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Next Generation Qualification: Guralp CMG-3V Seismometer Evaluation

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Next Generation Qualification: Guralp CMG-3V Seismometer Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated three seismometers, the CMG-3V, manufactured by Guralp. These seismometers measure a single axes of broadband ground velocity in a borehole package. The purpose of the seismometer evaluation was to determine a measured sensitivity, response, passband, self-noise, dynamic range, and self-calibration ability. The Guralp CMG-3V seismometers are being evaluated for potential use in U.S. Air Force seismic monitoring systems as part of their Next Generation Qualification effort.

ACKNOWLEDGMENTS

The equipment was purchased and setup using funds provided by the United States Department of Defense. The evaluation and generation of the report was funded by the United States Department of Energy Office of Nuclear Verification (NA-221).

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NOMENCLATURE

BB	Broadband
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
HNM	High Noise Model
JCGM	Joint Committee for Guides in Metrology
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories
SP	Short-period

1 INTRODUCTION

The evaluation of the three Guralp CMG-3V seismometers, serial numbers V3J45, V3J46, and V3J47, was performed to determine the performance characteristics of the instruments including sensitivity, self-noise, dynamic range, frequency response, passband, and self-calibration.

Figure 1 Guralp CMG-3V Seismometer and hole-lock (Guralp CMG-3V Manual)

The CMG-3V seismometer measures vertical-only ground motion across a customizable passband, in this case 0.0333 Hz (30 seconds) – 50 Hz, and a sensitivity of 20,000 V/(m/s). The seismometer is contained within a borehole package with a hole-lock. For the purpose of this evaluation, the seismometers were removed from the hole-lock and installed using a vault base-plate from Guralp.

Hybrid sensors	Velocity output bandwidth	0.1 – 50 Hz
	High pass filter output flat to acceleration	0.01 Hz – *spec**
	High pass filter output flat to velocity	*spec* – 50 Hz*
	Mass position output	DC – 0.1 Hz
	Velocity sensitivity	1400 V/m/s
	Acceleration sensitivity	2000 V/m/s^2
Velocity sensors	Velocity output bandwidth	*spec* – 50 Hz*
	Mass position output	DC – *spec* Hz*
	Velocity sensitivity	2 × 1000 V/m/s**
	Mass position sensitivity	1000 V/m/s^2
Controls	Mass locking and unlocking	remotely operated
	Mass centring	automatic, microprocessor controlled
Mechanics and electronics	Sensors	3 orthogonal sensors
	Sensor transducer type	capacitive displacement
	Feedback transducer type	magnet/coil
	Connector	pressure tight, waterproof
	Borehole diameter	89 – 229 mm
	Temperature range with masses locked	–20 to +75 °C
	Operational temperature range	–10 to +65 °C
Power	Supply requirements	11 – 36 V DC
	Current at 24 V DC	75 mA†
	Current at 24 V DC during centring (average)	115 mA†
	Current at 24 V DC during locking and unlocking	200 mA†

Table 1 Seismometer Specifications (Guralp Manual MAN-BHO-0004)

2 TEST PLAN

2.1 Test Facility

Testing of the seismometers 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 environment.

Figure 2 FACT Site Bunker

The seismometers were configured on the FACT Seismometer Pier within the underground bunker. The seismometers were operated alongside a reference STS-2 seismometer from April – August, 2017.

The SNL reference seismometer, a Kinemetrics STS-2 #120651, was used to compare against the seismometers under test. All results are made relative to this reference.

Figure 3 Picture of installed Seismometers

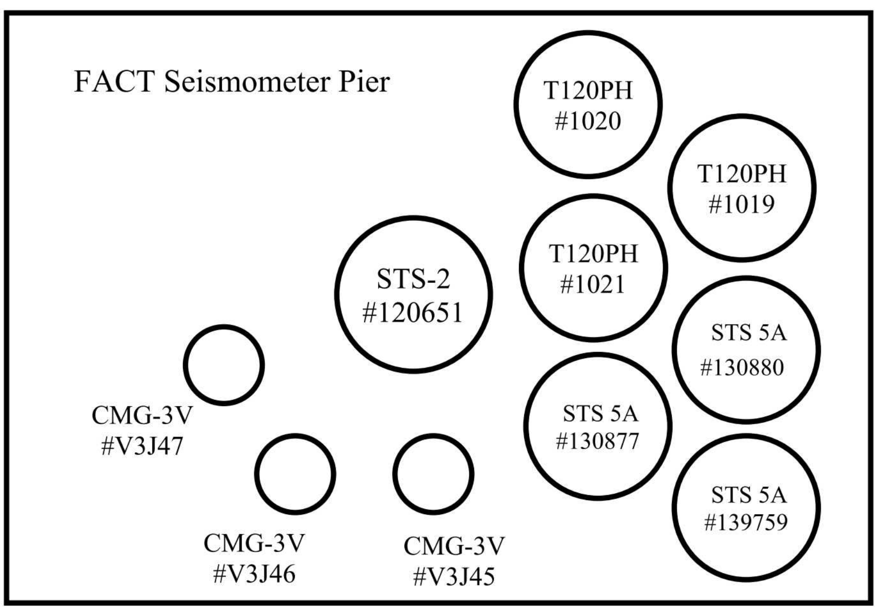


Figure 4 Diagram of installed Seismometers

Prior to performing the seismometer testing for the Next Generation Qualification project, SNL's reference STS-2 was taken to the USGS Albuquerque Seismic Laboratory (ASL) for re-calibration using their step-table, a Lennartz CT-E1 step calibration table. The resulting sensitivities for the reference STS-2 #120651 are shown below:

Table 2 Reference STS-2 #120651 Sensitivity

Axis	Sensitivity at 1 Hz
Z	1495.51 V/(m/s)
N	1488.72 V/(m/s)
E	1,492.25 V/(m/s)

The temperature within the bunker was monitored continuously throughout the testing. The temperature was maintained to be at least 23 Celsius with active heating by a radiant electric heater during the spring and early summer. During the summer months, the temperature increased due to ambient conditions and was stable at 27.3 Celsius.

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

Figure 5 GPS Re-broadcaster

The digitizers and seismometers were powered off of a laboratory power supply providing approximately 13.5 Volts.

Figure 6 Laboratory Power Supply

The Guralp CMG-3V seismometers were connected to Guralp Affinity digitizers for recording of the time series data. The seismometer and digitizer channel assignments are contained in the table below.

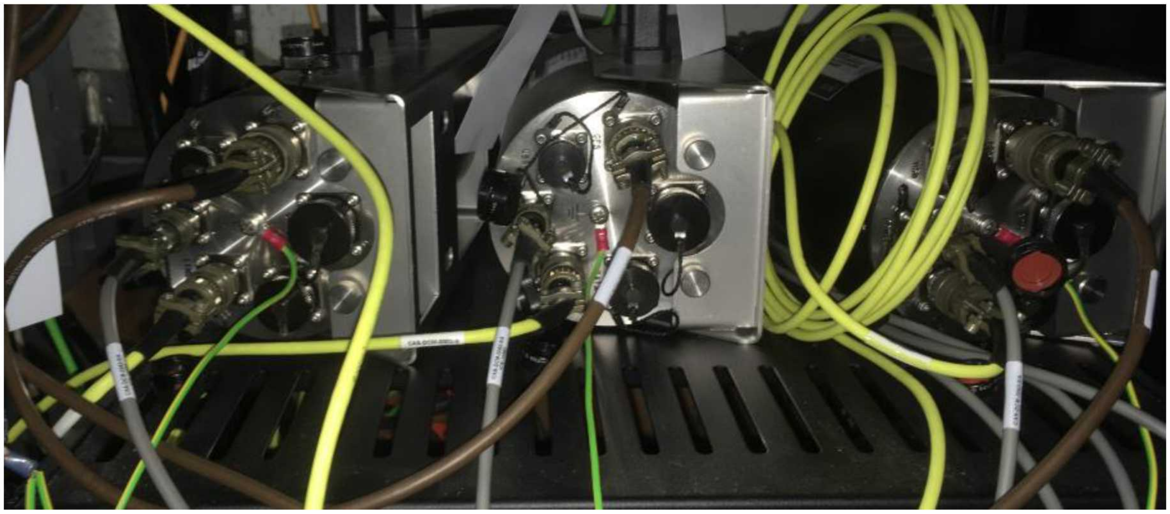


Figure 7 Guralp Affinity Digitizers

Before setting up the seismometer for testing, the digitizer bit-weights were calibrated against a reference meter with an active calibration from Sandia's PSL. The SNL reference digitizer, Kinemetrics Q330 #1551, was calibrated using the Agilent 3458A meter # MY45048371. The remaining digitizer bit-weights were obtained from the Next Generation Qualification digitizer evaluation reports. The bit-weights and digitizer channel assignments used are shown in the table below.

Table 3 Testbed Digitizer Channel Assignment and Bitweights

Manufacturer	Digitizer	Port	Seismometer	Channel Z	Channel N	Channel E
Kinemetrics	Q330 #1551	B	STS-2 #120651	2.38368 uV/count	2.38473 uV/count	2.38406 uV/count
Kinemetrics	Q330 #6164	B	STS-5A #139759	0.11872 uV/count	0.11881 uV/count	0.11873 uV/count
Kinemetrics	Q330 #6162	A	STS-5A #130877	29.72408 nV/count	29.73126 nV/count	29.73929 nV/count
Kinemetrics	Q330 #6162	B	STS-5A #130880	0.11879 uV/count	0.11876 uV/count	0.11877 uV/count
Guralp	Affinity #559A	A	CMG-3V #V3J45	0.99943 uV/count	N/A	N/A
Guralp	Affinity #55A1	A	CMG-3V #V3J46	0.99949 uV/count	N/A	N/A
Guralp	Affinity #559B	A	CMG-3V #V3J47	0.99936 uV/count	N/A	N/A
Nanometrics	Centaur #1776	A	T120PH #1020	0.12499 uV/count	0.12498 uV/count	0.12498 uV/count
Nanometrics	Centaur #1787	A	T120PH #1021	0.12495 uV/count	0.12499 uV/count	0.12494 uV/count
Nanometrics	Centaur #1797	A	T120PH #1019	0.12498 uV/count	0.125 uV/count	0.12498 uV/count

2.2 Scope

The following table lists the tests and resulting evaluations that were performed.

Table 4 Tests performed

Test
Sensitivity
Self-Noise
Dynamic Range
Frequency Response
Passband
Calibrator Sensitivity
Calibrator Frequency Response

2.3 Timeline

Testing of the seismometers was performed at Sandia National Laboratories between April 1 – August 31, 2017.

2.4 Evaluation Frequencies

The frequency range of the measurements is from 0.001 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 = -30, -29, …, 16, 17. The nominal center frequency values, in Hz, are:

0.001,	0.00125,	0.0016,	0.0020,	0.0025,	0.00315,	0.0040,	0.0050,	0.0063,	0.008,
0.01,	0.0125,	0.016,	0.020,	0.025,	0.0315,	0.040,	0.050,	0.063,	0.08,
0.10,	0.125,	0.16,	0.20,	0.25,	0.315,	0.40,	0.50,	0.63,	0.8,
1.0,	1.25,	1.6,	2.0,	2.5,	3.15,	4.0,	5.0,	6.3,	8.0,
10.0,	12.5,	16.0,	20.0,	25.0,	31.5,	40.0,	50.0,	63.0,	80.0

3 TEST EVALUATION

3.1 Sensitivity

The sensitivity of a sensor is defined to be the "quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured" (JCGM 200:2012). For a seismometer measuring velocity, the sensitivity value is expressed at a given frequency in units of V/(m/s), depending upon whether the sensor is measuring pressure or pressure rate.

This sensitivity value is to be measured at a 1 Hz calibration frequency, temperature, static pressure, and input amplitude that shall be specified.

3.1.1 Measurand

The quantity being measured is the sensor's sensitivity at 1 Hz in V/(m/s).

3.1.2 Configuration

The sensor under test and a reference sensor with known response characteristics are co-located so that they are both measuring a common earth motion.

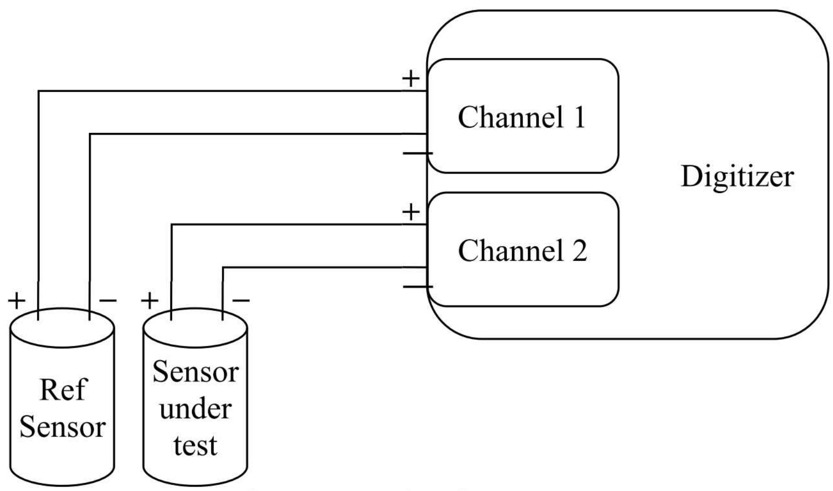


Figure 8 Sensitivity Configuration Diagram

The sensors are allowed to stabilize and then are operated until suitable ground-motion from an earthquake is recorded to provide high coherence between the sensors at the calibration frequency of 1 Hz.

Table 5 Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	Kinemetrics STS-2	# 120651	1500 V/(m/s)
Reference Digitizer	Kinemetrics Q330	# 1551	200 Hz, 40 Vpp
Sensor under test	Guralp CMG-3V	# V3J45, V3J46, V3J47	20 kV/(m/s)
Sensor Digitizers	Guralp Affinity	# 559A, 55A1, 559B	200 Hz, 40 Vpp

The digitizer records the output of the reference sensor and the sensor under test simultaneously. The reference sensor recording is used for comparison against the sensor under test recording.

3.1.3 Analysis

The data recorded using the reference sensor and digitizer has the calibrated bit-weight and sensitivity applied to convert the data to ground motion.

The data recorded using the sensor under test and digitizer has just the calibrated bit-weight applied to convert the data to voltage.

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

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

The amplitude response at 1 Hz is evaluated to compute the sensitivity of the sensor under test.

3.1.4 Result

The earthquake that was identified for use in determining sensitivity was a combination of two earthquakes that occurred in western Montana on July 6, 2017 as reported by the USGS. The first earthquake was a magnitude 5.8 located at 46.881 N, 112.575 W, a depth of 12.2 km, and at 06:30:17 (UTC). The second earthquake, approximately 5 minutes later, was a magnitude 5.0 located at 46.482 N, 112.658 W, a depth of 15.7 km, and at 06:35:35 (UTC).

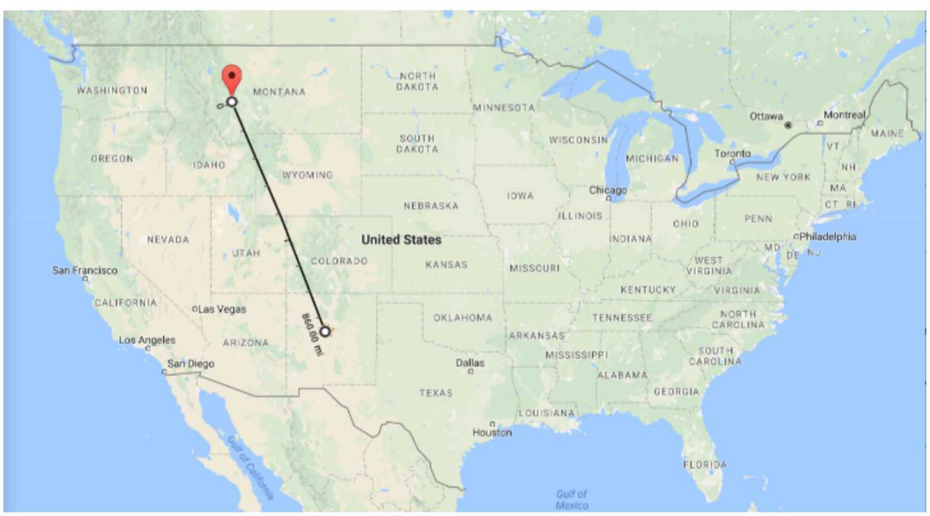


Figure 9 Sensitivity Earthquake Location

This earthquake was approximately 860 (1384 km) miles from the Sandia FACT site and resulted in an observable waveform signal that lasted over 1 hour in duration.
The figure below shows the waveform time series for the recordings. The window regions bounded by the red lines indicate the segment of data used for analysis.

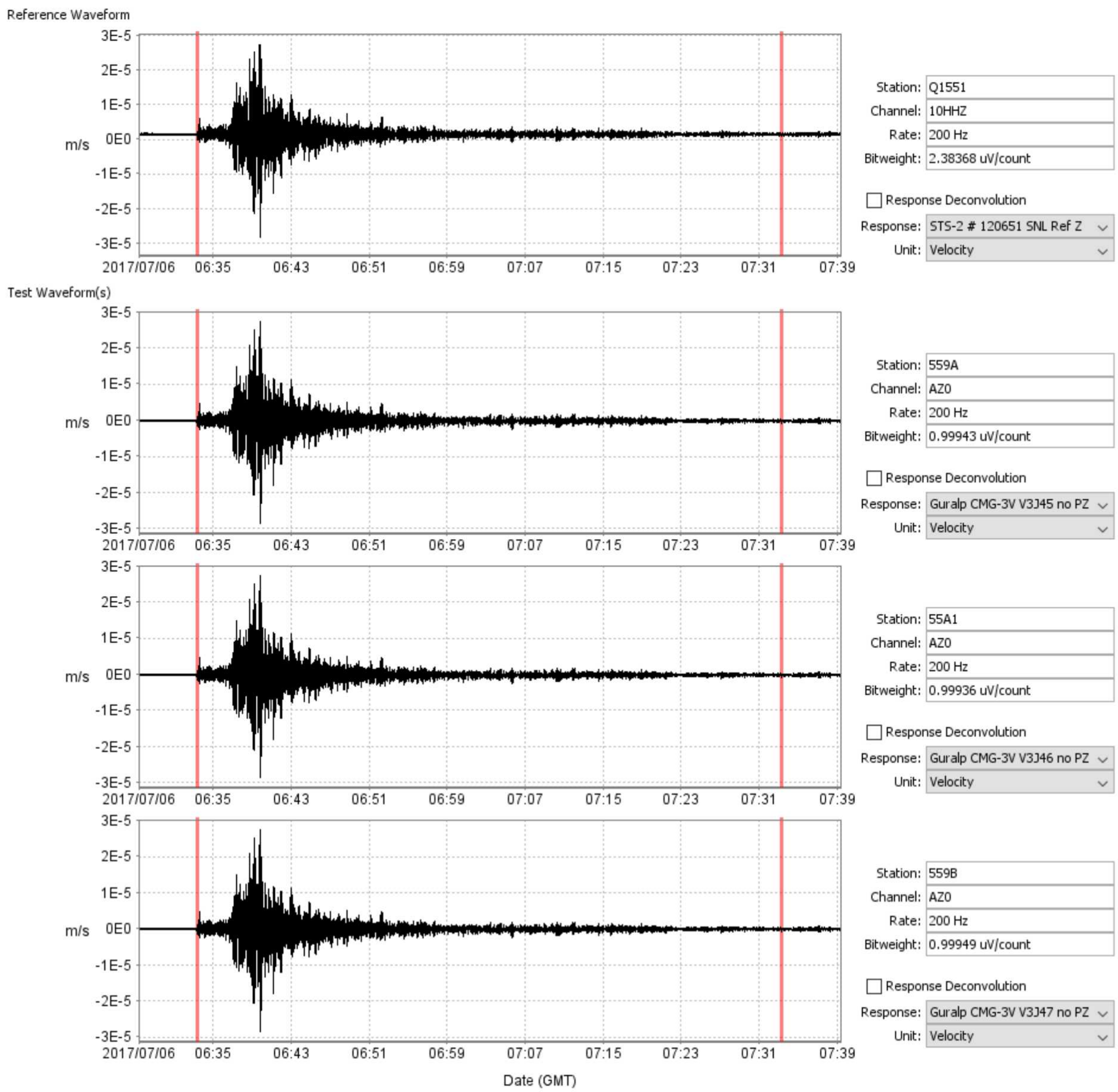


Figure 10 Sensitivity Time Series

The figures below show the power spectra, coherence, and amplitude response that were computed from the waveform time series.

