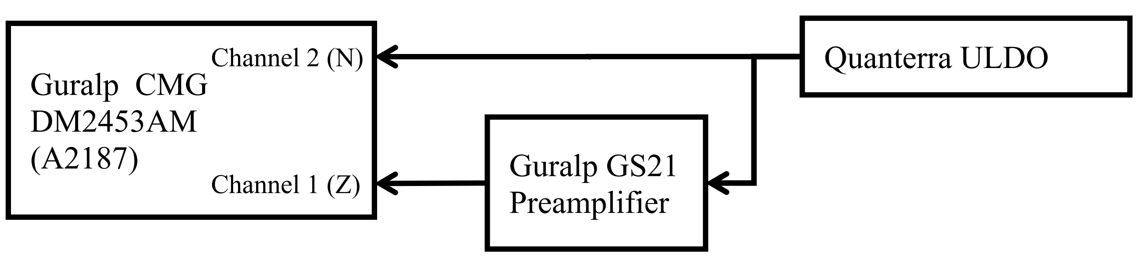


Figure 44 Preamplifier Response Verification Configuration Diagram

3.11.1 Complex Response

The complex (magnitude and phase) response of the preamplifiers are evaluated by examining the results of the 2-channel coherence analysis over the 0.5 to 16 Hz IMS passband.

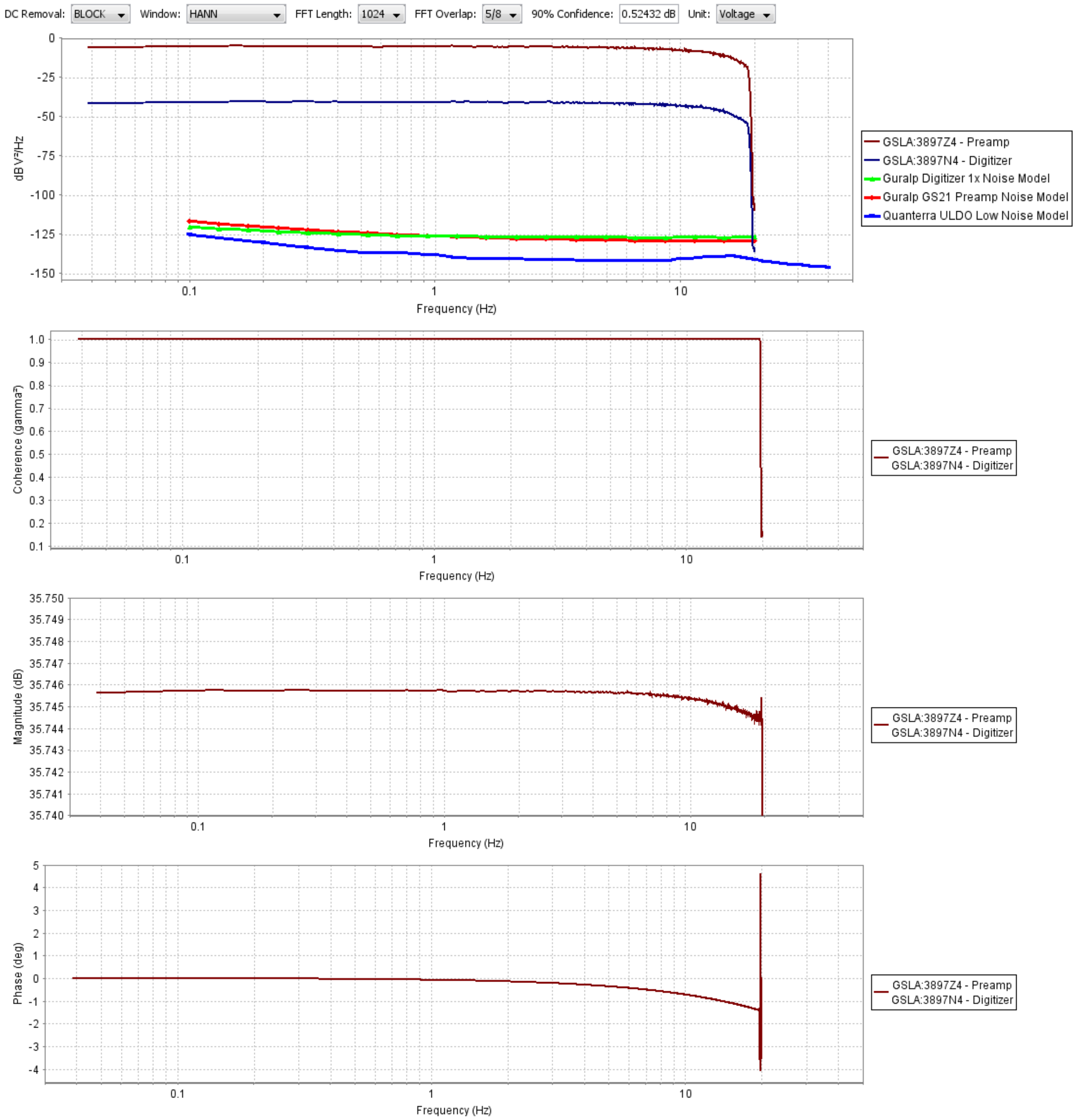


Figure 45 G20307 Complex Response – Power Spectra, Coherence, Magnitude, and Phase Response