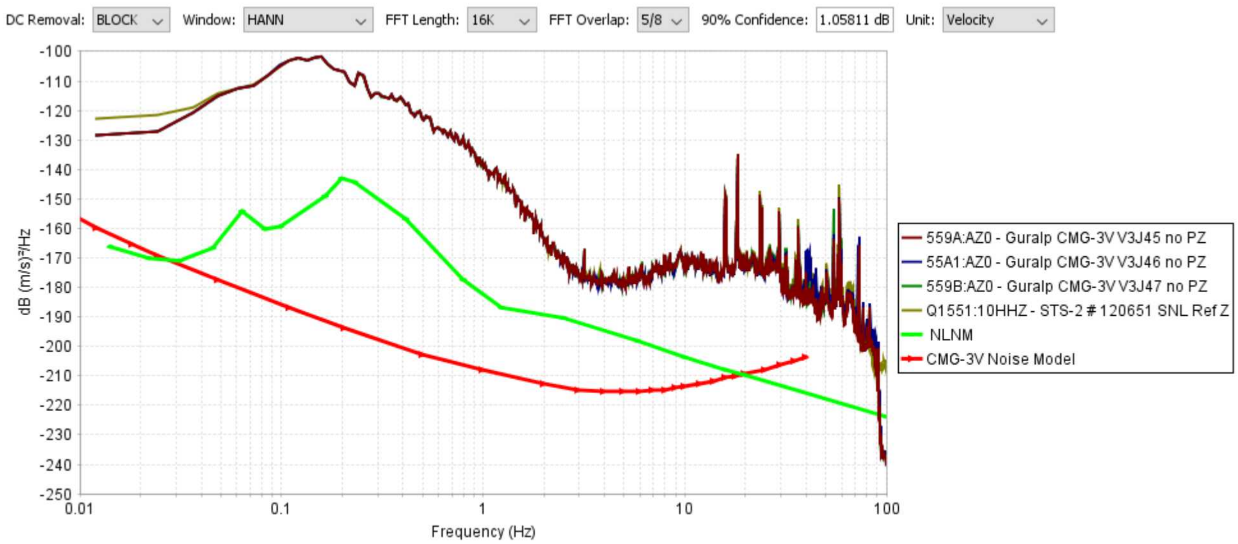


Figure 11 Sensitivity Power Spectra

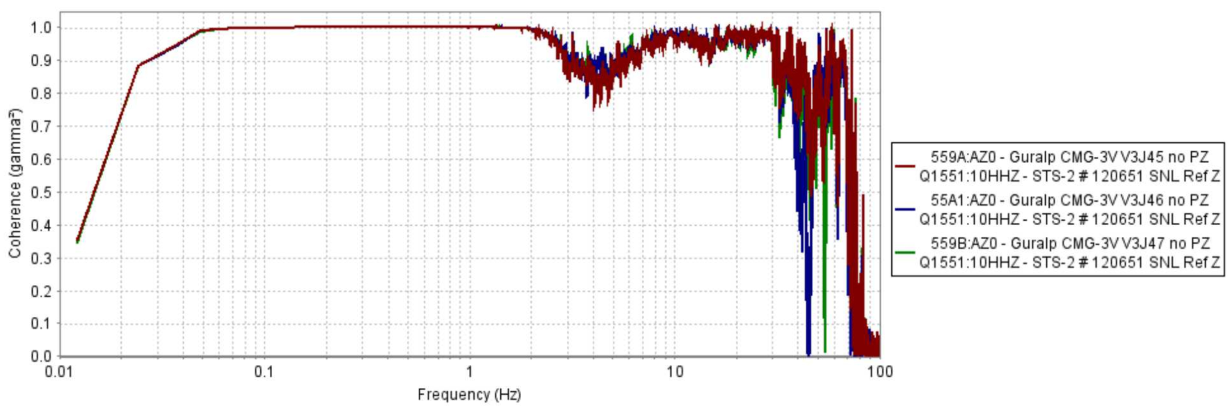


Figure 12 Sensitivity Coherence

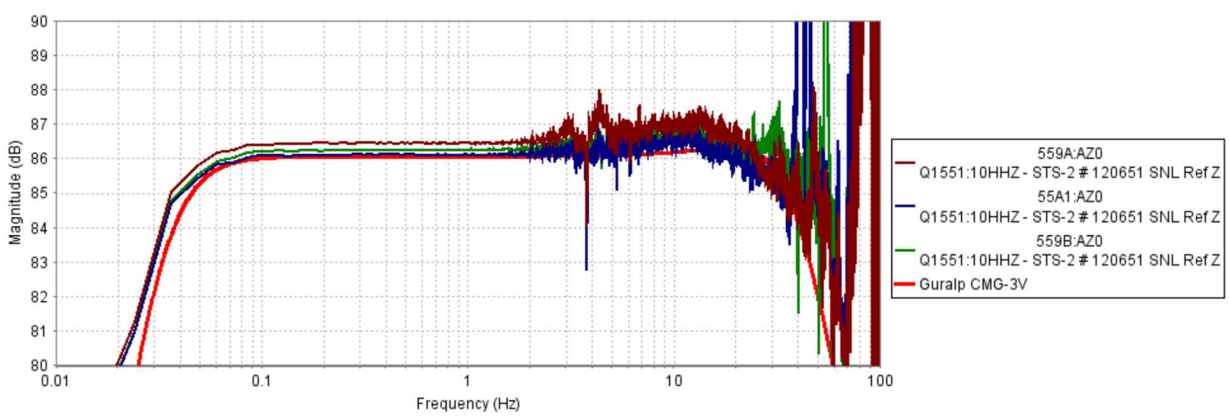


Figure 13 Sensitivity Amplitude Response

Note that the amplitude response curves shown above are consistent with the nominal amplitude response model for a Guralp CMG-3V, shown in red, with a sensitivity of 20 kV/(m/s) and applied poles and zeros. However, there is a slight shift in each of the amplitude responses, indicating that each seismometer has a unique sensitivity.

The measured sensitivity results, relative to the calibrated reference STS-2 seismometer, are shown in the table below:

Table 6 Sensor Sensitivity

Seismometer	Nominal	Calibration Sheet	Measured	% from nominal	% from Cal Sheet
CMG-3V #V3J45	20 kV/(m/s)	20.088 kV/(m/s)	20.95 kV/(m/s)	4.75%	4.29%
CMG-3V #V3J46	20 kV/(m/s)	19.658 kV/(m/s)	20.16 kV/(m/s)	0.80%	2.55%
CMG-3V #V3J47	20 kV/(m/s)	19.830 kV/(m/s)	20.49 kV/(m/s)	2.45%	3.33%

The measured sensitivities were between 20.16 and 20.95 kV/(m/s). These values differ from the nominal 20 kV/(m/s) by between 0.8 and 4.75 %. The differences between the observed sensitivities and the manufacturers calibration sheet were between 2.55 and 4.29 %.

Applying the measured sensitivities to the waveform data results in the amplitude response plot shown below:

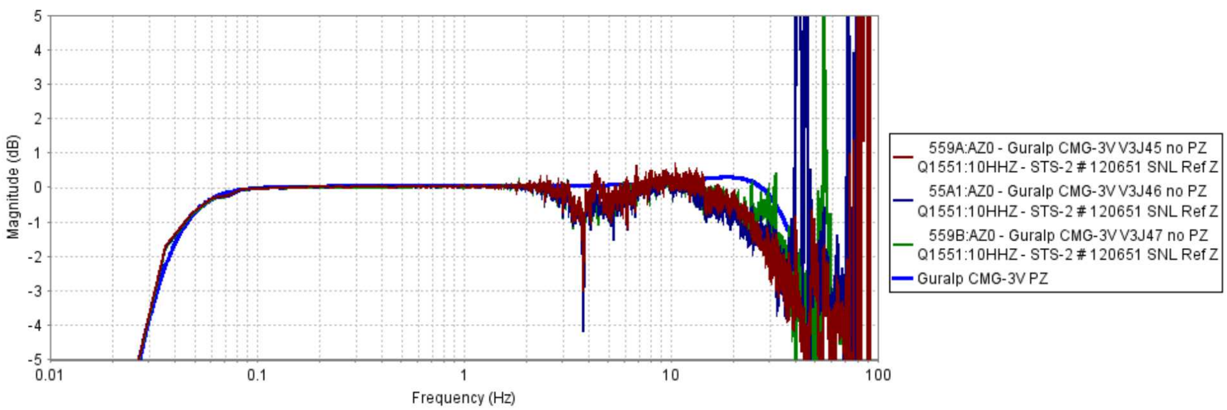


Figure 14 Sensitivity Corrected Amplitude Response

The amplitude response curves are now corrected for the measured sensitivities and show greater agreement with the nominal Guralp CMG-3V poles and zeros response model.

3.2 Self-Noise

The Self-Noise test measures the amount of noise present on a seismometer by collecting waveform data simultaneously from multiple seismometers during a long duration quiet time period. Data is collected from multiple sensors so that coherence analysis may be applied to remove any coherent signal, leaving only incoherence signal, which should approximate the self-noise of the seismometer.

3.2.1 Measurand

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

3.2.2 Configuration

The sensors under test are co-located so that they are both measuring a common earth motion.

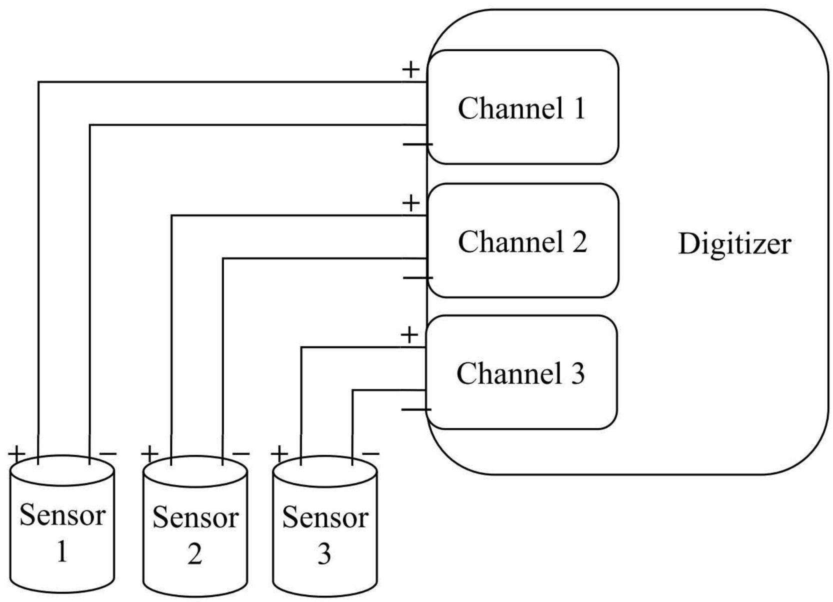


Figure 15 Self-Noise Configuration Diagram

The sensors are allowed to stabilize and then are operated until a suitably quiet long-duration period is observed, typically over-night or over a weekend.

Table 7 Self-Noise Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Sensor under test	Guralp CMG-3V	# V3J45, V3J46, V3J47	20 kV/(m/s)
Sensor Digitizers	Guralp Affinity	# 559A, 55A1, 559B	200 Hz, 40 Vpp

The digitizer records the output of the reference sensors.

3.2.3 Analysis

The data recorded using the sensor under test and digitizer has just the calibrated bit-weight, sensitivity, and poles and zeros applied to convert the data to ground motion.

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

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 of approximately 0.5 dB. The resulting 90% confidence interval was determined to be 0.56 dB.

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

Over frequencies (in Hertz):

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

Coherence analysis using the auto and cross power spectra is applied to determine the individual sensor self-noise levels. In the case of two co-located sensors, a 2-channel coherence method (Holcomb, 1989) is used. In the case of three co-located sensors, a 3-channel coherence method (Sleeman, 2007) is used:

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

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

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

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

3.2.4 Result

A review of the data recorded determined that the quietest time period occurred on July 16, 2017 between approximately 04:00 and 11:00 UTC. In local time, this corresponds to an overnight during a weekend between Saturday, July 15 20:00 and Sunday, July 16, 05:00.

The figure below shows the waveform time series for the recordings. The window regions bounded by the red lines indicate the 7 hour segment of data used for analysis.

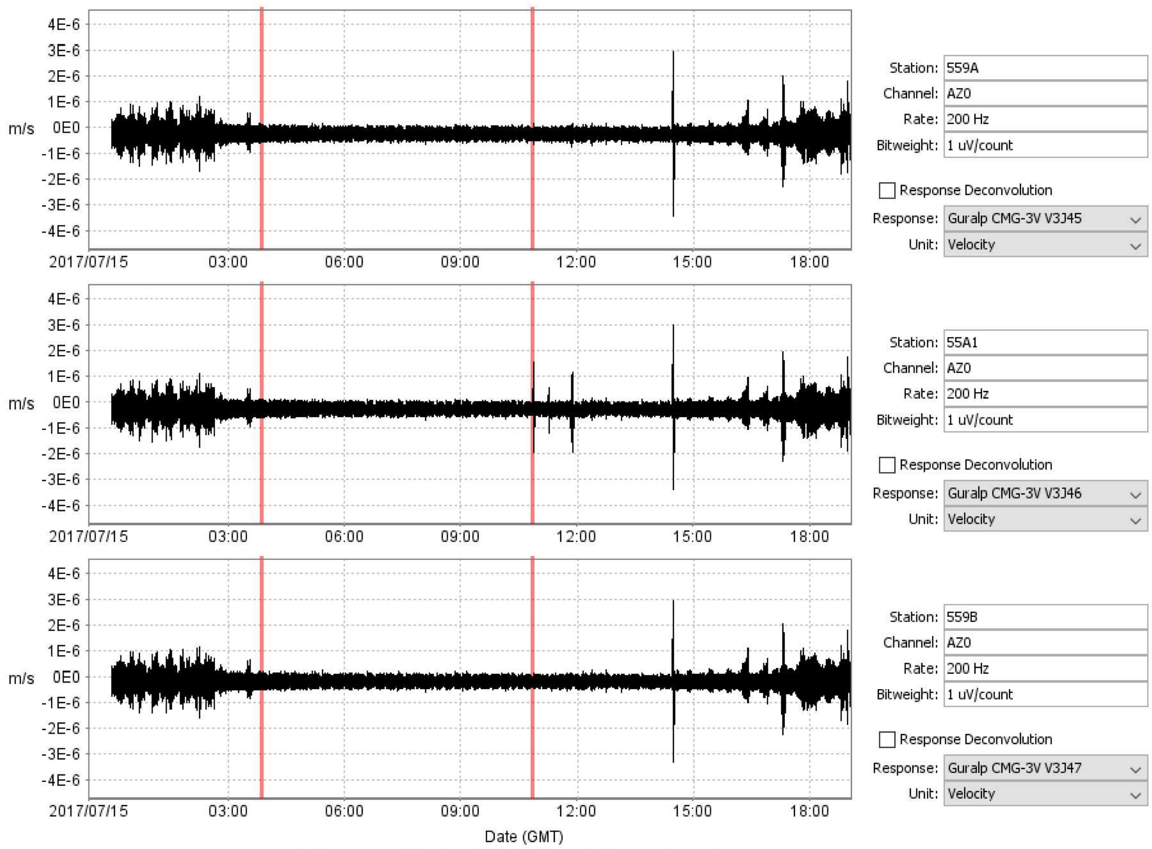


Figure 16 Self Noise Time Series

The figures below show the raw power spectra, corrected for the individual response models, and the coherence between all combinations of seismometer pairs.

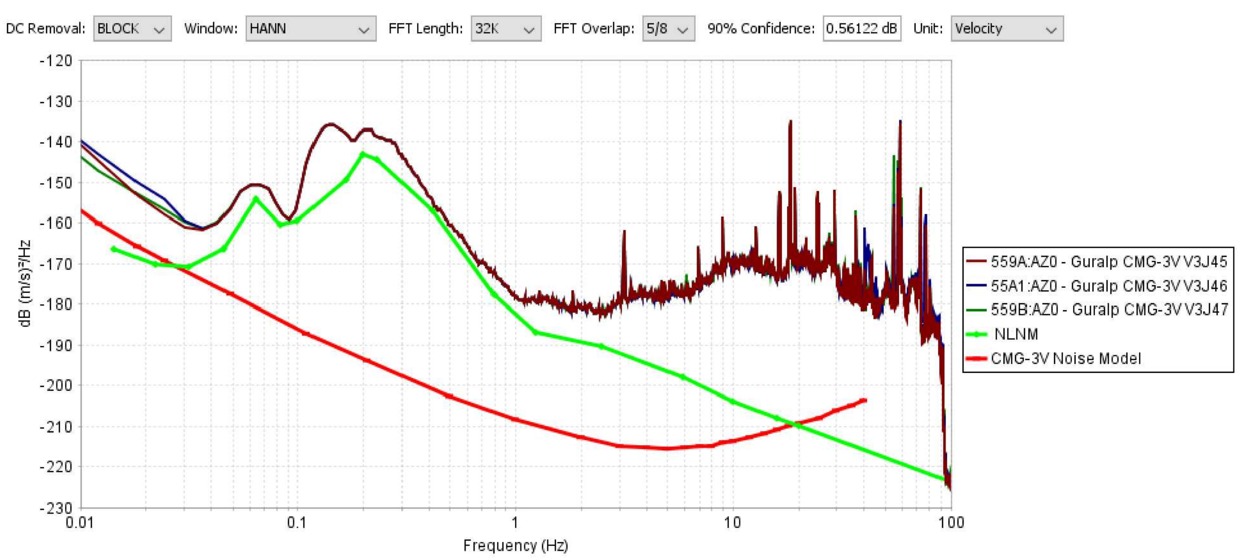


Figure 17 Self Noise Raw Power Spectra

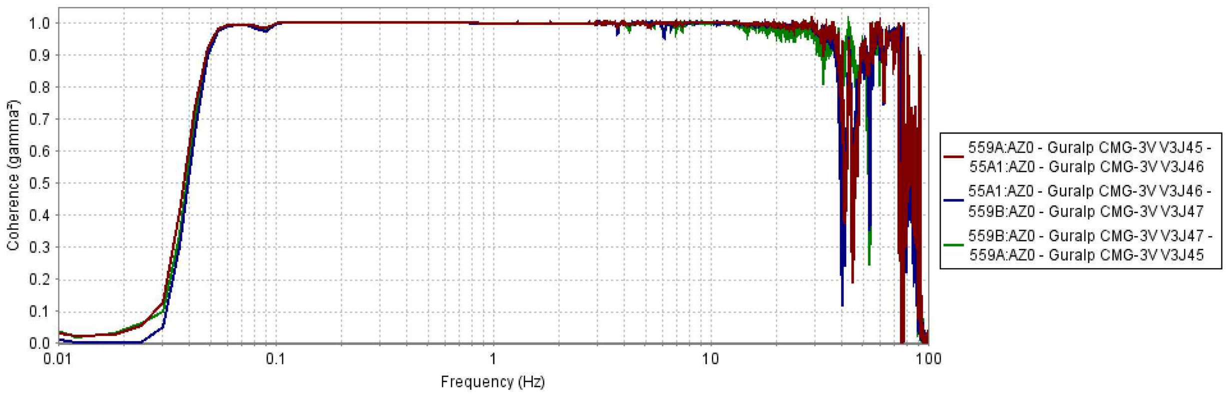


Figure 18 Self Noise Coherence

Computing the incoherent portion of the signal using the 3-channel coherence method (Sleeman, 2007) results in the following figure. Note that the Seismic Low Noise Model (NLNM) and the manufacturer supplied CMG-3V noise model are overlaid for comparison.

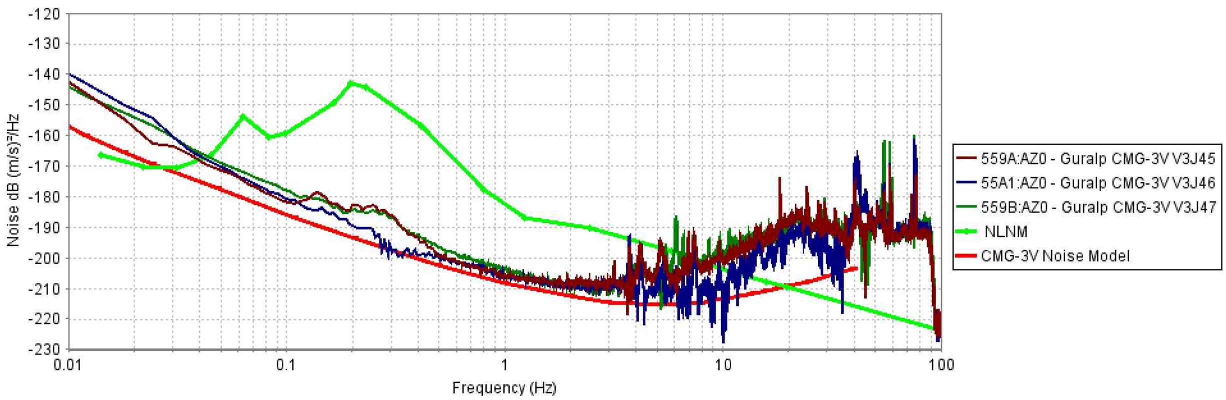


Figure 19 Self Noise

We observe that there is good signal coherence, even when recording just quiet background, between 0.06 and 30 Hz. Coherence is lost below 0.06 Hz due to the sensor self-noise rising above the level of the recorded background. Coherence is likely lost above 30 Hz due to the seismometers not being perfectly co-located and local site noise resulting in incoherent ground motion observed at the instruments.

When applying coherence analysis techniques, it is common for any imperfection in the system (axis alignment, sensor co-location, pier imperfections, etc.) to result in portions of the recorded signal being incoherent between the sensors. This is observable in the micro-seism that bleeds through between 0.1 and 0.5 Hz. In addition, there is some scatter in the estimate of the self-noise at higher frequencies, > 3 Hz, due to the levels of site-noise present.

The following table contain the RMS noise levels across several relevant pass-bands.

Table 8 Self Noise RMS

Seismometer	20 mHz - 1 Hz	20 mHz - 16 Hz	33 mHz - 50 Hz	0.5 Hz - 16 Hz
CMG-3V #V3J45	1.025 nm/s rms	1.129 nm/s rms	2.316 nm/s rms	0.4766 nm/s rms
CMG-3V #V3J46	1.790 nm/s rms	1.808 nm/s rms	4.642 nm/s rms	0.2611 nm/s rms
CMG-3V #V3J47	1.563 nm/s rms	1.660 nm/s rms	2.344 nm/s rms	0.5632 nm/s rms

The following table contains the seismometer self-noise values, smoothed with a median filter, expressed as dB relative to 1 $(m/s)^2/Hz$.

Table 9 Self Noise

Frequency	CMG-3V V3J45	CMG-3V V3J46	CMG-3V V3J47
0.0100 Hz	-145.39 dB	-140.41 dB	-146.17 dB
0.0125 Hz	-145.66 dB	-140.90 dB	-148.31 dB
0.0160 Hz	-151.94 dB	-147.33 dB	-150.89 dB
0.0200 Hz	-156.28 dB	-151.98 dB	-153.80 dB
0.0250 Hz	-160.22 dB	-153.51 dB	-157.67 dB
0.0315 Hz	-165.20 dB	-163.02 dB	-162.55 dB
0.0400 Hz	-169.91 dB	-166.82 dB	-165.53 dB
0.0500 Hz	-172.84 dB	-170.36 dB	-169.71 dB
0.0630 Hz	-175.93 dB	-174.53 dB	-171.43 dB
0.0800 Hz	-179.48 dB	-176.99 dB	-175.28 dB
0.1000 Hz	-180.69 dB	-180.96 dB	-178.20 dB
0.1250 Hz	-181.40 dB	-183.61 dB	-180.55 dB
0.1600 Hz	-182.68 dB	-185.75 dB	-182.88 dB
0.2000 Hz	-183.33 dB	-188.70 dB	-184.80 dB
0.2500 Hz	-184.51 dB	-191.70 dB	-185.64 dB
0.3150 Hz	-187.17 dB	-196.63 dB	-187.78 dB
0.4000 Hz	-193.71 dB	-198.81 dB	-193.11 dB
0.5000 Hz	-199.12 dB	-200.23 dB	-196.52 dB
0.6300 Hz	-201.78 dB	-201.98 dB	-199.45 dB
0.8000 Hz	-203.92 dB	-203.72 dB	-201.95 dB
1.0000 Hz	-205.82 dB	-205.90 dB	-203.96 dB
1.2500 Hz	-207.03 dB	-207.16 dB	-205.93 dB
1.6000 Hz	-207.88 dB	-208.36 dB	-207.79 dB
2.0000 Hz	-208.34 dB	-209.05 dB	-208.75 dB
2.5000 Hz	-208.51 dB	-209.34 dB	-209.31 dB
3.1500 Hz	-208.32 dB	-209.19 dB	-208.71 dB
4.0000 Hz	-206.74 dB	-209.22 dB	-207.06 dB
5.0000 Hz	-205.68 dB	-209.39 dB	-204.28 dB
6.3000 Hz	-203.60 dB	-209.43 dB	-201.58 dB
8.0000 Hz	-201.85 dB	-209.12 dB	-199.66 dB
10.0000 Hz	-199.87 dB	-206.99 dB	-196.91 dB
12.5000 Hz	-197.39 dB	-203.56 dB	-195.23 dB
16.0000 Hz	-193.16 dB	-198.92 dB	-192.89 dB
20.0000 Hz	-190.07 dB	-195.75 dB	-190.22 dB
25.0000 Hz	-190.09 dB	-196.06 dB	-190.01 dB
31.5000 Hz	-190.04 dB	-193.80 dB	-189.69 dB
40.0000 Hz	-190.31 dB	-189.38 dB	-190.12 dB
50.0000 Hz	-191.63 dB	-190.49 dB	-191.09 dB
63.0000 Hz	-192.01 dB	-189.97 dB	-190.70 dB
80.0000 Hz	-192.73 dB	-190.92 dB	-191.46 dB

3.3 Dynamic Range

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

3.3.1 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 seismometer. The smallest signal is defined to have power equal to the self-noise of the seismometer. 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).

3.3.2 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. The value for the smallest signal comes from the evaluated seismometer self-noise determined in section 3.2 Self-Noise.

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

3.3.4 Result

The RMS noise levels are obtained from the sensor self-noise. The full scale value provided by the manufacturer was 20 Volts peak output.

Table 10 Dynamic Range

	20 mHz - 1 Hz	20 mHz - 16 Hz	33 mHz - 50 Hz	0.5 Hz - 16 Hz
CMG-3V #V3J45	115.26 dB	114.60 dB	109.38 dB	123.06 dB
CMG-3V #V3J46	111.09 dB	111.01 dB	103.64 dB	128.46 dB
CMG-3V #V3J47	112.41 dB	111.95 dB	109.39 dB	121.81 dB

As may be observed in the table above, dynamic range values can vary considerably depending upon the frequency pass-band observed. However, for the application pass-band of 0.02 – 16 Hz, the dynamic range was evaluated to be between 111 and 114.6 dB.

3.4 Frequency Response Verification

The Frequency Response Verification tests measured the amplitude and phase response of a sensor over a frequency band of interest.

3.4.1 Measurand

The quantity being measured is the sensor's amplitude and phase response, over a frequency pass-band.

3.4.2 Configuration

The sensor under test and a reference sensor with known response characteristics are co-located so that they are both measuring a common earth motion.

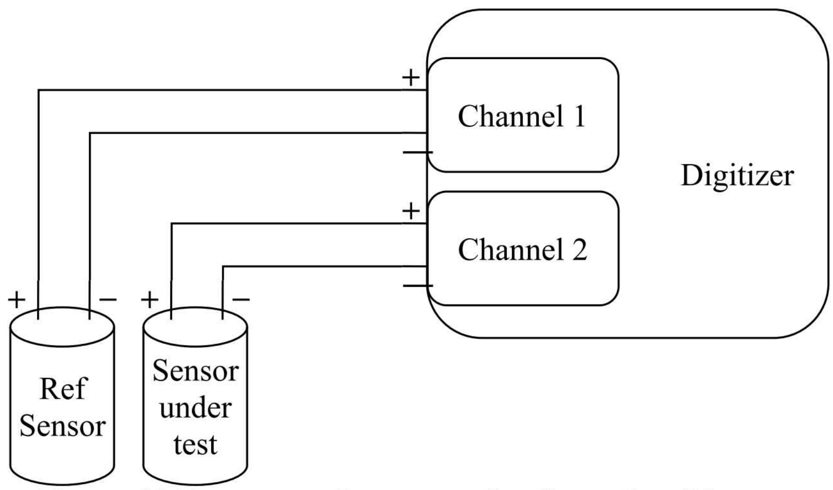


Figure 20 Frequency Response Configuration Diagram

The sensors are allowed to stabilize and then are operated until suitable ground-motion from an earthquake is recorded to provide high coherence between the sensors at the calibration frequency of 1 Hz.

Table 11 Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	Kinemetrics STS-2	# 120651	1500 V/(m/s)
Reference Digitizer	Kinemetrics Q330	# 1551	200 Hz, 40 Vpp
Sensor under test	Guralp CMG-3V	# V3J45, V3J46, V3J47	20 kV/(m/s)
Sensor Digitizers	Guralp Affinity	# 559A, 55A1, 559B	200 Hz, 40 Vpp

The digitizer records the output of the reference sensor and the sensor under test simultaneously. The reference sensor recording is used for comparison against the sensor under test recording.

3.4.3 Analysis

The data recorded using the reference sensor and digitizer has the calibrated bit-weight, sensitivity, and response model applied to convert the data to ground motion.

The data recorded using the sensor under test and digitizer has just the calibrated bit-weight and sensitivity applied to convert the data to ground motion. The response model shape is not applied so that any resulting amplitude or phase response may be observed and compared to the reference.

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

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

3.4.4 Result

Due to the difficulty in finding a single earthquake that would provide sufficient ground-motion across all frequencies, three separate earthquakes were identified that provided the required signal amplitudes for low frequencies (< 0.1 Hz), mid frequencies (0.1 – 1 Hz), and high frequencies (> 1 Hz). In summary, these earthquakes are:

Table 12 Frequency Response Earthquakes

Frequency Range	Date / Time (UTC)	Magnitude	Location
< 0.1 Hz	July 17, 2017, 23:44	7.7	Eastern Russia
0.1 – 1 Hz	June 6, 2017, 06:30	5.8	Montana
> 1 Hz	July 14, 2017, 13:46	4.2	Oklahoma

The following figures and table contain the composite seismometer response values, smoothed with a filter, expressed as dB of power (20 $\log_{10}$) relative to each seismometers sensitivity at 1 Hz and degrees of phase.

As may be seen, the measured response matches very closely with the expected nominal response. The only deviation is at low frequencies, below 0.003 Hz, where the lack of signal coherence limited the ability to resolve the response and at high frequencies where the phase response rolled off slightly slower than the nominal.