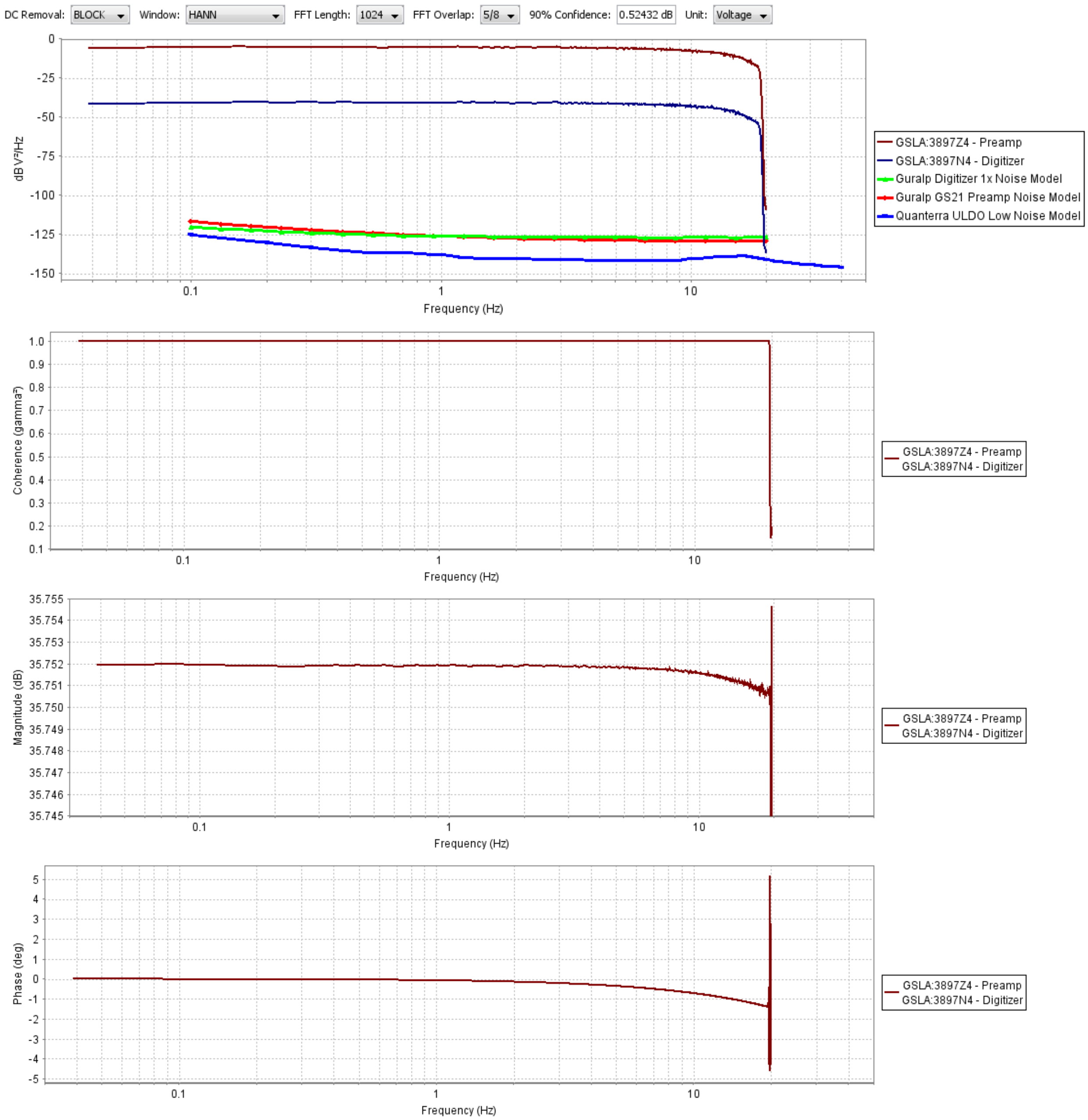


Figure 46 G20311 Complex Response – Power Spectra, Coherence, Magnitude, and Phase Response

Table 22 Complex Response Roll-off over 0.5 to 16 Hz

	Coherence	Magnitude Response	Phase Response
G20307	1.0	-0.001 dB	-1.16 degrees
G20311	1.0	-0.001 dB	-1.15 degrees

Both preamplifiers had near perfect coherence over 0.5 to 16 Hz. Their magnitude and phase response rolled off by less than 0.001 dB and 1.16 degrees, respectively, at 16 Hz. Further analysis of the time delay represented by the phase response is performed in the next section.

3.11.2 Time Delay

The phase response of the preamplifiers indicates that there is a slight delay introduced by the presence of the amplifier. The extent to which the phase response is linear indicates that it represents a delay of a constant time value.

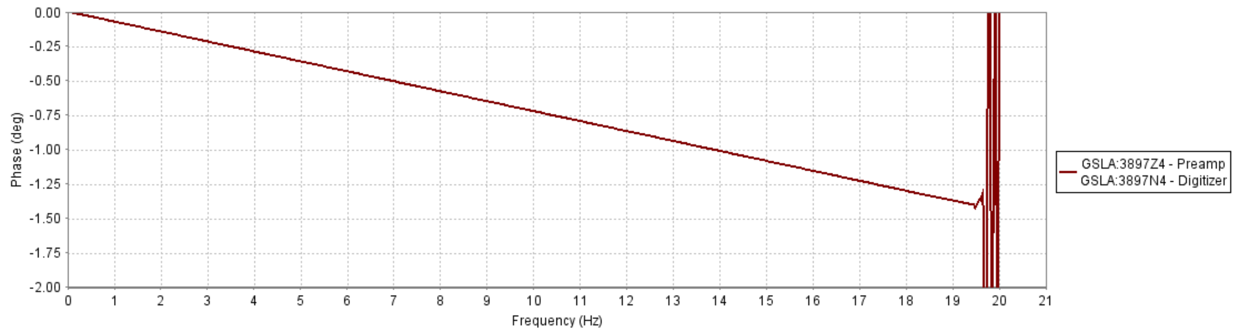


Figure 47 G20307 Time Delay

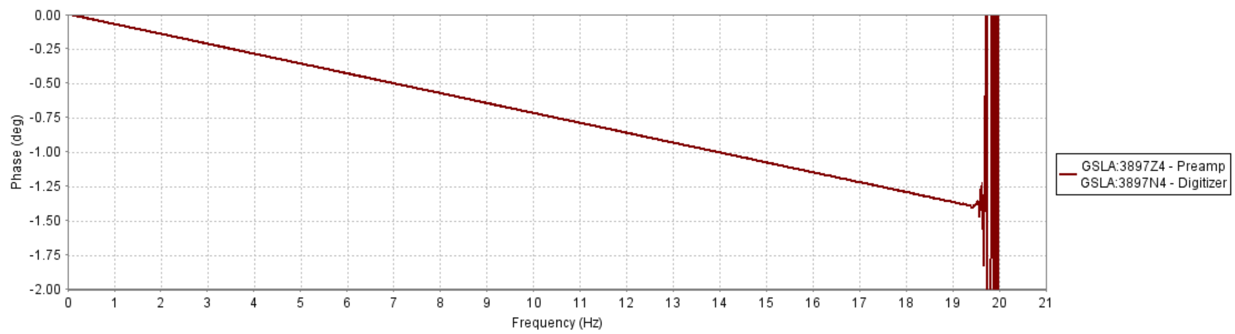


Figure 48 G20311 Time Delay

The time delays computed using a least-squared solution for a linear phase response over the 0.5 to 16 Hz pass-band are shown in the table below.