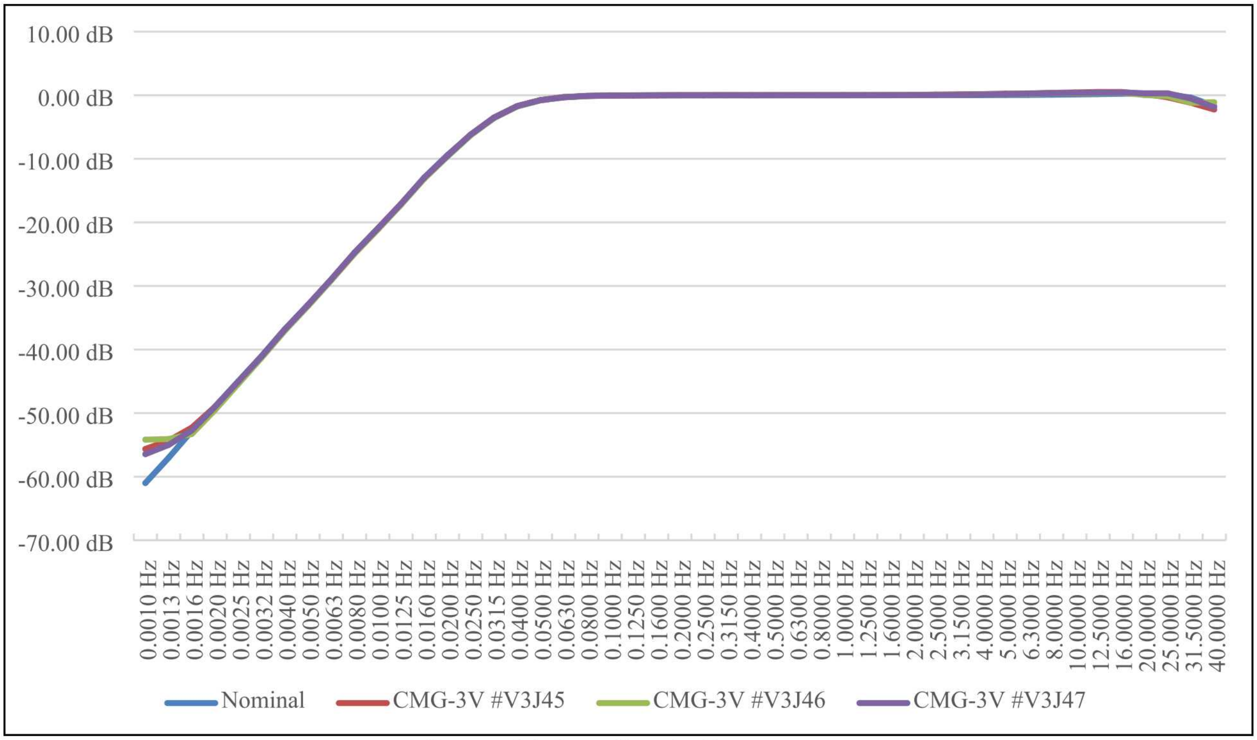


Figure 21 Amplitude Response

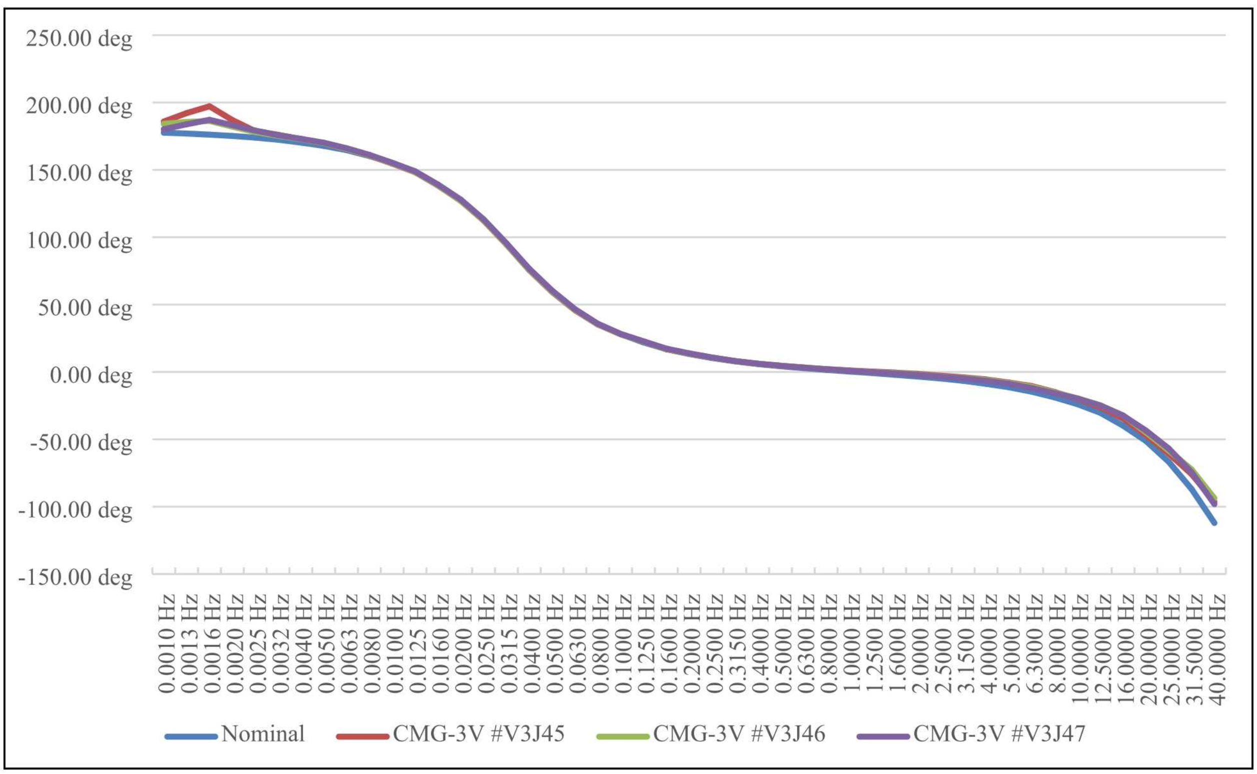


Figure 22 Phase Response

Table 13 Frequency Response

Frequency	Nominal		V3J45		V3J46		V3J47	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0.0010 Hz	-61.00 dB	177.59 deg	-55.64 dB	185.87 deg	-54.18 dB	184.20 deg	-56.45 dB	180.20 deg
0.0013 Hz	-57.03 dB	176.98 deg	-54.33 dB	192.15 deg	-54.08 dB	185.58 deg	-55.01 dB	183.85 deg
0.0016 Hz	-52.80 dB	176.14 deg	-52.28 dB	197.19 deg	-53.28 dB	186.33 deg	-52.72 dB	187.15 deg
0.0020 Hz	-48.96 dB	175.19 deg	-48.99 dB	186.99 deg	-49.49 dB	182.09 deg	-49.00 dB	183.20 deg
0.0025 Hz	-44.99 dB	173.95 deg	-45.25 dB	178.75 deg	-45.39 dB	178.08 deg	-45.01 dB	179.17 deg
0.0032 Hz	-41.02 dB	172.39 deg	-41.19 dB	176.03 deg	-41.30 dB	175.32 deg	-41.07 dB	175.78 deg
0.0040 Hz	-36.80 dB	170.27 deg	-36.91 dB	172.79 deg	-37.05 dB	172.80 deg	-36.85 dB	173.06 deg
0.0050 Hz	-32.96 dB	167.84 deg	-33.01 dB	169.88 deg	-33.16 dB	169.93 deg	-32.98 dB	170.18 deg
0.0063 Hz	-29.00 dB	164.65 deg	-28.98 dB	165.55 deg	-29.12 dB	165.65 deg	-28.95 dB	166.08 deg
0.0080 Hz	-24.78 dB	160.29 deg	-24.81 dB	160.60 deg	-24.94 dB	160.79 deg	-24.76 dB	161.16 deg
0.0100 Hz	-20.96 dB	155.18 deg	-21.01 dB	154.61 deg	-21.15 dB	154.78 deg	-20.98 dB	155.27 deg
0.0125 Hz	-17.17 dB	148.62 deg	-17.11 dB	148.30 deg	-17.24 dB	148.51 deg	-17.09 dB	148.98 deg
0.0160 Hz	-12.96 dB	138.83 deg	-13.03 dB	138.37 deg	-13.14 dB	138.49 deg	-12.97 dB	139.15 deg
0.0200 Hz	-9.42 dB	127.46 deg	-9.52 dB	127.06 deg	-9.64 dB	127.01 deg	-9.52 dB	127.97 deg
0.0250 Hz	-6.23 dB	113.09 deg	-6.20 dB	112.43 deg	-6.30 dB	112.66 deg	-6.18 dB	113.30 deg
0.0315 Hz	-3.51 dB	94.95 deg	-3.54 dB	94.60 deg	-3.61 dB	94.66 deg	-3.55 dB	95.55 deg
0.0400 Hz	-1.72 dB	76.04 deg	-1.73 dB	75.56 deg	-1.78 dB	75.76 deg	-1.72 dB	76.61 deg
0.0500 Hz	-0.79 dB	60.07 deg	-0.76 dB	59.37 deg	-0.80 dB	59.67 deg	-0.78 dB	60.41 deg
0.0630 Hz	-0.33 dB	46.26 deg	-0.28 dB	45.84 deg	-0.34 dB	46.11 deg	-0.33 dB	46.62 deg
0.0800 Hz	-0.13 dB	35.65 deg	-0.11 dB	35.22 deg	-0.13 dB	35.36 deg	-0.11 dB	35.79 deg
0.1000 Hz	-0.06 dB	28.03 deg	-0.05 dB	28.05 deg	-0.01 dB	27.91 deg	-0.04 dB	28.27 deg
0.1250 Hz	-0.02 dB	21.93 deg	-0.03 dB	22.68 deg	-0.01 dB	22.58 deg	-0.04 dB	22.77 deg
0.1600 Hz	-0.01 dB	16.91 deg	-0.01 dB	16.89 deg	0.01 dB	17.03 deg	-0.02 dB	17.34 deg
0.2000 Hz	0.00 dB	13.32 deg	0.01 dB	13.57 deg	0.00 dB	13.56 deg	-0.01 dB	13.84 deg
0.2500 Hz	0.00 dB	10.34 deg	0.01 dB	10.57 deg	0.00 dB	10.64 deg	-0.01 dB	10.79 deg
0.3150 Hz	0.00 dB	7.94 deg	0.02 dB	8.10 deg	0.01 dB	7.95 deg	-0.01 dB	8.12 deg
0.4000 Hz	0.00 dB	5.91 deg	0.01 dB	6.09 deg	0.02 dB	6.07 deg	-0.01 dB	6.16 deg
0.5000 Hz	0.00 dB	4.26 deg	0.00 dB	4.64 deg	0.01 dB	4.61 deg	0.00 dB	4.61 deg
0.6300 Hz	0.00 dB	2.84 deg	0.01 dB	3.37 deg	0.00 dB	3.18 deg	0.00 dB	3.18 deg
0.8000 Hz	0.00 dB	1.54 deg	0.00 dB	2.13 deg	0.00 dB	1.97 deg	0.00 dB	1.99 deg
1.0000 Hz	0.00 dB	0.35 deg	0.01 dB	1.14 deg	0.00 dB	1.02 deg	0.00 dB	0.97 deg
1.2500 Hz	0.00 dB	-0.77 deg	0.01 dB	0.32 deg	0.01 dB	-0.06 deg	0.00 dB	-0.17 deg
1.6000 Hz	0.00 dB	-2.10 deg	0.03 dB	-0.44 deg	0.01 dB	-0.77 deg	0.01 dB	-1.06 deg
2.0000 Hz	0.00 dB	-3.38 deg	0.03 dB	-1.41 deg	0.02 dB	-1.92 deg	0.03 dB	-2.19 deg
2.5000 Hz	0.01 dB	-4.82 deg	0.10 dB	-2.76 deg	0.05 dB	-3.33 deg	0.04 dB	-3.52 deg
3.1500 Hz	0.01 dB	-6.57 deg	0.14 dB	-3.96 deg	0.10 dB	-4.37 deg	0.07 dB	-4.68 deg
4.0000 Hz	0.02 dB	-8.82 deg	0.18 dB	-5.54 deg	0.15 dB	-6.01 deg	0.11 dB	-6.57 deg
5.0000 Hz	0.03 dB	-11.33 deg	0.24 dB	-7.86 deg	0.17 dB	-8.30 deg	0.17 dB	-8.78 deg
6.3000 Hz	0.05 dB	-14.65 deg	0.24 dB	-10.46 deg	0.23 dB	-10.97 deg	0.28 dB	-11.95 deg
8.0000 Hz	0.08 dB	-18.86 deg	0.37 dB	-14.85 deg	0.32 dB	-15.26 deg	0.34 dB	-15.77 deg
10.0000 Hz	0.12 dB	-23.88 deg	0.43 dB	-20.09 deg	0.32 dB	-19.55 deg	0.39 dB	-19.69 deg
12.5000 Hz	0.17 dB	-30.29 deg	0.50 dB	-26.18 deg	0.37 dB	-24.77 deg	0.42 dB	-24.84 deg
16.0000 Hz	0.24 dB	-39.88 deg	0.51 dB	-34.56 deg	0.40 dB	-32.26 deg	0.45 dB	-32.40 deg
20.0000 Hz	0.26 dB	-51.19 deg	0.20 dB	-46.77 deg	0.04 dB	-44.73 deg	0.29 dB	-43.48 deg
25.0000 Hz	0.14 dB	-66.72 deg	-0.33 dB	-60.61 deg	-0.14 dB	-58.33 deg	0.30 dB	-56.84 deg
31.5000 Hz	-0.38 dB	-86.93 deg	-1.19 dB	-75.84 deg	-1.18 dB	-72.36 deg	-0.52 dB	-74.48 deg
40.0000 Hz	-1.68 dB	-112.09 deg	-2.25 dB	-96.30 deg	-1.10 dB	-93.79 deg	-1.90 dB	-98.09 deg

3.4.4.1 Low Frequency

The earthquake that was identified for use in determining the low-frequency (< 0.1 Hz) response was reported by USGS as a magnitude 7.7 located at 54.471 N, 168.816 E, and a depth of 11.0 km on July 14, 2017 06:30:17 (UTC).

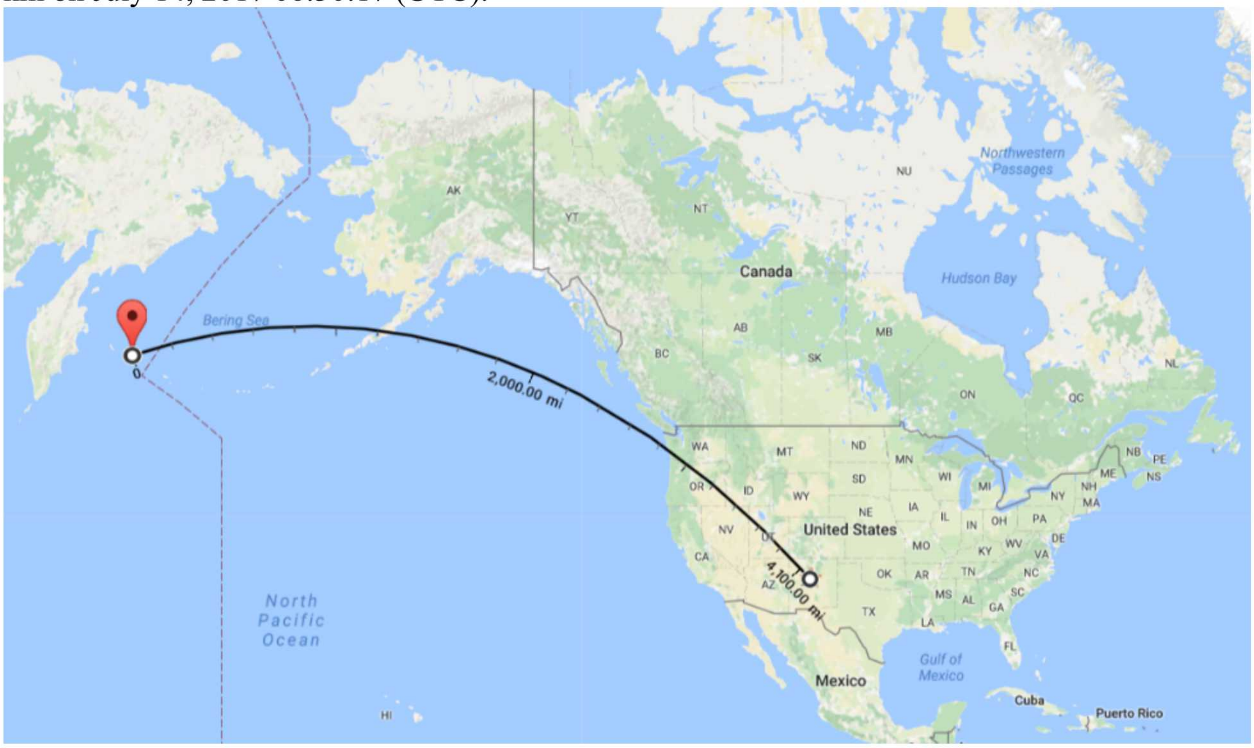


Figure 23 Low Frequency Earthquake Location

This earthquake was approximately 4100 miles (6600 km) from the Sandia FACT site and resulted in an observable waveform signal that lasted over 4 hours in duration.

The figure below shows the waveform time series for the recordings. The window regions bounded by the red lines indicate the segment of data used for analysis.

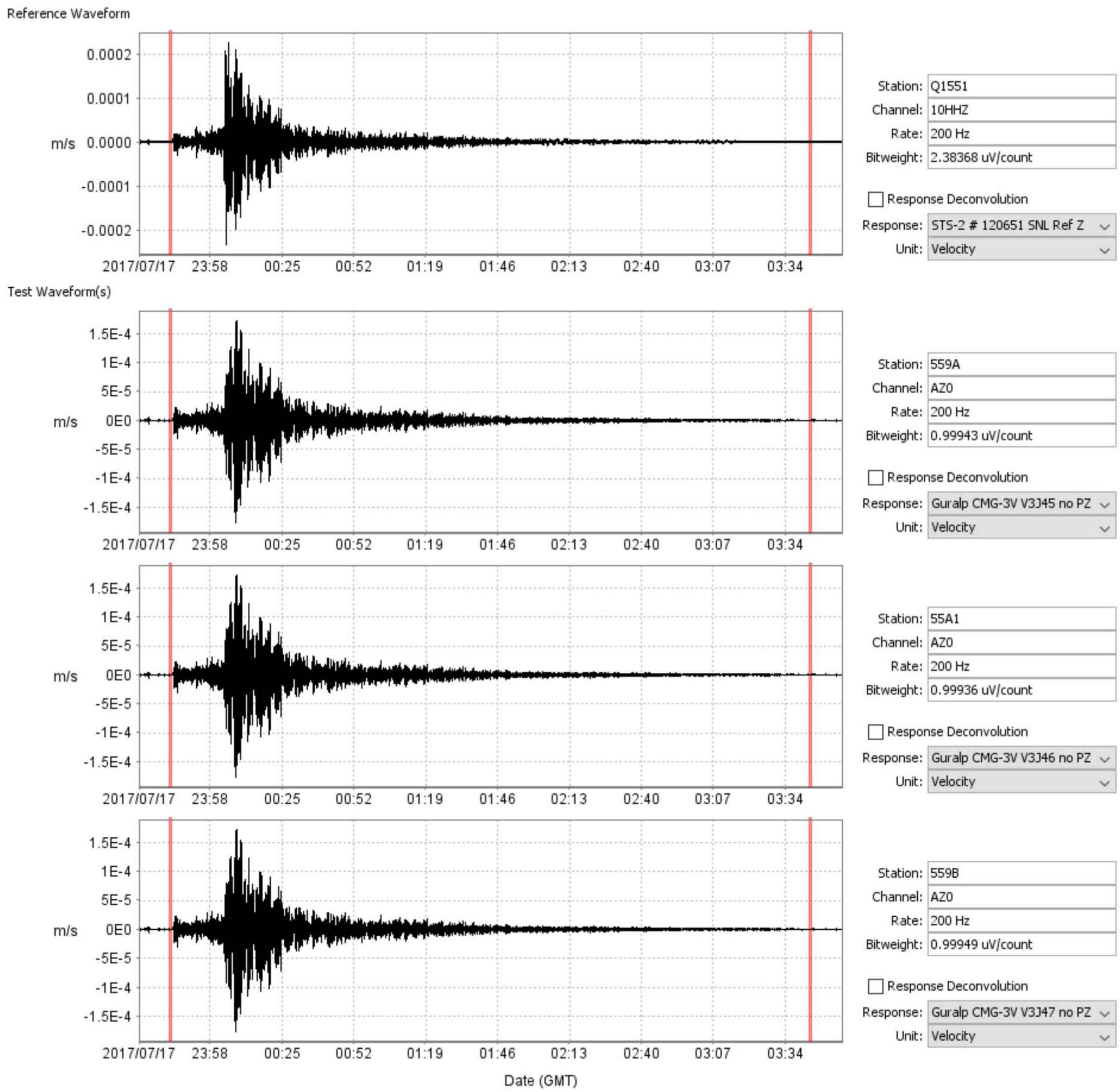


Figure 24 Low Frequency Response Time Series

The figures below show the power spectra, coherence, amplitude response, and phase that were computed from the waveform time series.

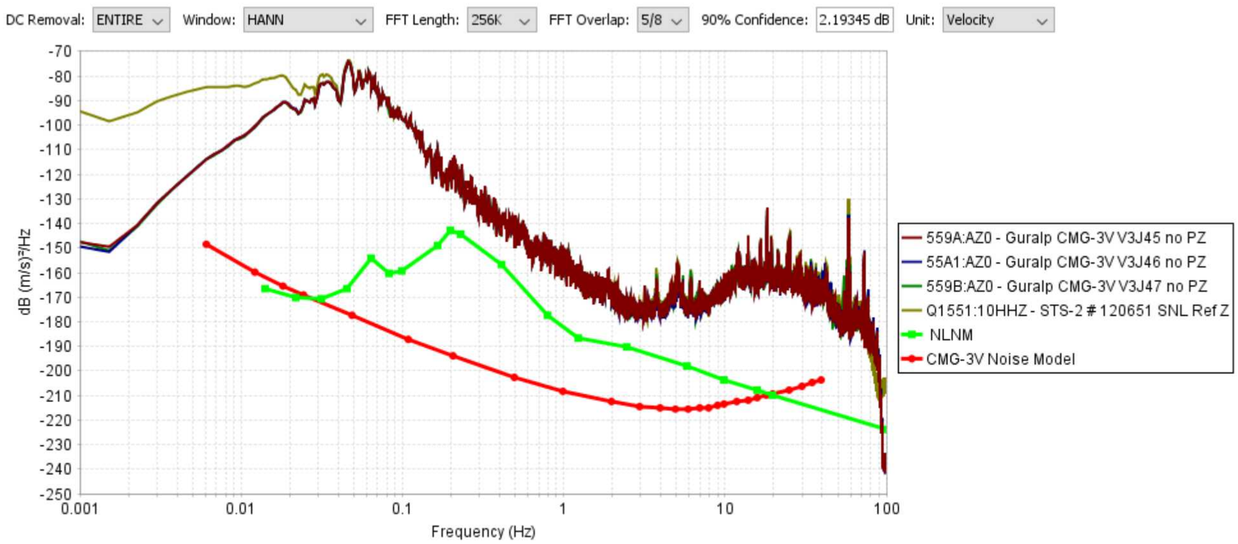


Figure 25 Low Frequency Response Power Spectra

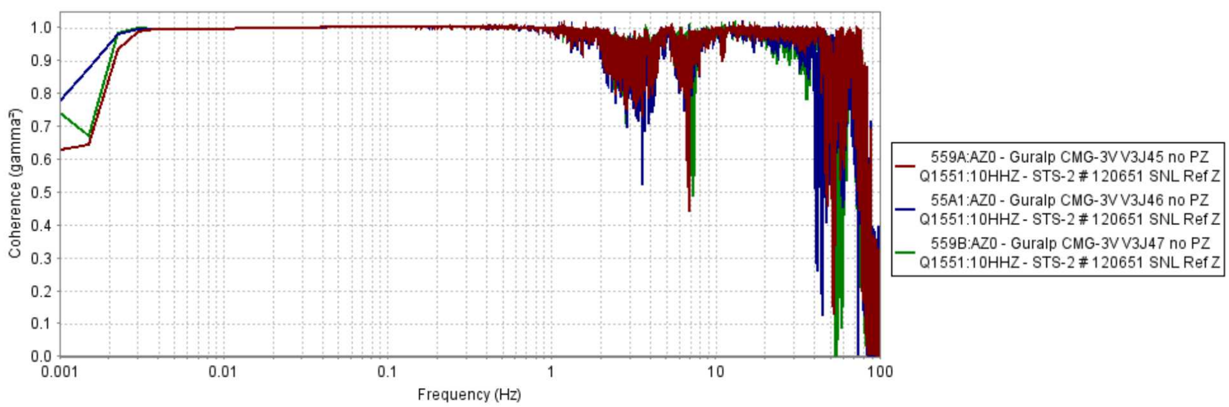


Figure 26 Low Frequency Response Coherence

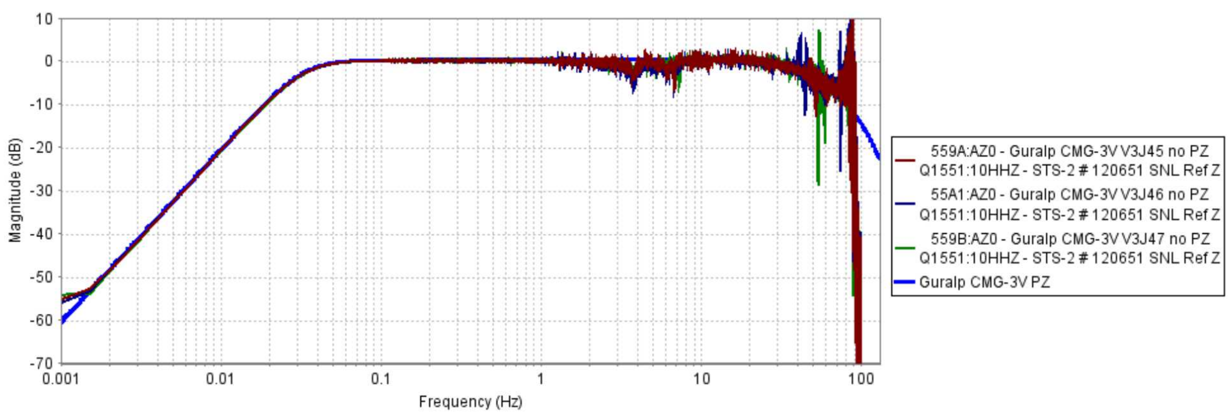


Figure 27 Low Frequency Amplitude Response

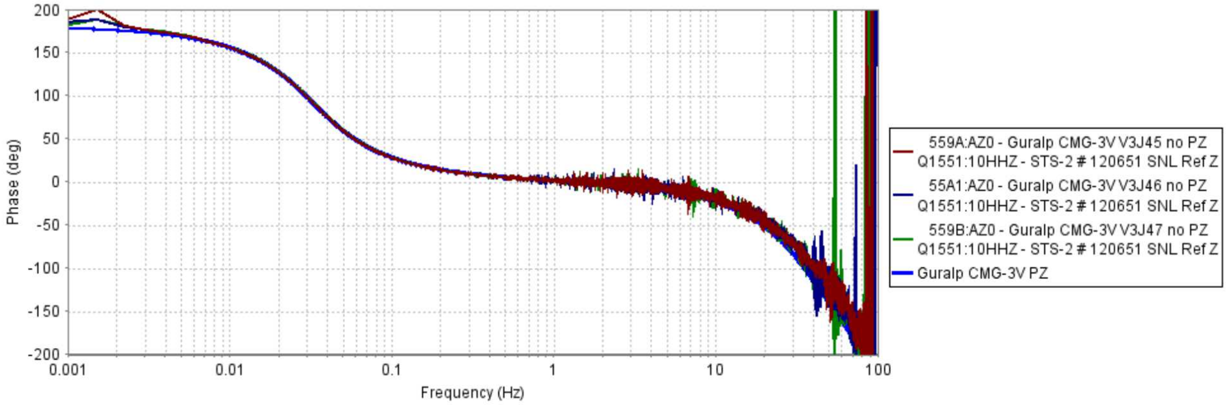


Figure 28 Low Frequency Phase Response

Note that the amplitude and phase response curves should only be interpreted for frequency pass-bands in which the observed coherence is high, in this case between 0.003 and 1 Hz. Across this pass-band the amplitude and phase response match very closely with the nominal CMG 3V response model, shown with a blue line.

3.4.4.2 Mid Frequency

The earthquake that was identified for use in determining the mid-frequency (0.1 – 1 Hz) response was a combination of two earthquakes that occurred in western Montana on July 6, 2017 as reported by the USGS. The first earthquake was a magnitude 5.8 located at 46.881 N, 112.575 W, a depth of 12.2 km, and at 06:30:17 (UTC). The second earthquake, approximately 5 minutes later, was a magnitude 5.0 located at 46.482 N, 112.658 W, a depth of 15.7 km, and at 06:35:35 (UTC).

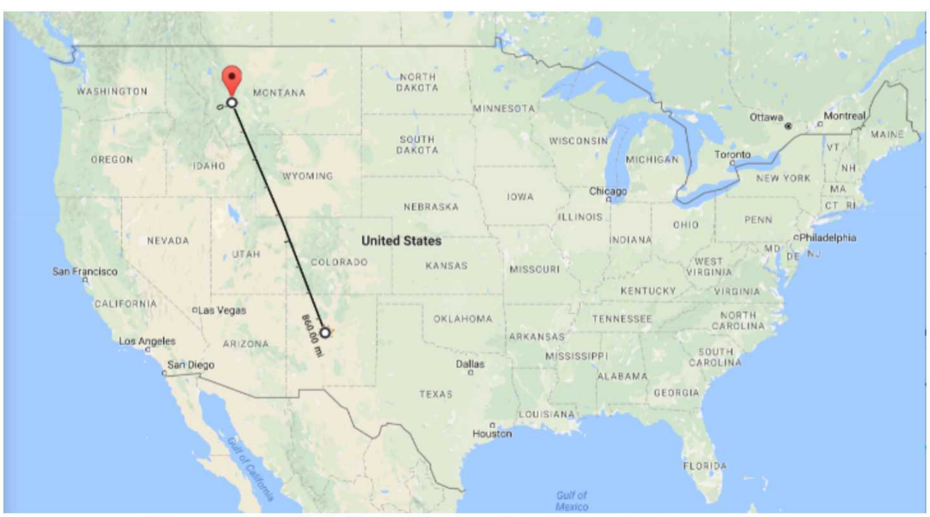


Figure 29 Mid Frequency Earthquake Location

This earthquake was approximately 860 (1384 km) miles from the Sandia FACT site and resulted in an observable waveform signal that lasted over 1 hour in duration.
The figure below shows the waveform time series for the recordings. The window regions bounded by the red lines indicate the segment of data used for analysis.

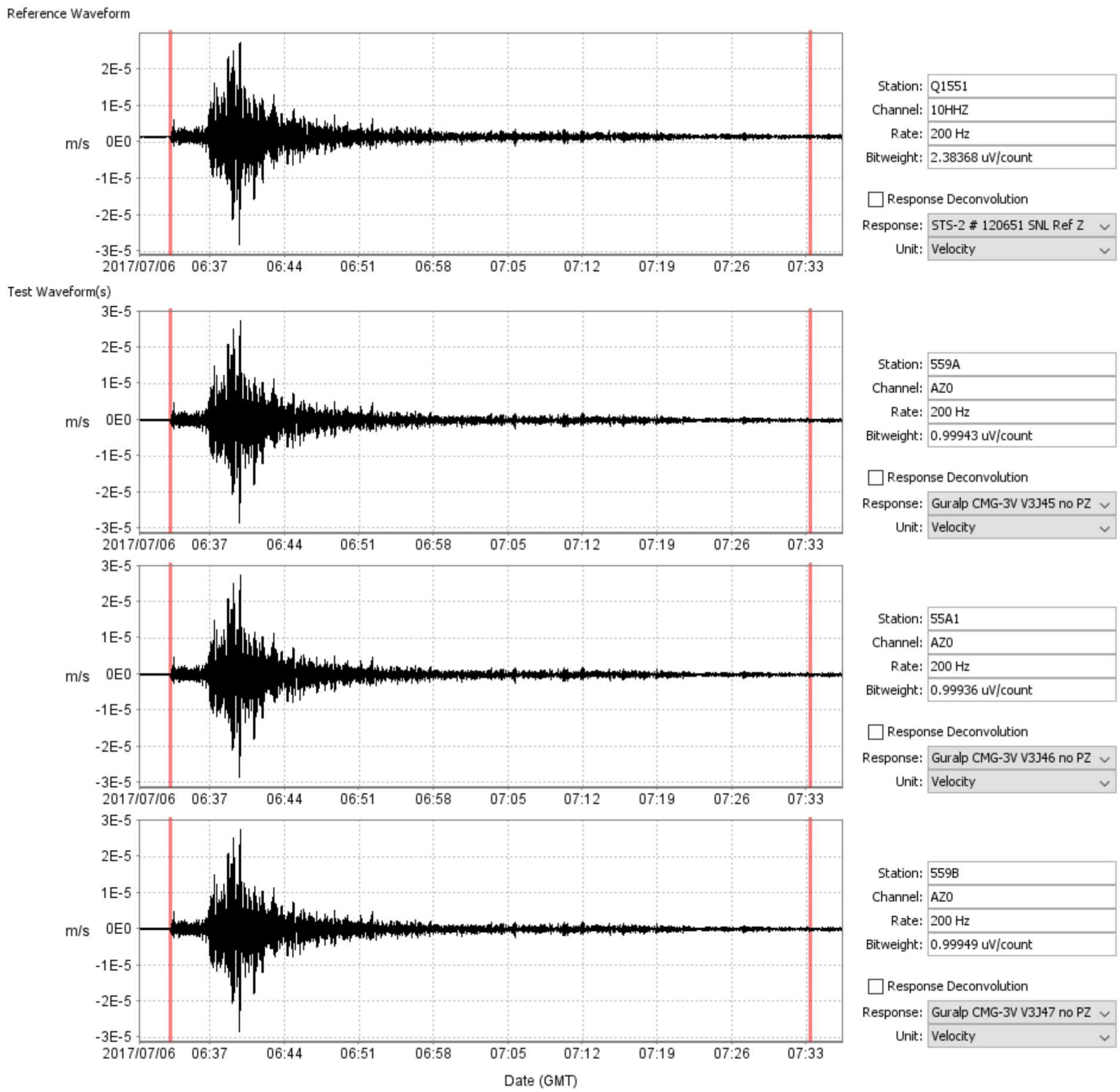


Figure 30 Mid Frequency Response Time Series

The figures below show the power spectra, coherence, amplitude response, and phase that were computed from the waveform time series.

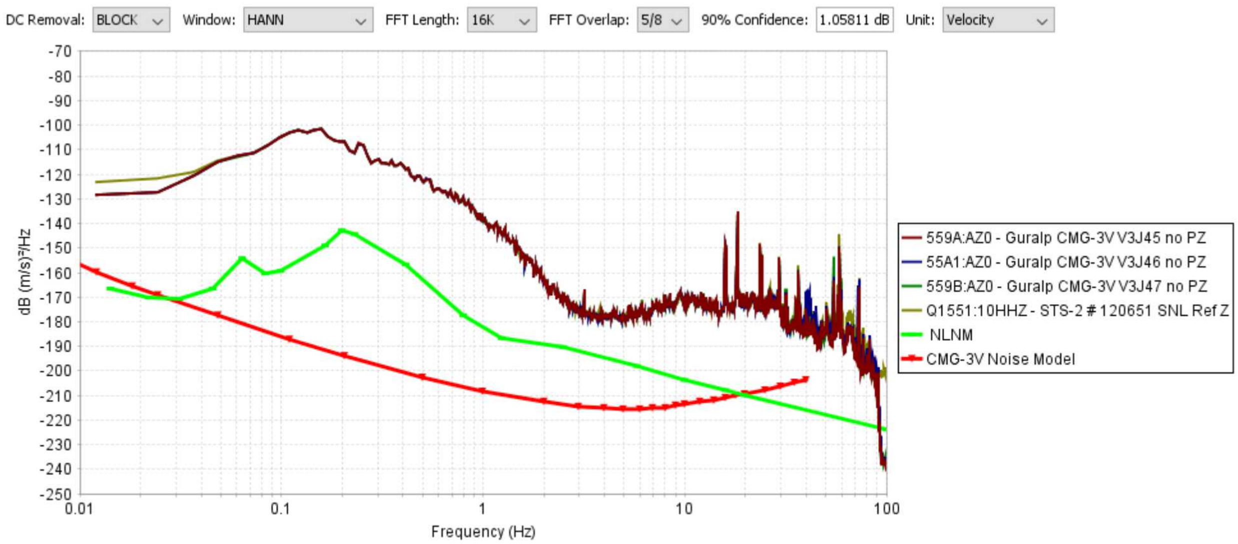


Figure 31 Mid Frequency Response Power Spectra

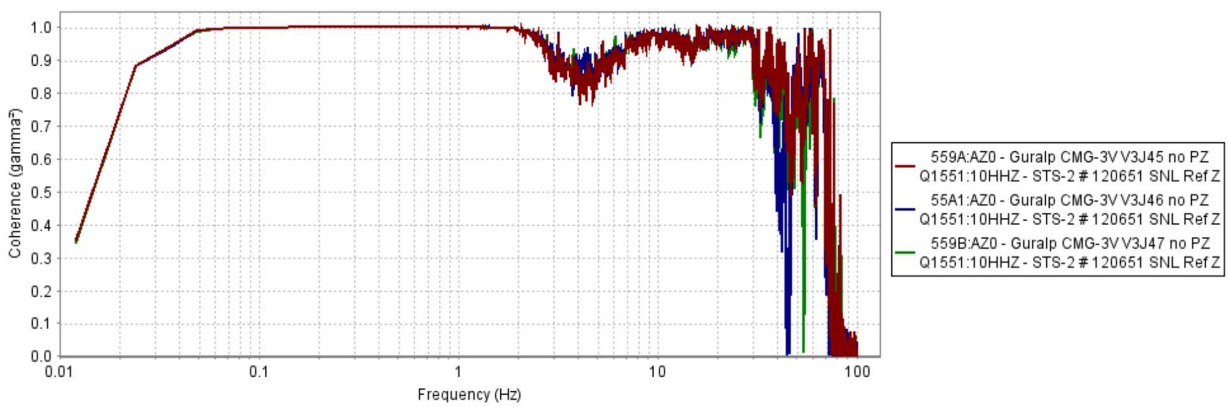


Figure 32 Mid Frequency Response Coherence

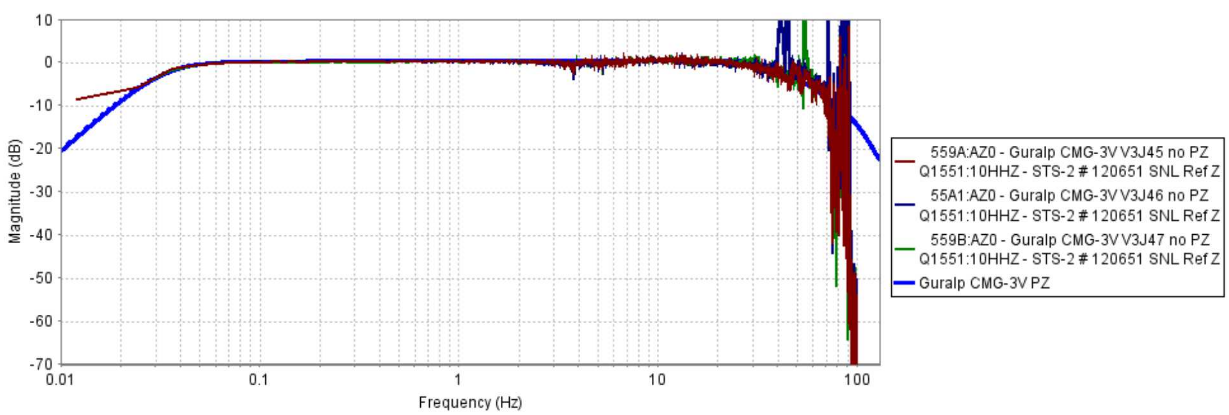


Figure 33 Mid Frequency Amplitude Response

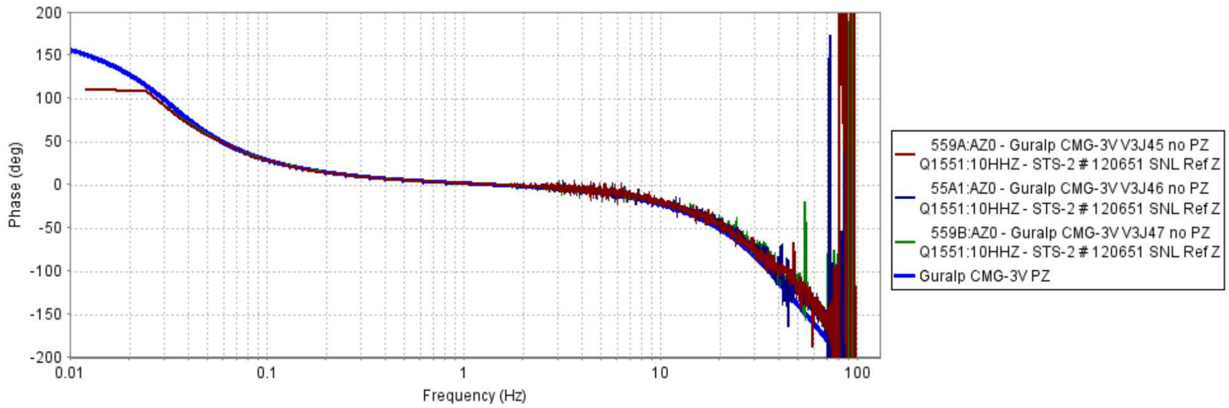


Figure 34 Mid Frequency Phase Response

Note that the amplitude and phase response curves should only be interpreted for frequency pass-bands in which the observed coherence is high, in this case between 0.07 and 2 Hz. Across this pass-band the amplitude and phase response match very closely with the nominal CMG 3V response model, shown with a blue line.