Table 23 Complex Response Time Delay

	Time Delay
G20307	200.8 us
G20311	200.2 us

Both preamplifiers introduce a time delay of approximately 200 micro-seconds over the application pass-band. The timing skew of digitizer channels 1 and 2 was measured prior to evaluating the preamplifier was determined to be approximately 0.6 microseconds. This indicates that the observed 200 micro-second time delay may be attributed to the preamplifier.

In addition, an earlier time tag test was also performed in which synchronous timing pulses from a GPS receiver were recorded on both digitizer channels.

3.11.3 Passband

Evaluating the passband of the Guralp GS21 Preamplifiers will examine the coherence and relative magnitude between the amplified and unamplified channels to examine their corner frequencies. Data was collected at 80 Hz on the Guralp digitizer in order to evaluate outside of the IMS pass-band.

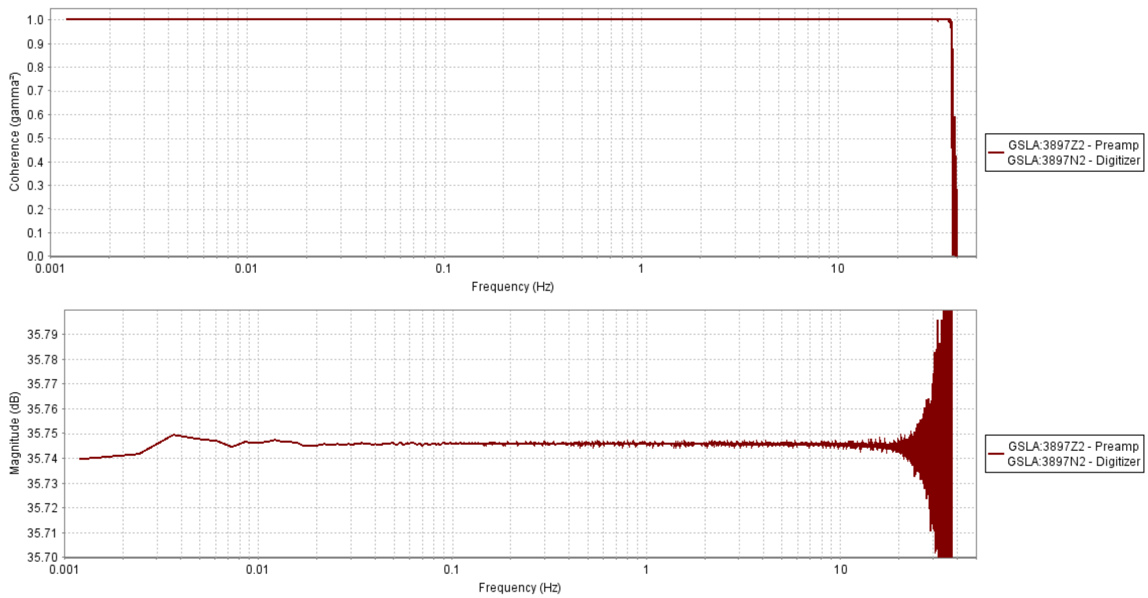


Figure 49 G20307 Passband Coherence and Magnitude Response

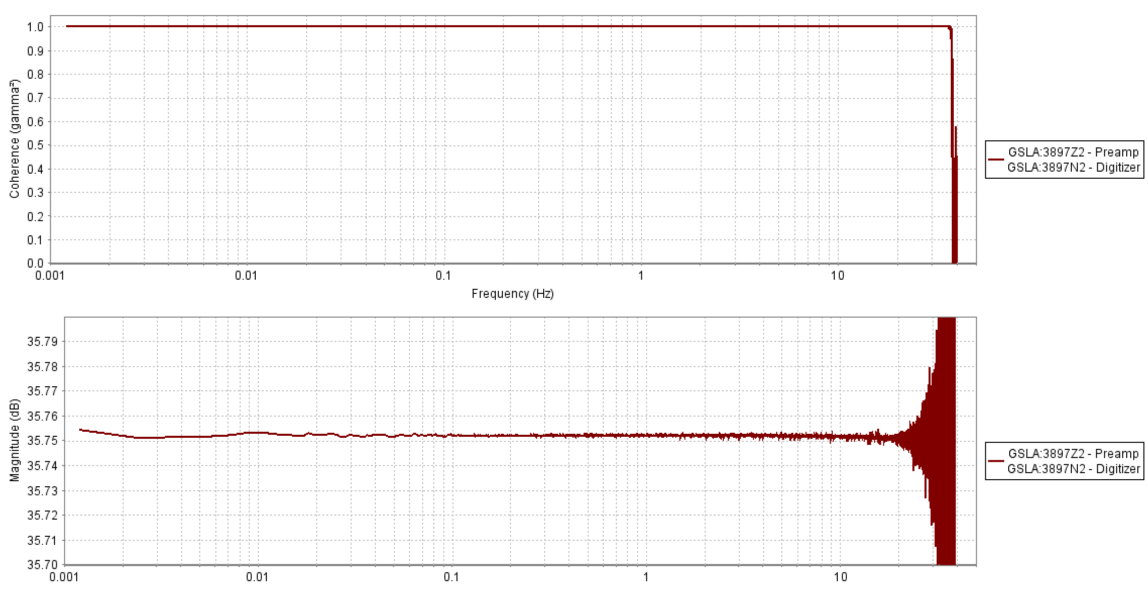


Figure 50 G20311 Passband Coherence and Magnitude Response

Both the G20307 and G20311 preamplifiers have a bandwidth that exceeds 0.01 to 20 Hz.

3.11.4 Dynamic Noise

Evaluating the incoherent noise present between the preamplifier input and output results in the noise power spectra plots below.