3.4.4.3 High Frequency

The earthquake that was identified for use in determining the high-frequency (> 1 Hz) response was reported by USGS as a magnitude 4.2 located at 35.859 N, 96.683 W, and a depth of 6.8 km on July 14, 2017 13:47 (UTC).

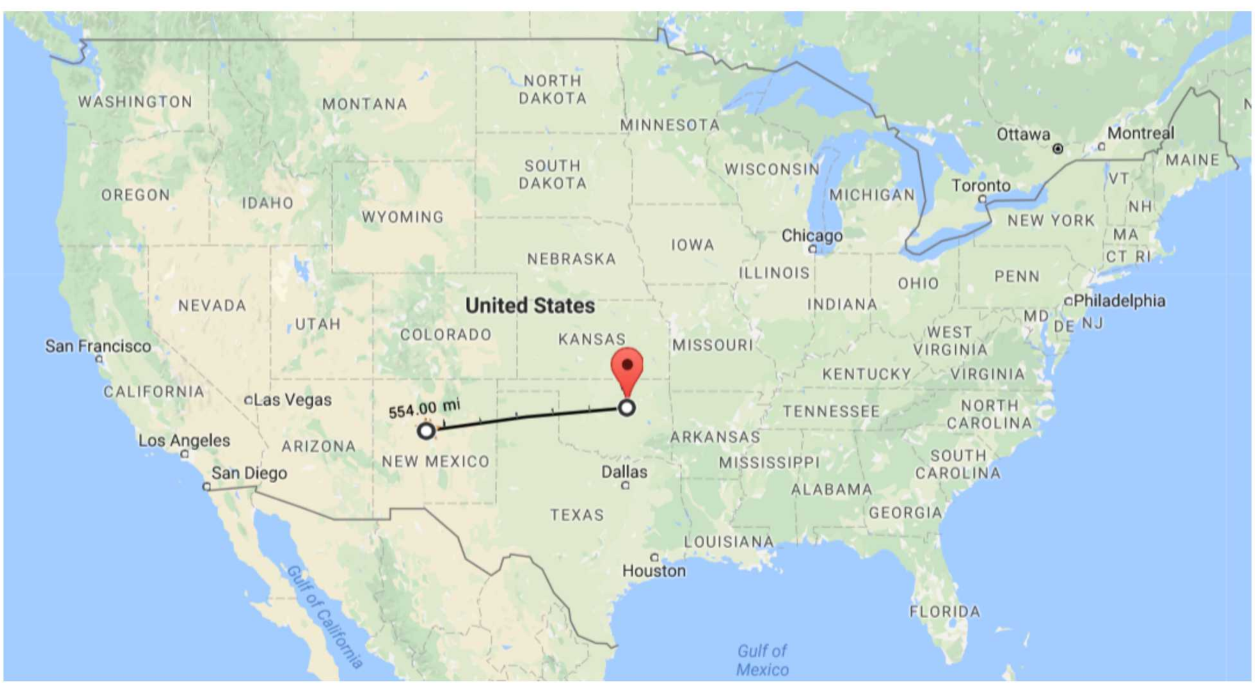


Figure 35 High Frequency Earthquake Location

This earthquake was approximately 554 miles (890 km) from the Sandia FACT site and resulted in an observable waveform signal that lasted 10 minutes in duration.

The figure below shows the waveform time series for the recordings. The window regions bounded by the red lines indicate the segment of data used for analysis.

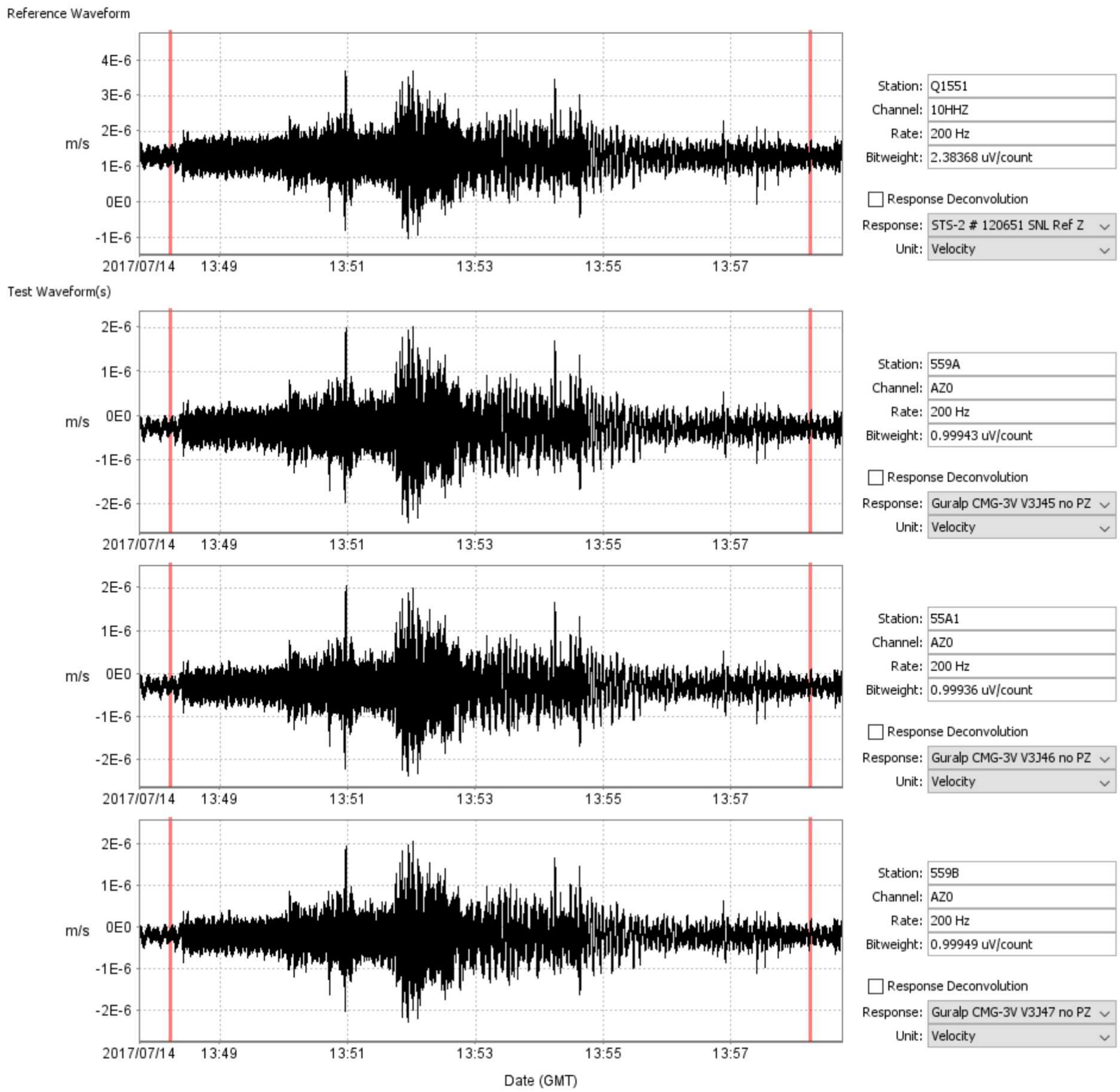


Figure 36 High Frequency Response Time Series

The figures below show the power spectra, coherence, amplitude response, and phase that were computed from the waveform time series.

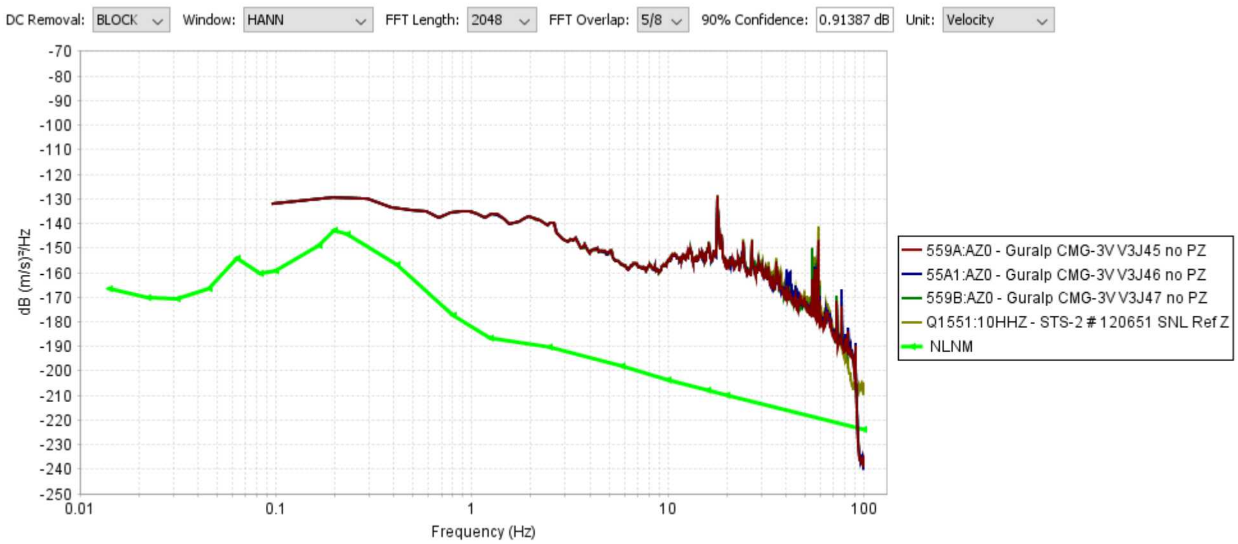


Figure 37 High Frequency Response Power Spectra

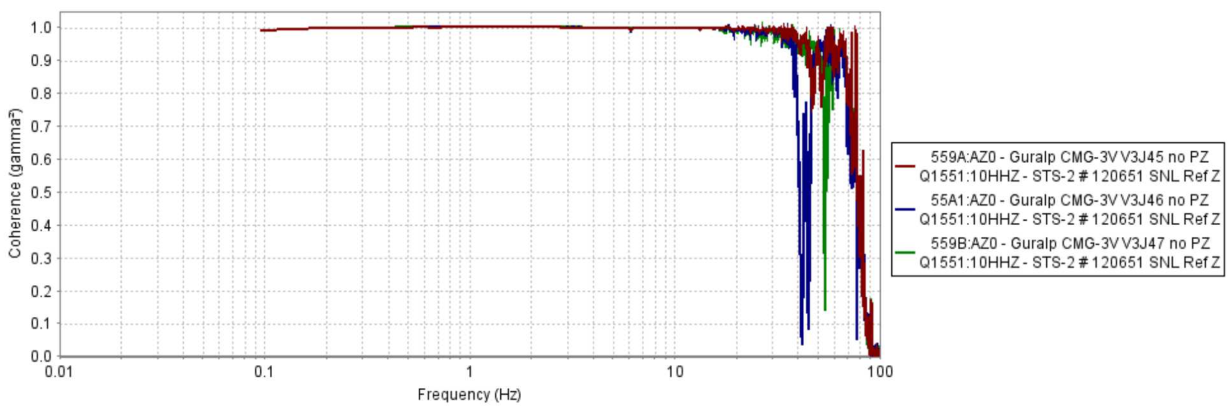


Figure 38 High Frequency Response Coherence

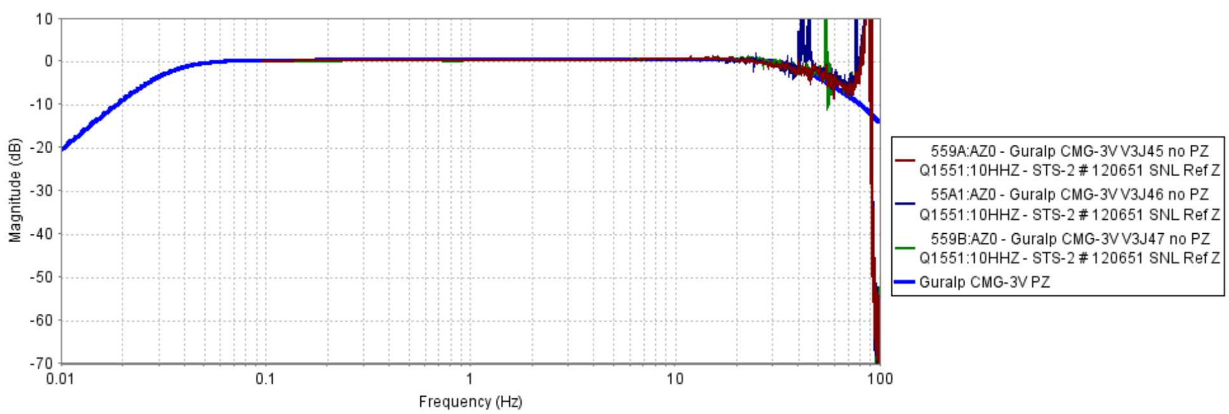


Figure 39 High Frequency Amplitude Response

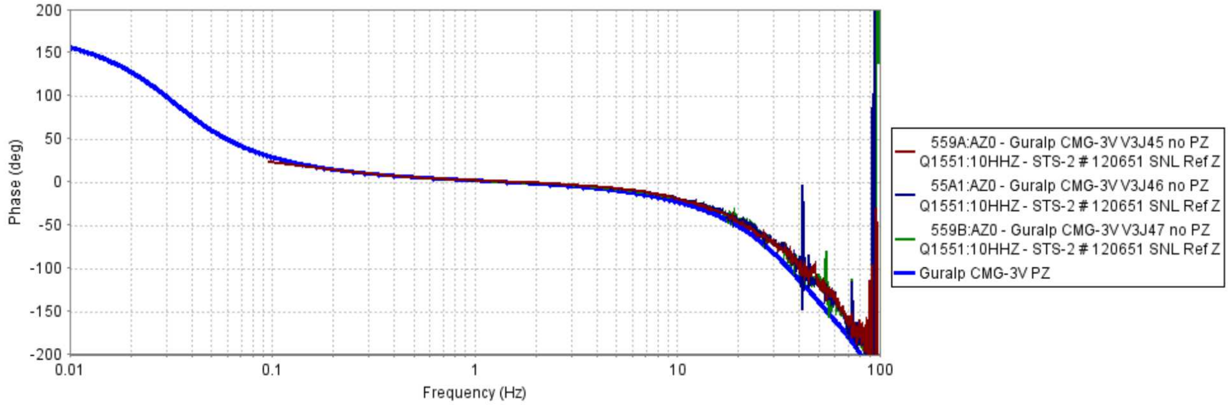


Figure 40 High Frequency Phase Response

Note that the amplitude and phase response curves should only be interpreted for frequency pass-bands in which the observed coherence is high, in this case between 0.1 and 30 Hz. Across this pass-band the amplitude and phase response match very closely with the nominal CMG 3V response model, shown with a blue line.

3.5 Passband

The Passband test measures the bandwidth of the seismometer determined from the measured amplitude response.

3.5.1 Measurand

The quantity being measured is the low and high frequency limits of the sensor's passband.

3.5.2 Configuration

The sensor under test and a reference sensor with known response characteristics are co-located so that they are both measuring a common earth motion.

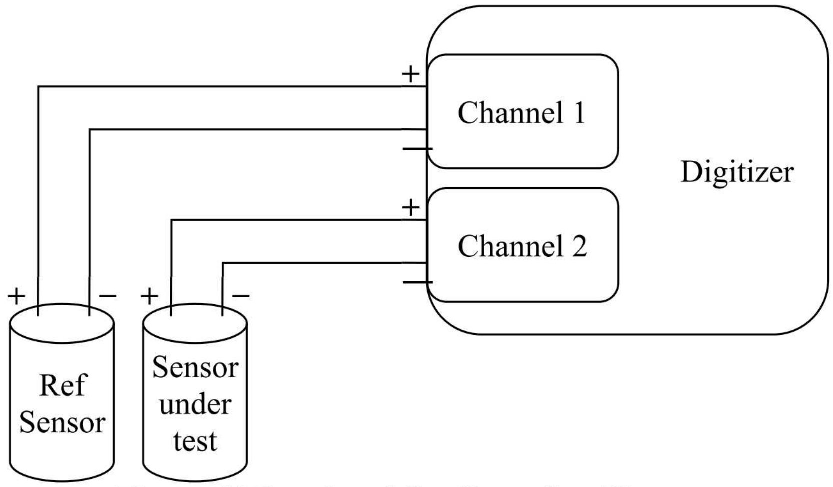


Figure 41 Passband Configuration Diagram

The sensors are allowed to stabilize and then are operated until suitable ground-motion from an earthquake is recorded to provide high coherence between the sensors at the calibration frequency of 1 Hz.

Table 14 Passband Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	Kinematrics STS-2	# 120651	1500 V/(m/s)
Reference Digitizer	Kinematrics Q330	# 1551	200 Hz, 40 Vpp
Sensor under test	Guralp CMG-3V	# V3J45, V3J46, V3J47	20 kV/(m/s)
Sensor Digitizers	Guralp Affinity	# 559A, 55A1, 559B	200 Hz, 40 Vpp

The digitizer records the output of the reference sensor and the sensor under test simultaneously. The reference sensor recording is used for comparison against the sensor under test recording.

3.5.3 Analysis

The data recorded using the reference sensor and digitizer has the calibrated bit-weight, sensitivity, and response model applied to convert the data to ground motion.

The data recorded using the sensor under test and digitizer has just the calibrated bit-weight and sensitivity applied to convert the data to ground motion. The response model shape is not applied so that any resulting amplitude or phase response may be observed and compared to the reference.

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

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

The frequencies at which the response is down 3 dB are measured.

3.5.4 Result

The figures below show the expanded sections of the low and high frequency passband roll-off from the amplitude response data along with the nominally expected response drawn in light blue.

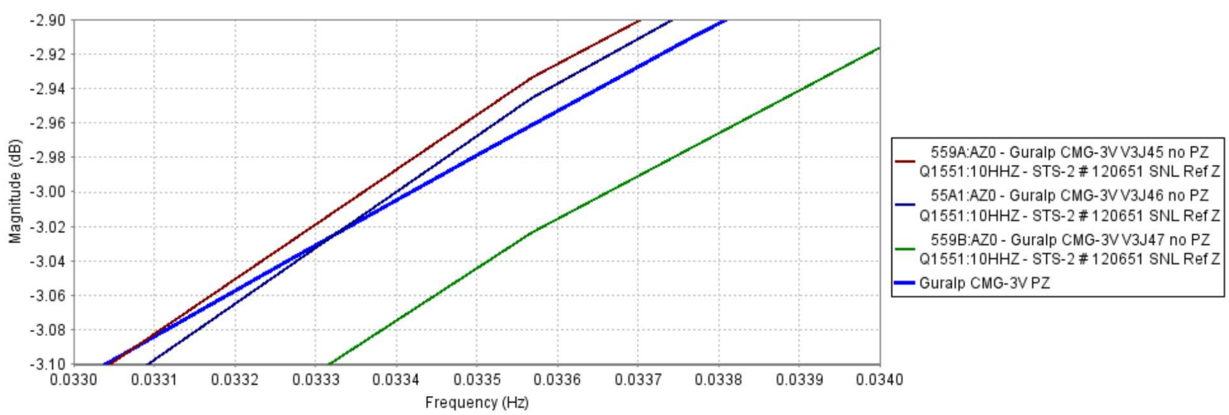


Figure 42 Passband Low Frequency

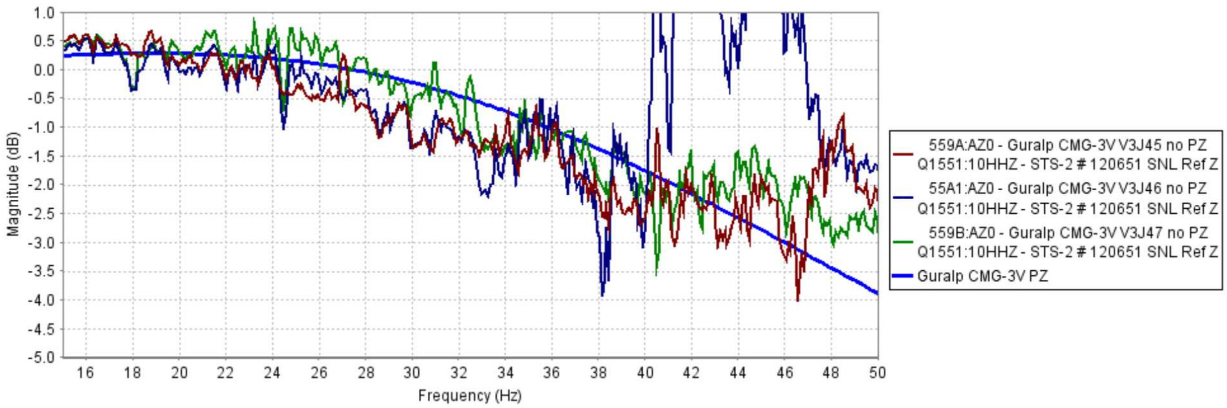


Figure 43 Passband High Frequency

The amplitude response from the Response Verification tests are reviewed to determine at what frequencies the amplitude response is reduce by 3 dB from the sensitivity at 1 Hz.

Table 15 Passband

	Low Frequency	High Frequency
Nominal	0.0334 Hz (30 sec)	50 Hz
CMG-3V #V3J45	0.0334 Hz	> 40 Hz
CMG-3V #V3J46	0.0334 Hz	> 40 Hz
CMG-3V #V3J47	0.0337 Hz	> 40 Hz

We can observe that the low frequency corner matches very closely with the nominal 30 second, or 0.0333 Hz, corner specified for the CMG-3V. Due to the data available, it is difficult to evaluate outside of the region in which there is coherence. However, it appears that the high frequency corner exceeds 40 Hz.

3.6 Calibrator Sensitivity

The Calibrator Sensitivity test is used to measure the sensitivity of the seismometer calibrator.

3.6.1 Measurand

The quantity being measured is the seismometer calibration sensitivity at 1 Hz.

3.6.2 Configuration

The seismometer is connected to a digitizer. The digitizer both recorded the seismometer output and provides a calibration signal that is internally looped back and recorded as shown in the diagram below.

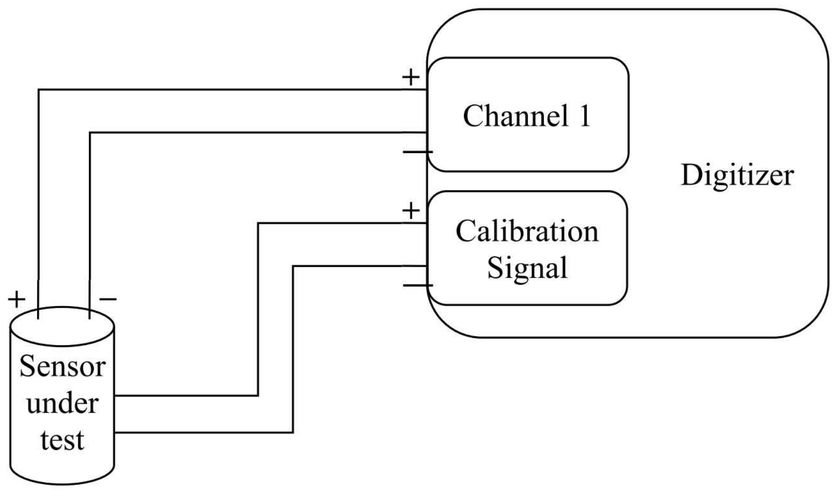


Figure 44 Calibrator Sensitivity Configuration Diagram

Table 16 Calibrator Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Sensor under test	Guralp CMG-3V	# V3J45, V3J46, V3J47	20 kV/(m/s)
Sensor Digitizers	Guralp Affinity	# 559A, 55A1, 559B	200 Hz, 40 Vpp

The digitizer is configured to generate a 1 Hz sinusoid for a minimum of 1 minute.

3.6.3 Analysis

A minimum of a 10 cycles, or 10 seconds at 1 Hz, of data is defined 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:

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

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

The seismometer calibrator sensitivity in V/(m/s^2) is computed:

$$G_{calib} = \frac{V_{in}}{\frac{V_{out}}{G_{seis}} * 2\pi f}$$

3.6.4 Result

The Guralp Affinity digitizers have the ability to generate a variety of signals for calibration (Sinsuoidal, Broadband, and Step). In addition, the Affinity digitizers reserve a separate fourth 24-bit channel for looping back the recorded calibration signal without having to re-purpose an existing recording channel.

The figure below shows a representative waveform time series for the recording made of the seismometer calibration. The window regions bounded by the blue lines indicate the segment of data used for analysis. The figure from only one seismometer is shown as the remaining figures are otherwise identical in appearance.

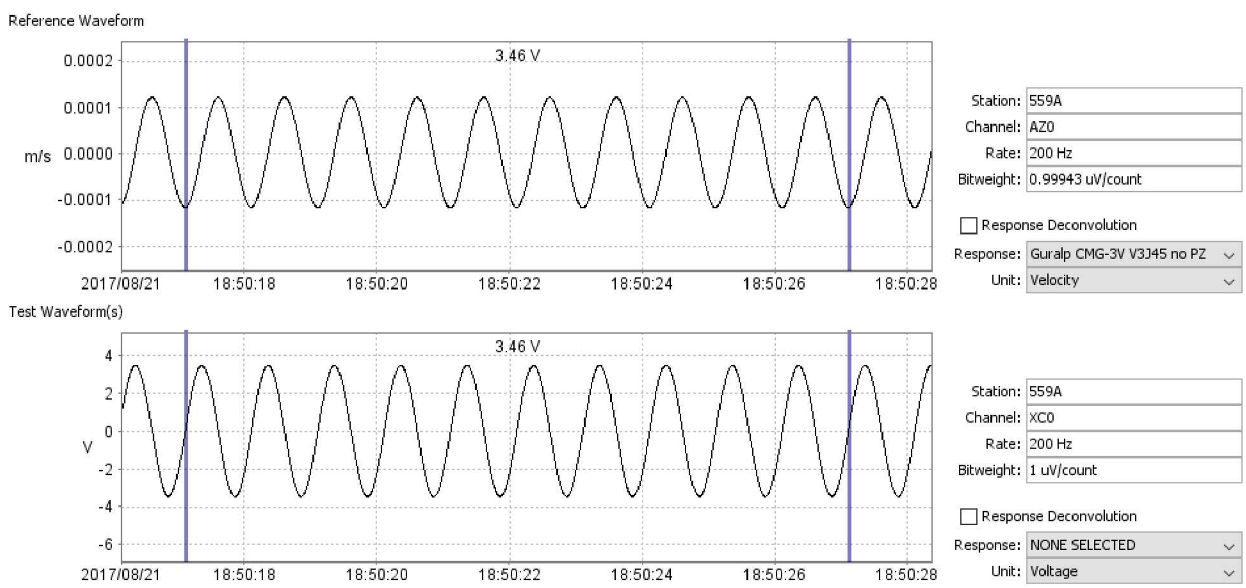


Figure 45 Calibrator Sensitivity Time Series

The following table contains the computed calibration sensitivities.

Table 17 Calibrator Sensitivity

	CMG-3V #V3J45	CMG-3V #V3J46	CMG-3V #V3J47
Input Voltage (Vin)	3.4641 V	3.4561 V	3.4628 V
Input Frequency (f)	1.0 Hz	1.0 Hz	1.0 Hz
Output Voltage (Vout)	2.4927 V	2.4245 V	2.4132 V
Seismometer Sensitivity (Gseis)	20960 V/(m/s)	20160 V/(m/s)	20490 V/(m/s)
Output Velocity	1.190E-4 m/s	1.203E-4 m/s	1.178E-4 m/s
Calibrator Sensitivity (Gcalib)	4634 V/(m/s^2)	4574 V/(m/s^2)	4680 V/(m/s^2)

3.7 Calibrator Frequency Response Verification

The Calibrator Frequency Response Verification tests measured the amplitude and phase response of the seismometer calibrator over a frequency band of interest.

3.7.1 Measurand

The quantity being measured is the seismometer calibration frequency response.

3.7.2 Configuration

The seismometer is connected to a digitizer. The digitizer both records the seismometer output and provides a calibration signal that is internally looped back and recorded as shown in the diagram below.

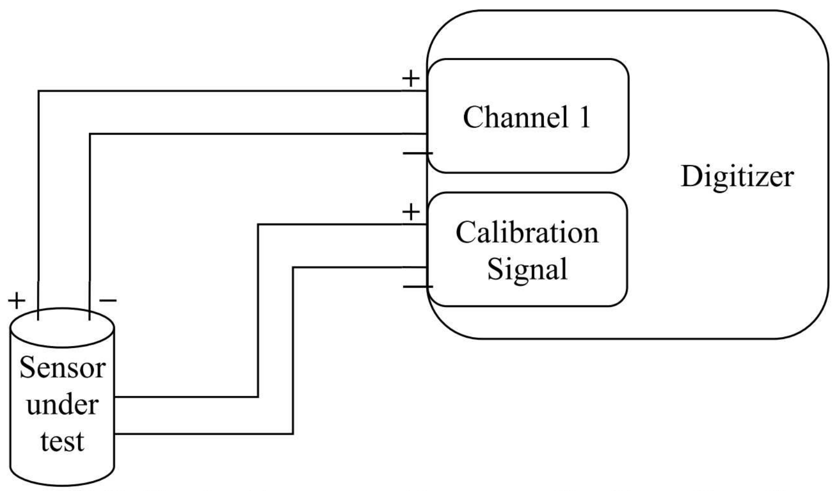


Figure 46 Calibrator Frequency Response Configuration Diagram

Table 18 Calibrator Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Sensor under test	Guralp CMG-3V	# V3J45, V3J46, V3J47	20 kV/(m/s)
Sensor Digitizers	Guralp Affinity	# 559A, 55A1, 559B	200 Hz, 40 Vpp

The digitizer is configured to generate a white noise signal with an amplitude of approximately +/- 1 V for a minimum of one hour.

3.7.3 Analysis

The data recorded using the seismometer output and digitizer has the calibrated bit-weight, sensitivity, and response model applied to convert the data to ground motion corrected for the response shape.

The data recorded from the calibrator loopback has the bit-weight and calibration sensitivity applied to convert the input calibration to ground motion. Note that the calibrator results in an acceleration of the seismometer proof-mass and the seismometer output is in velocity, therefore a conversion between acceleration and velocity is necessary to compare the two signals.

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

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

3.7.4 Result

The figure below shows a representative waveform time series for the recording made of the seismometer calibration. The window regions bounded by the red lines indicate the segment of data used for analysis. The figures from only one seismometer are shown as the remaining figures are otherwise identical in appearance.