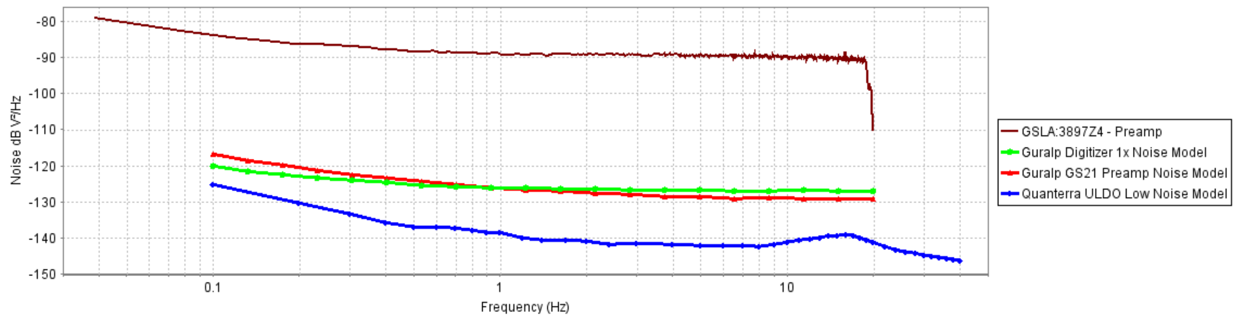


Figure 51 G20307 Incoherent Dynamic Noise

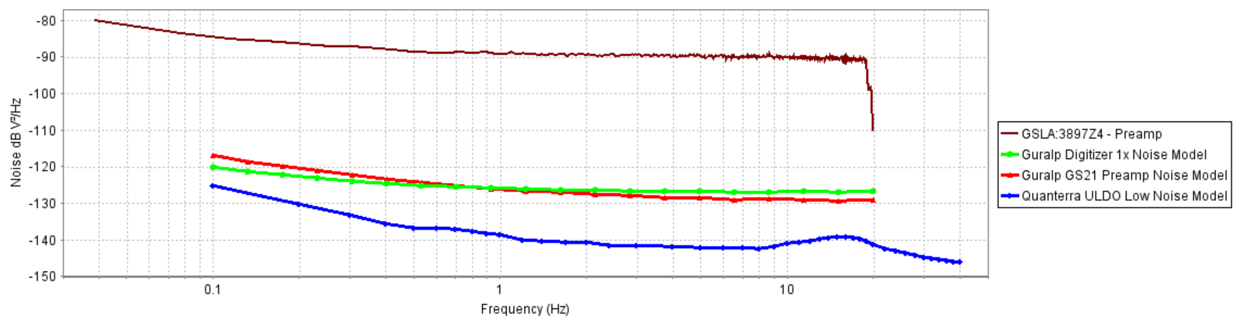


Figure 52 G20311 Incoherent Dynamic Noise

Over the 0.5 to 16 Hz passband, the G20307 and G20311 preamplifiers have incoherent noise in their output that is approximately 35 dB greater than what was measured when the preamplifiers inputs were terminated with a resistor. However, these noise levels are still more than 80 dB below the preamplifier output signal amplitudes.

3.12 Calibrator Pass-through

Test description: The purpose of the Calibrator Pass-through test is to validate that the preamplifier is able to pass the calibration signal from the digitizer to the GS21 seismometer.

The digitizer calibrator output is connected to the calibrator input connection on the preamplifier. Note that the calibrator-enable and active-high select lines must also be connected between the digitizer and preamplifier. The input to the preamplifier is split off and recorded on the digitizer channel 2. The preamplifier output of the calibration signal is recorded on digitizer channel 1.

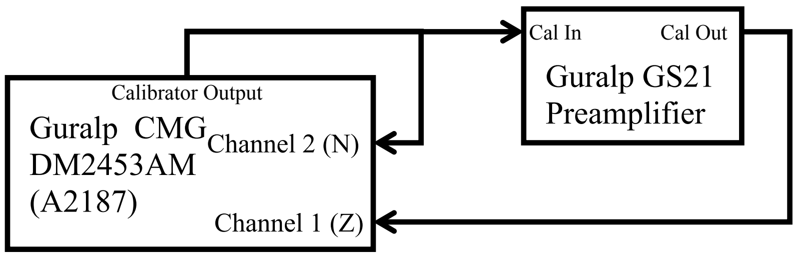


Figure 53 Preamplifier Calibrator Pass-through Configuration Diagram

Figure 54 Preamplifier Calibrator Pass-through Configuration Diagram

3.12.1 5 Hz Sinusoid

In the first iteration of the Calibrator Pass-through test, a 5 Hz sinusoid was generated from the Guralp digitizer. The waveforms recorded at the output of the digitizer calibrator and the preamplifier calibrator are shown below.

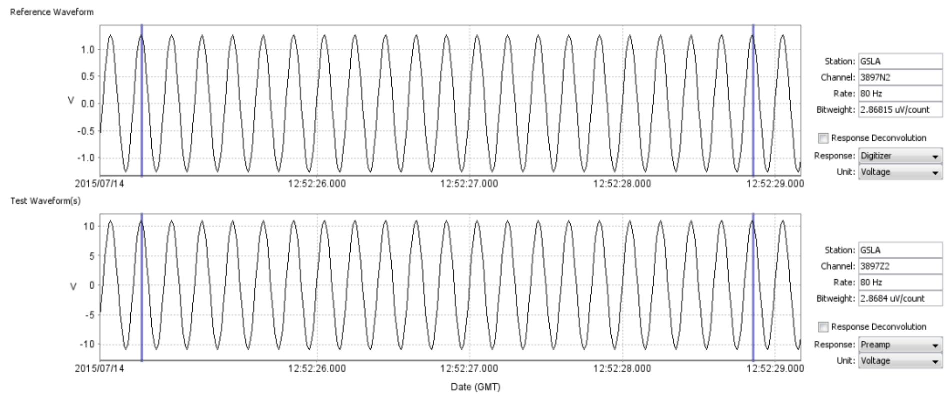


Figure 55 G20307 5 Hz Calibrator Loopback Waveforms

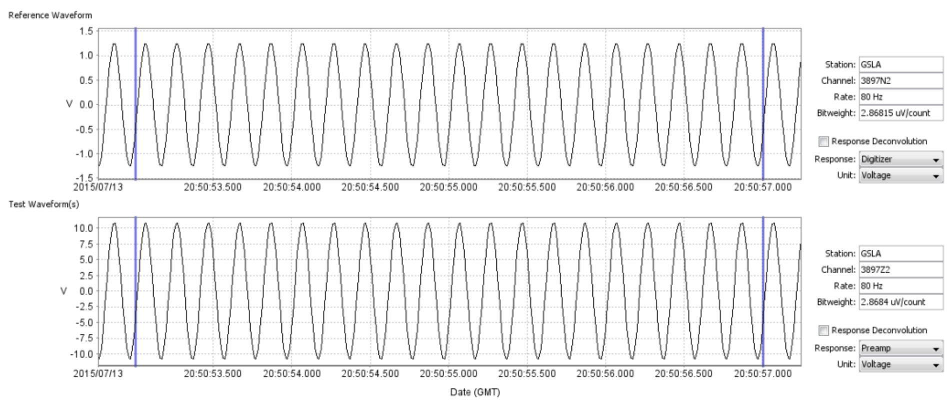


Figure 56 G20311 5 Hz Calibrator Loopback Waveforms

The Guralp calibrator output is single sided and the GS21 requires a differential calibration signal. Therefore, the preamplifier converts the input calibration signal and applies some amount of amplification.

A 20 cycle sine fit of the 5 Hz calibration signal was performed. A ratio of the input and output peak amplitudes of the preamplifier calibration signal provides the following sensitivity terms for the preamplifiers. In addition, the relative phase delay between the sinusoids is observed.

Table 23 Preamplifier 5 Hz Calibrator Loopback

	Input Amplitude	Output Amplitude	Calibrator Gain	Phase Delay
G20307	1.26337 V	10.9224 V	8.645	0.157 degrees
G20311	1.26332 V	10.9344 V	8.655	0.164 degrees

3.12.2 Broadband

In the second iteration of the Calibrator Pass-through test, a broadband signal was generated from the Guralp digitizer for 20 minutes for each preamplifier. The waveforms for the output of the digitizer calibrator and the preamplifier calibrator are shown below.

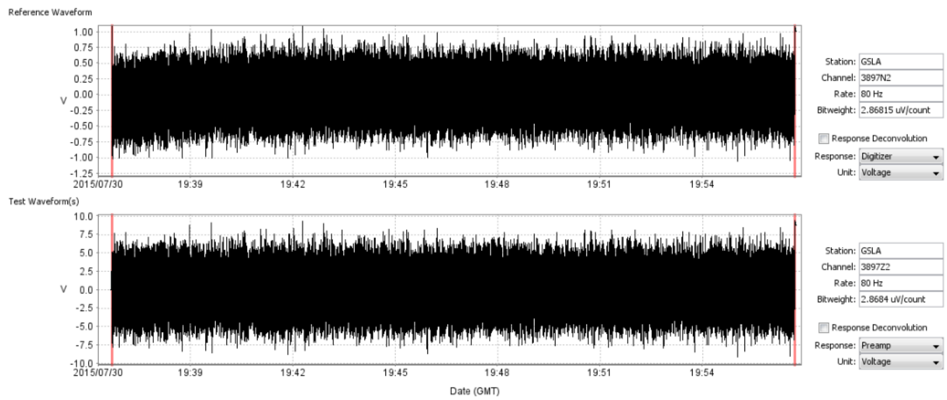


Figure 57 G20307 Broadband Calibrator Loopback Waveforms

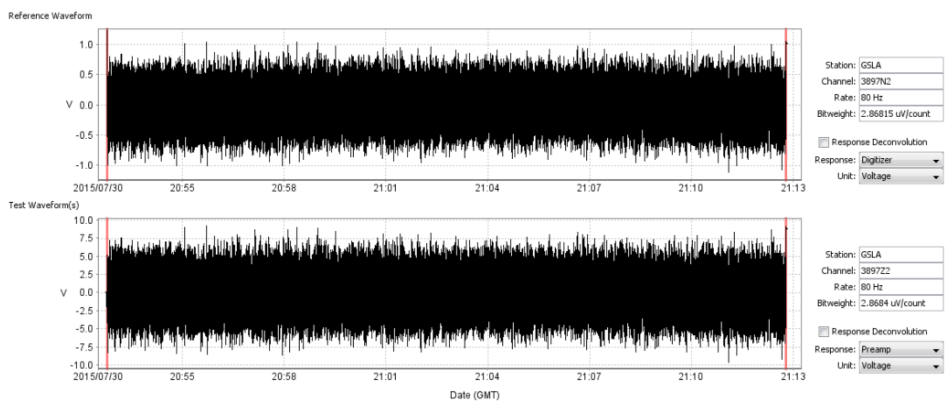


Figure 58 G20311 Broadband Calibrator Loopback Waveforms

Performing 2 channel coherence analysis (Holcomb, 1989) on each of the sets of broadband signals, we are able to observe the power spectra, coherence, and relative magnitude and phase below.

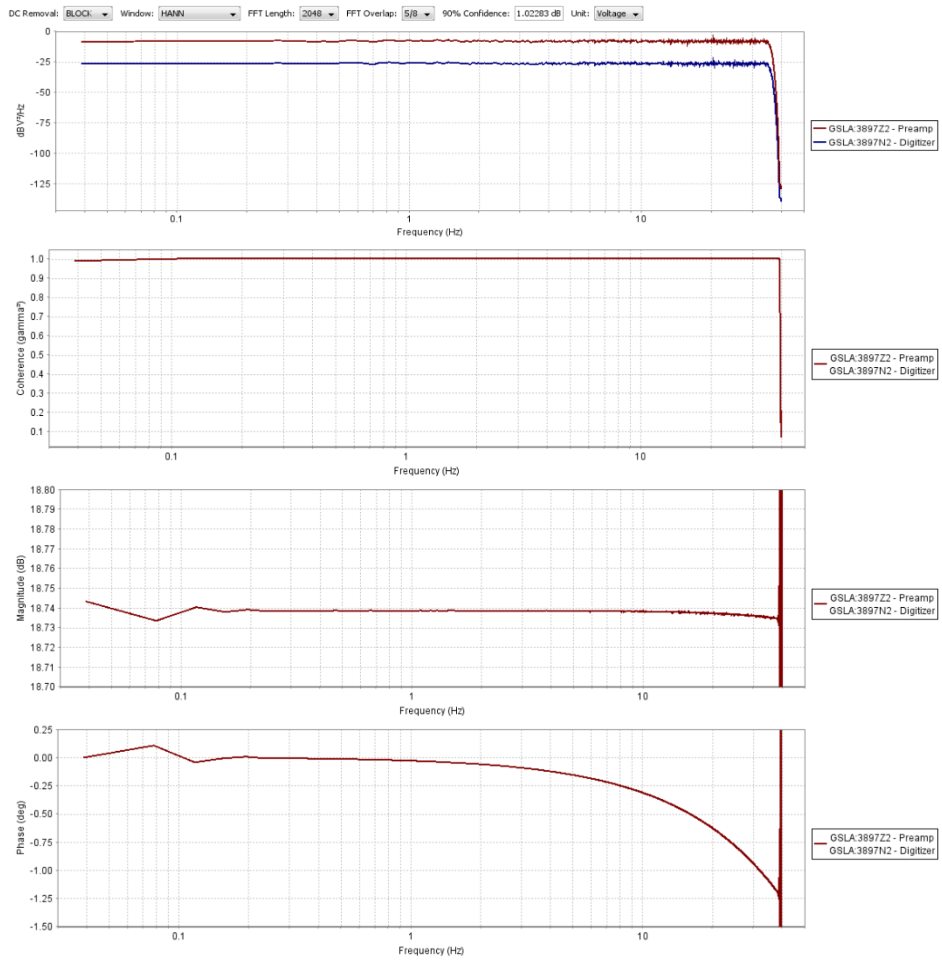
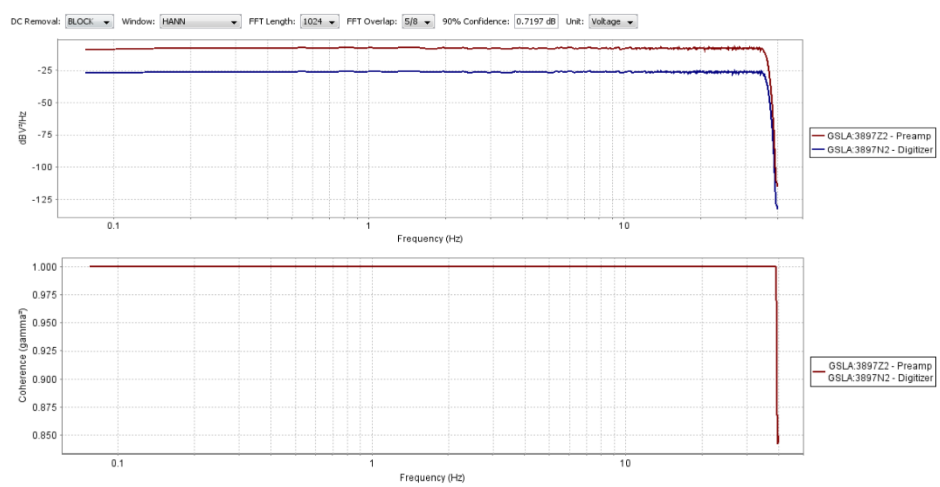