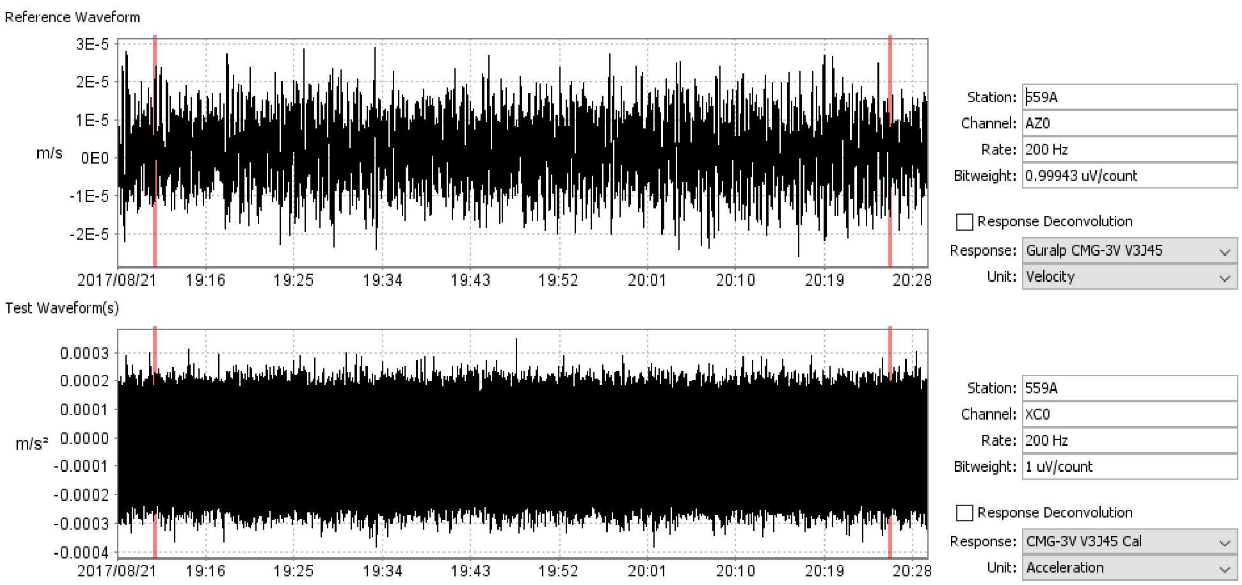


Figure 47 Calibrator Frequency Response Time Series

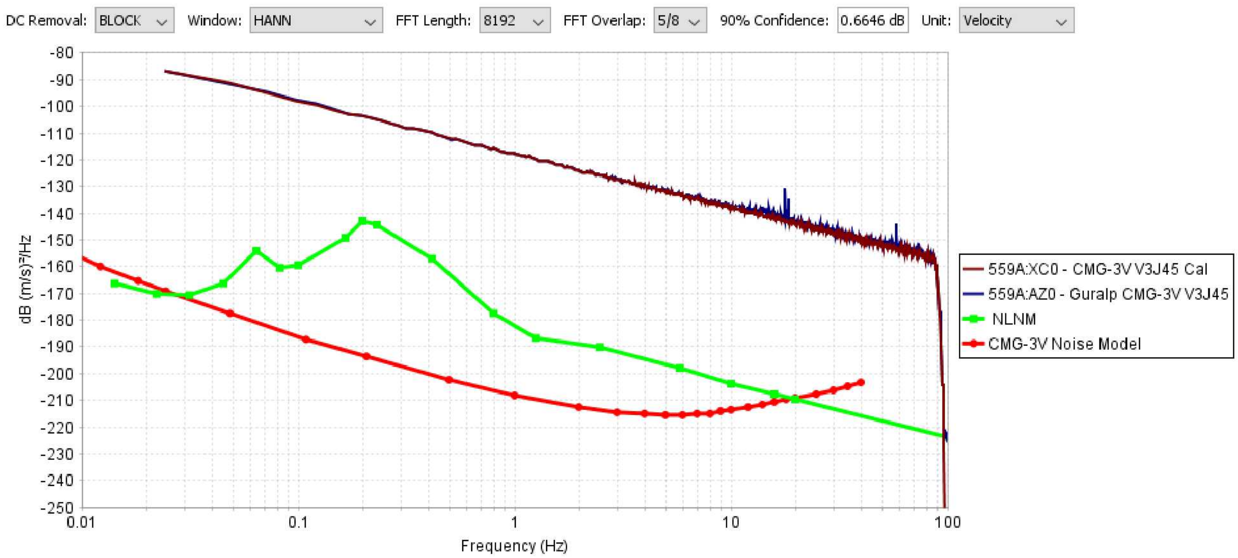


Figure 48 Calibrator Frequency Response Power Spectra

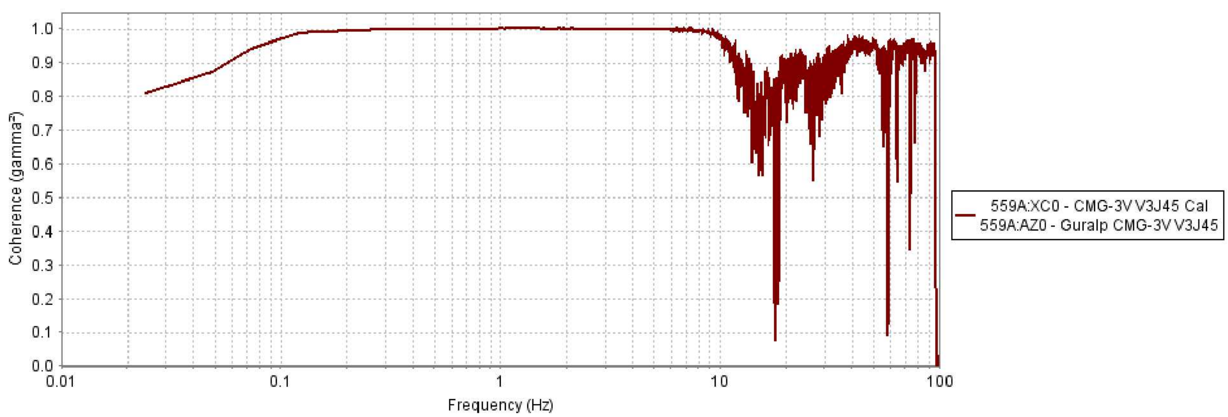


Figure 49 Calibrator Frequency Response Coherence

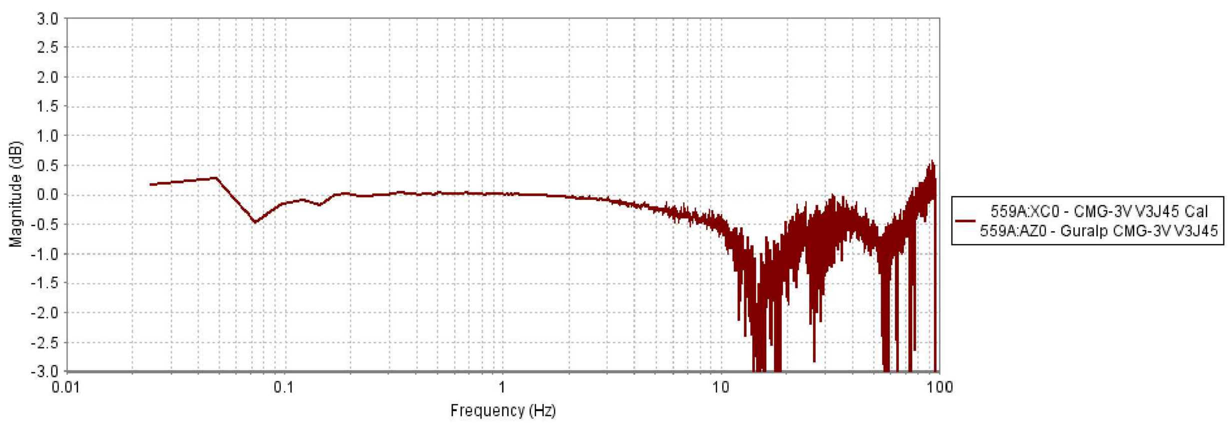


Figure 50 Calibrator Frequency Response Amplitude Response

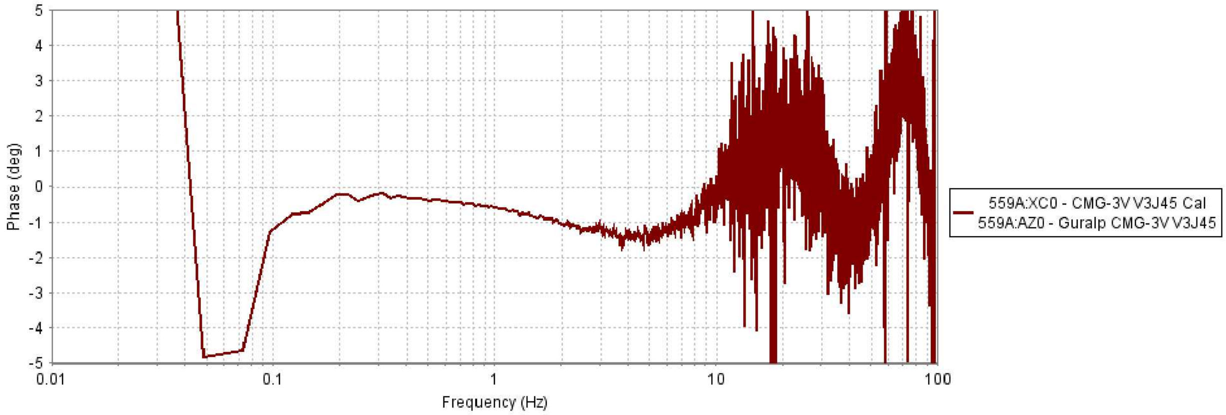


Figure 51 Calibrator Frequency Response Phase Response

The calibrator frequency response values are shown in the table below for dB of power (20 $\log_{10}$) relative to the previously determined calibrator sensitivity and degrees of phase.

Table 19 Calibrator Frequency Response

	CMG-3V #V3J45		CMG-3V #V3J45		CMG-3V #V3J46	
Frequency	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0.1000 Hz	-0.17 dB	-1.32 deg	-0.25 dB	-1.15 deg	-0.31 dB	-1.69 deg
0.1250 Hz	-0.11 dB	-0.78 deg	-0.25 dB	-0.92 deg	-0.21 dB	-0.97 deg
0.1600 Hz	-0.02 dB	-0.49 deg	-0.16 dB	-0.47 deg	-0.08 dB	-0.46 deg
0.2000 Hz	-0.02 dB	-0.24 deg	-0.07 dB	-0.43 deg	-0.08 dB	-0.37 deg
0.2500 Hz	-0.03 dB	-0.32 deg	-0.04 dB	-0.43 deg	-0.01 dB	-0.33 deg
0.3150 Hz	0.00 dB	-0.23 deg	0.01 dB	-0.30 deg	-0.01 dB	-0.38 deg
0.4000 Hz	0.01 dB	-0.35 deg	0.00 dB	-0.35 deg	0.00 dB	-0.41 deg
0.5000 Hz	0.02 dB	-0.40 deg	0.01 dB	-0.37 deg	0.01 dB	-0.43 deg
0.6300 Hz	0.01 dB	-0.47 deg	0.00 dB	-0.45 deg	0.01 dB	-0.46 deg
0.8000 Hz	0.01 dB	-0.53 deg	0.00 dB	-0.53 deg	0.01 dB	-0.55 deg
1.0000 Hz	0.00 dB	-0.62 deg	0.00 dB	-0.63 deg	0.00 dB	-0.64 deg
1.2500 Hz	-0.01 dB	-0.73 deg	-0.01 dB	-0.73 deg	-0.01 dB	-0.77 deg
1.6000 Hz	-0.03 dB	-0.88 deg	-0.03 dB	-0.85 deg	-0.03 dB	-0.91 deg
2.0000 Hz	-0.05 dB	-1.04 deg	-0.05 dB	-1.01 deg	-0.05 dB	-1.10 deg
2.5000 Hz	-0.08 dB	-1.19 deg	-0.07 dB	-1.17 deg	-0.08 dB	-1.20 deg
3.1500 Hz	-0.12 dB	-1.27 deg	-0.12 dB	-1.31 deg	-0.11 dB	-1.43 deg
4.0000 Hz	-0.19 dB	-1.45 deg	-0.17 dB	-1.42 deg	-0.17 dB	-1.57 deg
5.0000 Hz	-0.25 dB	-1.41 deg	-0.25 dB	-1.47 deg	-0.25 dB	-1.62 deg
6.3000 Hz	-0.33 dB	-1.21 deg	-0.32 dB	-1.32 deg	-0.33 dB	-1.57 deg
8.0000 Hz	-0.41 dB	-0.81 deg	-0.42 dB	-1.00 deg	-0.42 dB	-1.14 deg
10.0000 Hz	-0.55 dB	-0.24 deg	-0.62 dB	-0.35 deg	-0.61 dB	-0.80 deg

The amplitude response was found to identically match the calibrator sensitivity measured when using a sinusoidal tone, as indicated by the 0 dB amplitude response at 1 Hz. Examining the amplitude and phase response of the calibrator over 0.1 to 10 Hz, there does appear to be a slight roll-off in the amplitude and phase response. However, no poles and zeros were provided with the Guralp CMG-3V sensors against which to compare the calibrator response.

4 SUMMARY

Sensitivity
The CMG-3V seismometers were found to have sensitivities at 1 Hz of 20.96 kV/(m/s), 20.16 kV/(m/s), and 20.49 kV/(m/s) for units V3J45, V3J46, and V3J47, respectively. These values differ by between 0.8 % and 4.75 % of the nominal 20 kV/(m/s) and between 2.55 % and 4.29 % of the manufacturer calibration sheet.

Self-Noise
All three CMG-3V seismometers exhibited self-noise levels that are consistent with the manufacturer's nominal noise model. Self-noise levels were observed to be below the seismic low noise model between 0.04 Hz – 8 Hz. Note that above 3 Hz, local site-noise impacted the ability to fully resolve the instrument self-noise and that actual instrument self-noise may be lower than observed.

Dynamic Range
The seismometers were found to have a dynamic range across 0.02 – 16 Hz of between 111 and 114.6 dB.

Frequency Response Verification
The seismometers were found to have a frequency response that closely matched the manufacturers nominal response model.

Passband
All three seismometers were found to have a low frequency limit consistent with the nominal 0.0334 Hz. V3J45 and V3J46 matched this lower limit exactly while V3J47 had a slightly higher corner of 0.0337 Hz. Due to the limitation of the data available, the high frequency corner was found to exceed a minimum of 40 Hz.

Calibrator Sensitivity
The CMG-3V seismometers were found to have calibrator sensitivities at 1 Hz of 4634 V/(m/s^2), 4574 V/(m/s^2), and 4680 V/(m/s^2) for units V3J45, V3J46, and V3J47, respectively.

Calibrator Response Verification
The CMG-3V seismometer calibration frequency responses were able to be measured over 0.1 Hz to 10 Hz. The resulting amplitude response matched nearly identically at 1 Hz the values obtained from the Calibrator Sensitivity test.

REFERENCES

1. Guralp, *CMG-3V / 3ESPV Vertical Borehole Seismometers*, Document Number: MAN-BHO-0004, Issue B, May 10, 2006.

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

3. Hutt, C.R., Evans, J.R., Followill, F., Nigbor, R.L., and Wielandt, E., *Guidelines for Standardized Testing of Broadband Seismometers and Accelerometers*, USGS Open-File Report 2009-1295.

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

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

6. JCGM 200:2012 - International vocabulary of metrology -- Basic and general concepts and associated terms. 2012: BIPM.

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

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

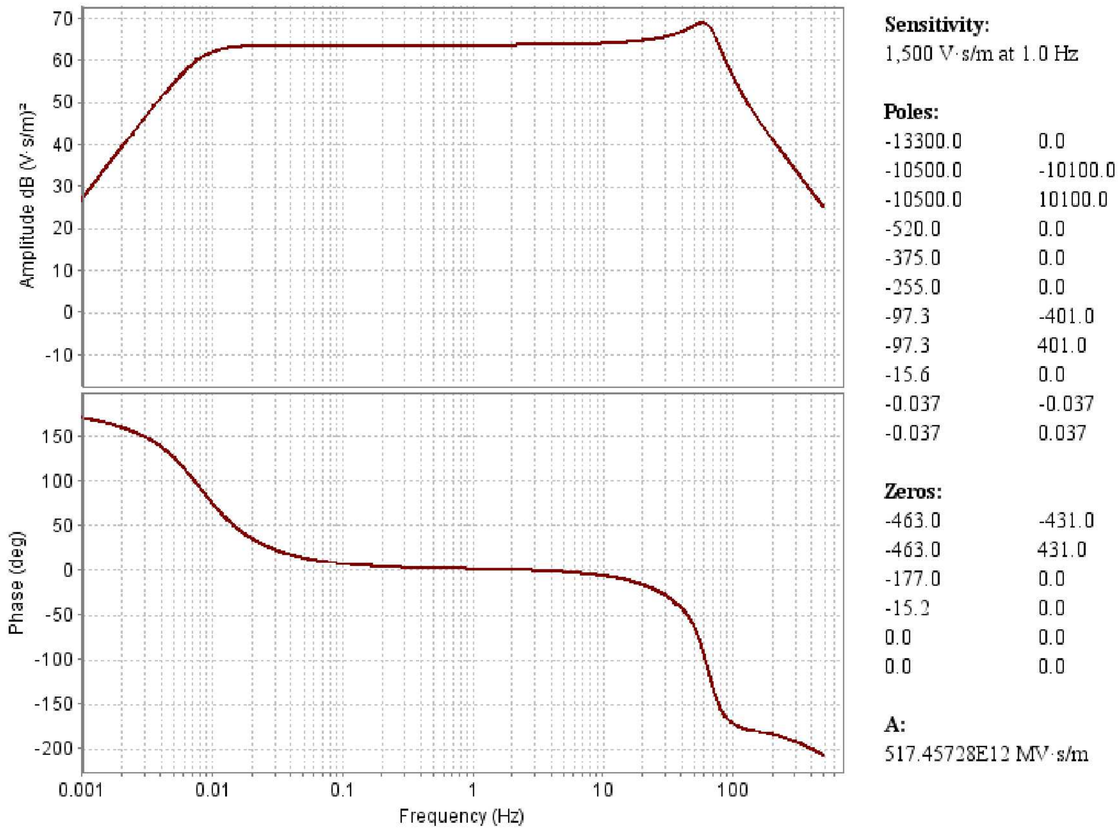
9. Merchant, B. John, and Darren M. Hart (2011), *Component Evaluation Testing and Analysis Algorithms*, SAND2011-8265.

10. 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

Kinematics STS-2 #120651 SNL Reference Response

The SNL reference STS-2 #120651 is a 3rd generation STS with poles and zeros as shown below:

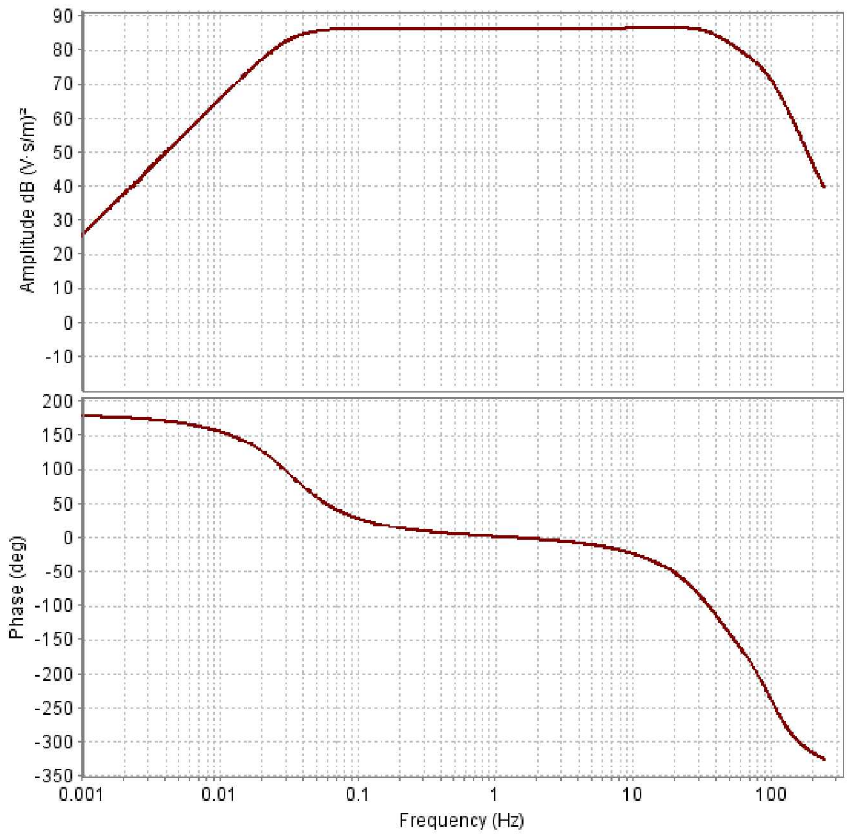


The reference STS-2 was calibrated at the USGS Albuquerque Seismic Laboratory (ASL) in November, 2016 using their step-table, a Lennartz CT-E1 step calibration table. The resulting sensitivities at 1 Hz for the reference STS-2 #120651 are shown below:

Axis	Sensitivity at 1 Hz
Z	1495.51 V/(m/s)
N	1488.72 V/(m/s)
E	1,492.25 V/(m/s)

Guralp CMG-3V Response

The CMG-3V poles and zeros, provided by Guralp, along with the custom sensitivity of 20kV/(m/s) are shown below.



Sensitivity:
20 kV·s/m at 1.0 Hz

Poles:

-265.4017474	595.0176486
-265.4017474	-595.0176486
-158.1477742	184.3486569
-158.1477742	-184.3486569
-0.148283173	0.148283173
-0.148283173	-0.148283173

Zeros:

0.0	0.0
0.0	0.0

A:
500.76834E6 MV·s/m

APPENDIX B: CALIBRATION SHEETS

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

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: 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

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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.
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~


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

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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	10.000220	9.99552	10.00043	10.00492	V	>10	4	
10.00000 V @ 20 kHz	10.000190	9.99549	9.99959	10.00489	V	>10	13	
10.00000 V @ 50 kHz	10.000207	9.99001	10.00030	10.01041	V	>10	1	
10.00000 V @ 100 kHz	9.999795	9.97960	9.99935	10.01999	V	>10	2	
10.00000 V @ 300 kHz	10.001654	9.90064	9.99865	10.10267	V	>10	3	
100.0000 V @ 10 Hz	100.00266	99.8007	100.0055	100.2047	V	>10	1	
100.0000 V @ 40 Hz	100.00218	99.9552	100.0044	100.0492	V	>10	5	
100.0000 V @ 20 kHz	100.00295	99.9559	100.0003	100.0500	V	>10	6	
100.0000 V @ 50 kHz	100.00901	99.9070	100.0129	100.1110	V	>10	4	
100.0000 V @ 100 kHz	100.01336	99.8113	100.0096	100.2154	V	>10	2	
100.0000 V @ 200 kHz	100.06044	99.0498	100.0300	101.0710	V	>10	3	
700.0000 V @ 40 Hz	700.01590	699.4359	700.0061	700.5959	V	>10	2	
700.0000 V @ 20 kHz	700.02470	699.4447	699.7809	700.6047	V	>10	42	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000099	10.005000	Hz	>10	2	
40.00000 Hz @ 1 V		39.996000	40.000416	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	500.003401	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	8.0000558	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

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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;
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Authorization

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

End-of-Document

Guralp CMG-3V #V3J45

CMG-3V CALIBRATION SHEET

WORKS ORDER:	20349	DATE:	28-Jun-2016
SERIAL NUMBER:	V3J45	TESTED BY:	P. Kenna

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 10044	1345	0.02637

Power Consumption: 100mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.

Guralp CMG-3V #V3J46

CMG-3V CALIBRATION SHEET

WORKS ORDER:	20349	DATE:	29-Jun-2016
SERIAL NUMBER:	V3J46	TESTED BY:	S. Goddard

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 9829	870	0.02637

Power Consumption: 100mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.

Guralp CMG-3V #V3J47

CMG-3V CALIBRATION SHEET

WORKS ORDER:	20349	DATE:	29-Jun-2016
SERIAL NUMBER:	V3J47	TESTED BY:	S. Goddard

	Velocity Output V/m/s (Differential)	Mass Position Output (Acceleration output) $V/m/s^2$	Feedback Coil Constant $Amp/m/s^2$
VERTICAL	2 x 9915	886	0.02684

Power Consumption: 100mA @ +12V input
Calibration Resistor: 51000

NOTE: A factor of 2 x must be used when the sensor outputs are used differentially (also known as push-pull or balanced output). Under no conditions should the negative outputs be connected to the signal ground. A separate signal ground pin is provided.

Distribution

1	MS0899	Technical Library	9536 (electronic copy)

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