Figure 59 G20307 Broadband Calibrator Loopback Power Spectra, Coherence, Relative Magnitude, and Relative Phase



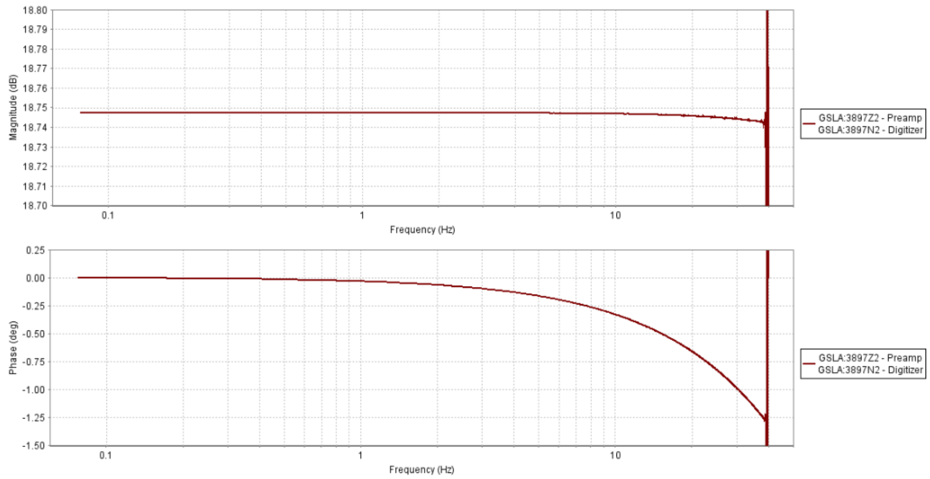


Figure 60 G20311 Broadband Calibrator Loopback Power Spectra, Coherence, Relative Magnitude, and Relative Phase

Both preamplifiers exhibit excellent coherence between the input and the output of the calibration signal across the pass-band, indicating that there is minimal distortion of the broadband signal. The observed gain levels and time delays across the 0.5 to 16 Hz passband are shown in the table below.

Table 23 Preamplifier Broadband Calibrator Loopback

	Gain	Roll-off at 16 Hz	Phase at 16 Hz	Time Delay
G20307	18.738 dB	0.0008 dB	-0.50 degrees	87 uS
G20311	18.747 dB	0.001 dB	-0.53 degrees	92 uS

For the G20307 and G20311 preamplifiers, the gain levels of 18.738 dB and 18.747 dB, in dB of power, are equivalent to gains of 8.6477x and 8.6567x, respectively. These values are equivalent to what was observed with the 5 Hz sinusoid calibrator loopback. The observed phase delays of -0.50 and -0.53 degrees at 16 HGz are linear across frequency, corresponding to constant time delays of 87microseconds and 92 microseconds for G20307 and G20311, respectively.

3.13 GS21 Calibration

Test description: The purpose of the GS21 Calibration test is to demonstrate a functional calibration using a Guralp digitizer, Guralp preamplifier, and Geotech GS21 Seismometer.

The digitizer calibrator output is connected to the calibrator input connection on the preamplifier. Note that the calibrator-enable and active-high select lines must also be connected between the digitizer and preamplifier. A resistor calibration is being performed using a 91 ohm resistor in series with the calibration input to the GS21 Seismometer. The current into the calibration coil is monitoring by recording the voltage drop across the resistor on channel 2. This will result in an acceleration of the GS21 mass that is proportional to the current input. The seismometer output is fed back into the preamplifier input. The preamplifier output is then recorded on channel 1 of the digitizer.

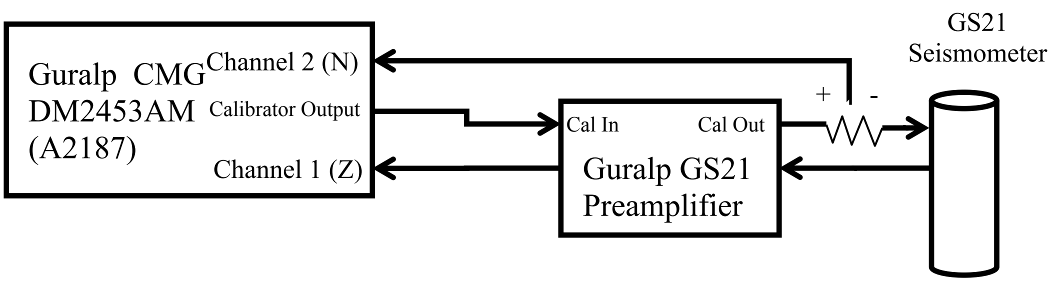
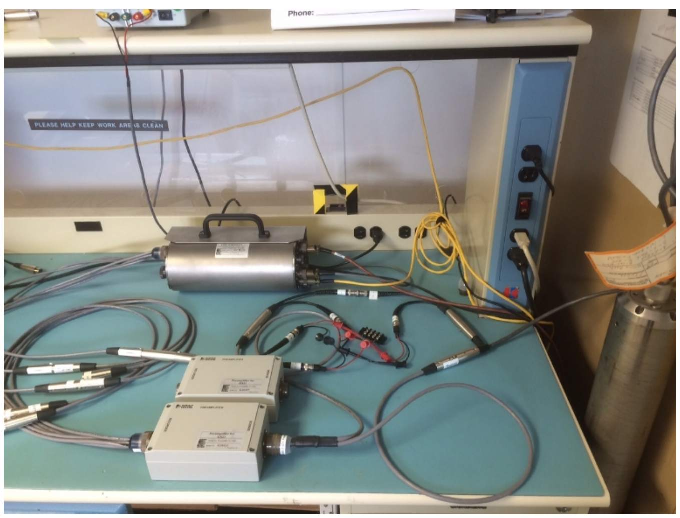


Figure 61 GS21 Calibration Configuration Diagram



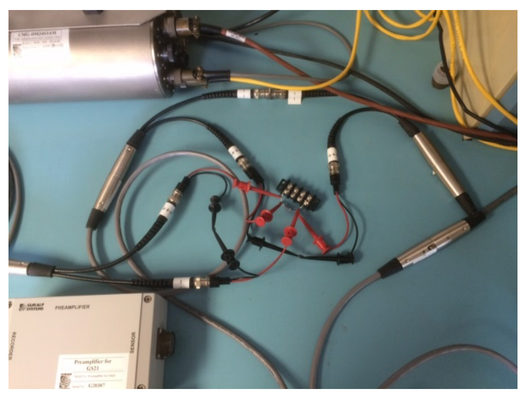


Figure 62 GS21 Calibration Configuration

The evaluation of the preamplifier using a GS21 seismometer was performed in a lab environment. Although this was non-ideal from the perspective of evaluating a seismometer, it was sufficient for verifying the ability of the preamplifier to perform a calibration on the seismometer. The expected output from the preamplifier is:

$$V_{out} = \frac{\frac{V_{cr}}{R_c} G_{cal\ coil}}{M} * \frac{1}{2\pi f} * G_{gs21} * G_{preamp}$$

Where

V_{out}	Output of the preamplifier in volts recorded by the digitizer
V_{cr}	Voltage drop across the calibration resistor recorded by the digitizer
R_c	Calibration resistor, 91 ohms
$G_{cal\ coil}$	Calibration coil motor constant, 0.1975 N/A
M	Inertial mass, 5 kg
$2\pi f$	Conversion from velocity to acceleration at a frequency of 5 Hz
G_{gs21}	Generator constant of the GS21, 458 V/(m/s)
G_{preamp}	Gain of the Guralp GS21 preamplifier, 61.39

A 5 Hz sinusoid is generated on the calibrator output of the digitizer. A 20 cycle sine fit of the 5 Hz calibration signal was performed. The waveform was filtered with a 2 – 10 Hz Butterworth filter to remove noise that may complicate the results of the sine fit.

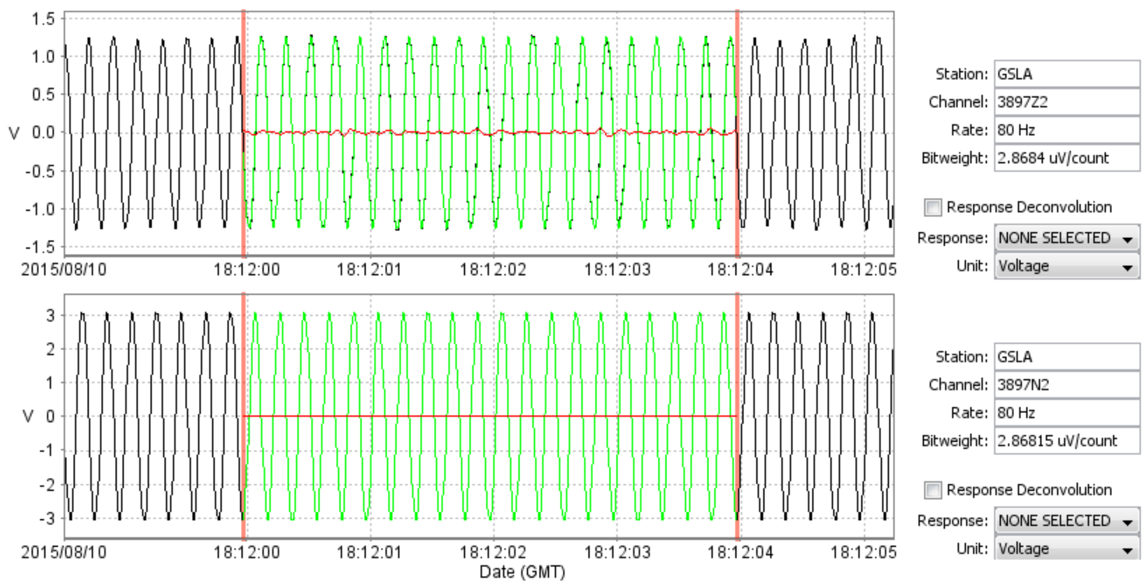


Figure 63 GS21 Calibration Configuration Waveforms

A ratio of the input and output of the preamplifier calibration signal provides the following sensitivity terms for the preamplifiers:

Table 27 GS21 Calibration

	V_{cr}	G_{preamp}	Theoretical V_{out}	Measured V_{out}
G20307	3.112 V	61.28	1.207 V	1.275 V
G20311	3.122 V	61.32	1.211 V	1.28 V

A resistor calibration of a Geotech GS21 seismometer was successfully performed using a Guralp digitizer and the Guralp GS21 preamplifier with calibration pass-through. The results of the calibration deviated by the expected amount by approximately 5.5 %. However, this was using the nominal GS21 sensitivity and calibration coil motor constant.

4 EVALUATION SUMMARY

Power:
The measured power consumption of the two Guralp GS21 preamplifiers was just under 1 watt at 12 V.

Input Impedance:
The measured sensor input impedance of the Guralp G20307 and G20311 GS21 preamplifiers was 1.468 Mohm and 1.620 Mohm, respectively.

Input Terminated Noise:
The measured sensor input terminated noise across 0.5 to 16 Hz of the Guralp G20307 and G20311 GS21 preamplifiers was as low as 1.47571 uV rms and 1.44004 uV rms, respectively. These noise levels are only fully resolved at a digitizer gain of 8x. At lower digitizer gains of 1x, 2x, and 4x the digitizer self-noise has a more significant presence in the observed system noise. However, trade-offs must be made in dynamic range at higher gain levels.

AC Clip
The measured output clip level at 1 Hz the Guralp G20307 and G20311 GS21 preamplifiers was 44.4292 Vpp and 44.0042 Vpp, respectively. This corresponds to input clip levels of 0.7237 Vpp and 0.7168 Vpp, respectively.

Dynamic Range:
The computed dynamic range of the Guralp G20307 and G20311 GS21 preamplifiers, using the results of the input terminated noise and the combined digitizer and amplifier clip levels across the 0.5 to 16 Hz passband was approximately 136.7 dB at 1x gain, 134 dB at 2x gain, 129 dB at 4x gain, and 123 dB at 8x gain.

Seismic System Noise:
The computed seismic system noise, using the input terminated noise data and the GS21 response model, places the preamplifier self-noise below the seismic low noise model and above the GS21 noise model across the 0.5 to 16 Hz passband.

DC Accuracy:
The measured DC gain of the Guralp G20307 and G20311 GS21 preamplifiers was 61.28 and 61.33, respectively. This represents a deviation from the nominal gain of 61.39 by less than 0.2%.

AC Accuracy:
The measured AC gain at 1 Hz of the Guralp G20307 and G20311 GS21 preamplifiers was 61.277 and 61.318, respectively. This represents a deviation from the nominal gain of 61.39 by less than 0.2%. The gain was not observed to vary significantly across amplitude with only a slight roll-off across frequency. The G20307 and G20311 preamplifiers had a roll-off in gain at 16 Hz of -0.0126 % and -0.0147 %, respectively.

Harmonic Distortion:

The measured harmonic distortion of the Guralp G20307 and G20311 GS21 preamplifiers was -126.7 dB and -120.9 dB, respectively.

Time Tag:
The measured time tag accuracy of the Guralp G20307 and G20311 GS21 preamplifiers measured a timing delay of 169.4 and 176.5 microseconds, respectively.

Response Verification:
The broadband response of the Guralp G20307 and G20311 GS21 preamplifiers was measured to have a roll-off of less than 0.001 dB in magnitude and 1.16 degrees in phase across 0.5 to 16 Hz. The phase response roll-off is linear and corresponds to a constant time delay of 200 microseconds. The bandwidth of the preamplifiers exceeds 0.01 to 20 Hz. The incoherent noise present in the output of the preamplifiers in the presence of a broadband signal approximately half of full scale was measured to be 24 dB greater than the input terminated noise, but still more than 80 dB below the amplitude of the input signal.

Calibrator Pass-through:
The calibrator pass-through evaluation determined that the Guralp GS21 preamplifiers were successfully passing the calibration signal when commanded by the digitizer using both tonal and broadband signals. The Guralp G20307 and G20311 GS21 preamplifiers are performing a single ended to balanced conversion with observed gains at 5 Hz of 8.645 and 8.655, respectively. Both preamplifiers calibrator pass-through was observed to have a constant time delay of approximately 90 microseconds.

GS21 Seismometer Calibration:
A successful resistor calibration of a Geotech GS21 seismometer was performed using a Guralp digitizer and each of the Guralp GS21 preamplifiers. The results of the seismometer calibration were consistent to within 5.5 % of the expected values when using the nominal seismometer sensitivity and calibration coil motor constant.

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APPENDIX

Geotech GS21 Response

Geotech GS21 response provided to SNL by the CTBTO.

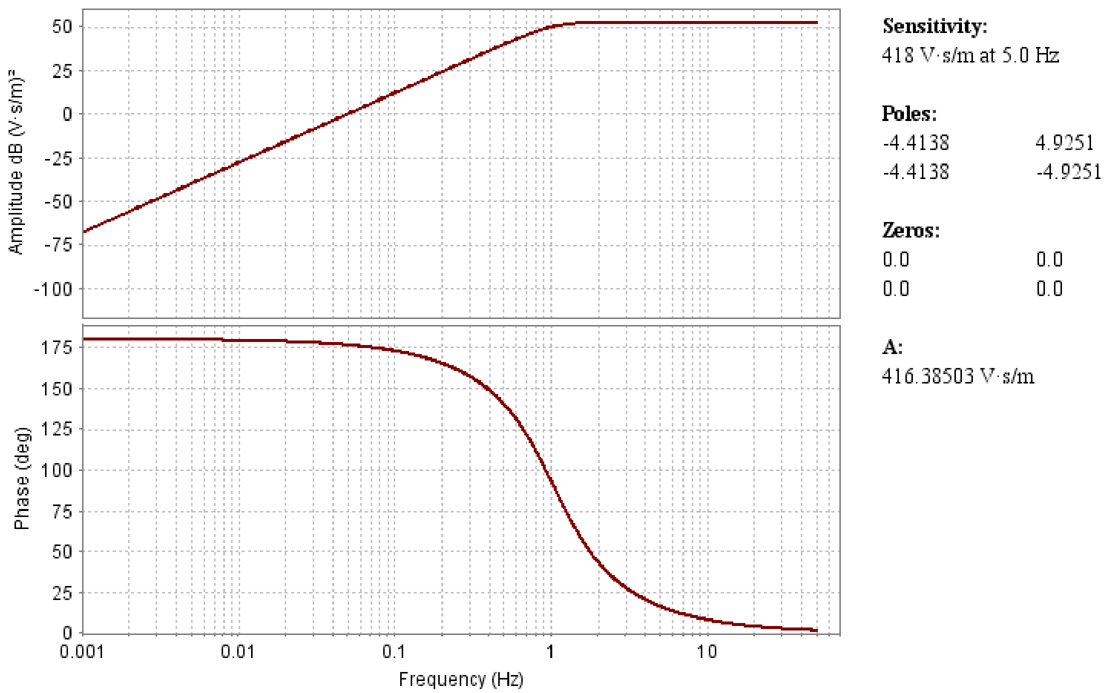

Figure 64 Geotech GS21 Response

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