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SAND2017-11186
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Printed October 2017

Next Generation Qualification: Nanometrics T120PH Seismometer Evaluation

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Ground-Based Monitoring R&E
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Abstract

Sandia National Laboratories has tested and evaluated three seismometers, the Trillium 120PH, manufactured by Nanometrics. These seismometers measure broadband ground velocity using a UVW configuration with feedback control in a mechanically levelled borehole package. The purpose of the seismometer evaluation was to determine a measured sensitivity, response, self-noise, dynamic range, and self-calibration ability. The Nanometrics Trillium 120PH seismometers are being evaluated for the U.S. Air Force 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

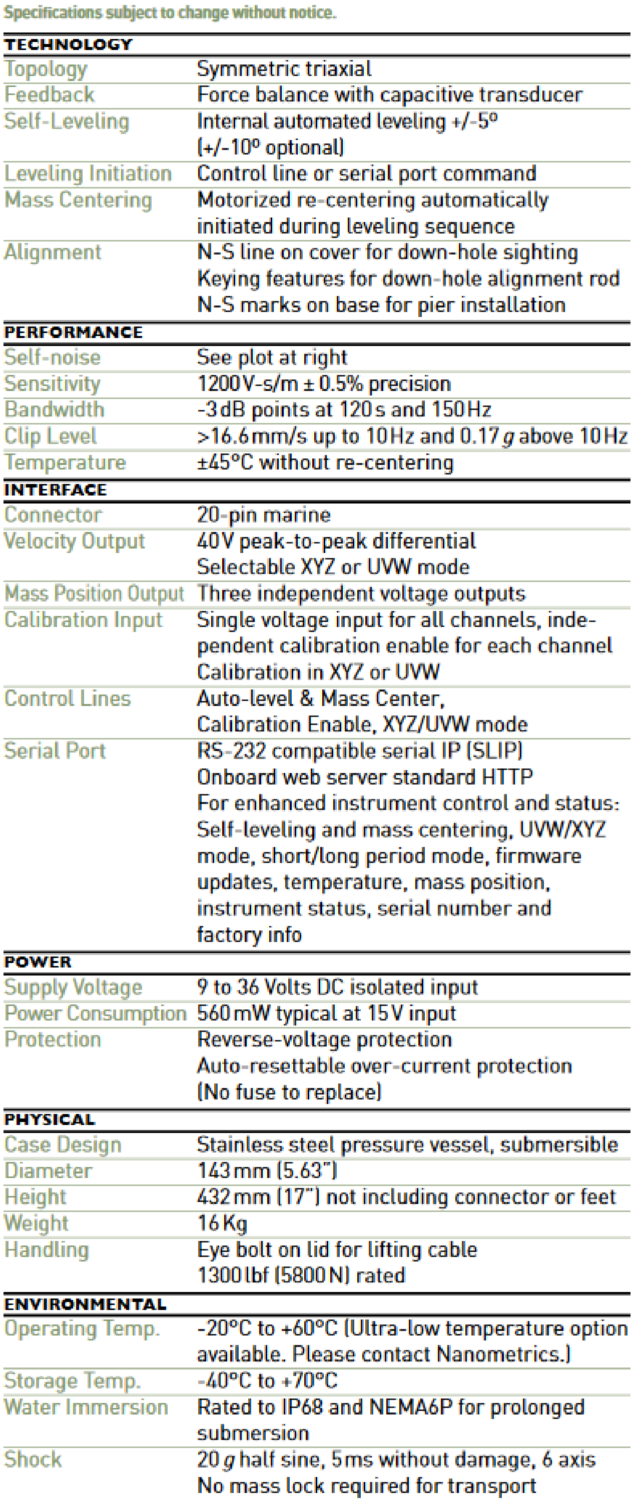
BB	Broadband
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
HNM	High Noise Model
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories
SP	Short-period

1 INTRODUCTION

The evaluation of the three Nanometrics Trillium 120PH seismometers, serial numbers 1019, 1020, and 1021 was performed to determine the performance characteristics of the instruments including sensitivity, self-noise, dynamic range, frequency response, and passband.

Figure 1 Nanometrics Trillium 120PH (Nanometrics website)

The Trillium 120PH seismometer measures 3-axes of ground motion across a customizable passband, in this case 0.00833 Hz (120 seconds) – 150 Hz, and a sensitivity of 1500 V/(m/s). The seismometer is contained within a borehole package and typically installed with a hole-lock. For the purpose of this evaluation, the seismometers were installed in a vault configuration alongside a reference sensor.



Specifications subject to change without notice.

TECHNOLOGY	
Topology	Symmetric triaxial
Feedback	Force balance with capacitive transducer
Self-Leveling	Internal automated leveling +/-5º (+/-10º optional)
Leveling Initiation	Control line or serial port command
Mass Centering	Motorized re-centering automatically initiated during leveling sequence
Alignment	N-S line on cover for down-hole sighting Keying features for down-hole alignment rod N-S marks on base for pier installation
PERFORMANCE	
Self-noise	See plot at right
Sensitivity	1200 V-s/m ± 0.5% precision
Bandwidth	-3 dB points at 120 s and 150 Hz
Clip Level	>16.6 mm/s up to 10 Hz and 0.17 *g* above 10 Hz
Temperature	±45°C without re-centering
INTERFACE	
Connector	20-pin marine
Velocity Output	40 V peak-to-peak differential Selectable XYZ or UVW mode
Mass Position Output	Three independent voltage outputs
Calibration Input	Single voltage input for all channels, independent calibration enable for each channel Calibration in XYZ or UVW
Control Lines	Auto-level & Mass Center, Calibration Enable, XYZ/UVW mode
Serial Port	RS-232 compatible serial IP (SLIP) Onboard web server standard HTTP For enhanced instrument control and status: Self-leveling and mass centering, UVW/XYZ mode, short/long period mode, firmware updates, temperature, mass position, instrument status, serial number and factory info
POWER	
Supply Voltage	9 to 36 Volts DC isolated input
Power Consumption	560 mW typical at 15 V input
Protection	Reverse-voltage protection Auto-resettable over-current protection (No fuse to replace)
PHYSICAL	
Case Design	Stainless steel pressure vessel, submersible
Diameter	143 mm (5.63")
Height	432 mm (17") not including connector or feet
Weight	16 Kg
Handling	Eye bolt on lid for lifting cable 1300 lbf (5800 N) rated
ENVIRONMENTAL	
Operating Temp.	-20°C to +60°C (Ultra-low temperature option available. Please contact Nanometrics.)
Storage Temp.	-40°C to +70°C
Water Immersion	Rated to IP68 and NEMA6P for prolonged submersion
Shock	20 *g* half sine, 5 ms without damage, 6 axis No mass lock required for transport

Table 1 Seismometer Specifications (Nanometrics T120PH datasheet)

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.

Figure 2 FACT Site Bunker

The seismometers were configured on the FACT Seismometer Pier within the underground bunker. They were covered in cardboard tubes which were filled with cellulose insulation in order to improve thermal stability. The seismometers were operated alongside a reference STS-2 seismometer from April – August, 2017.

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

Figure 3 Picture of installed seismometers, before insulation

Figure 4 Picture of installed seismometers, overhead

Figure 5 Picture of installed Seismometers

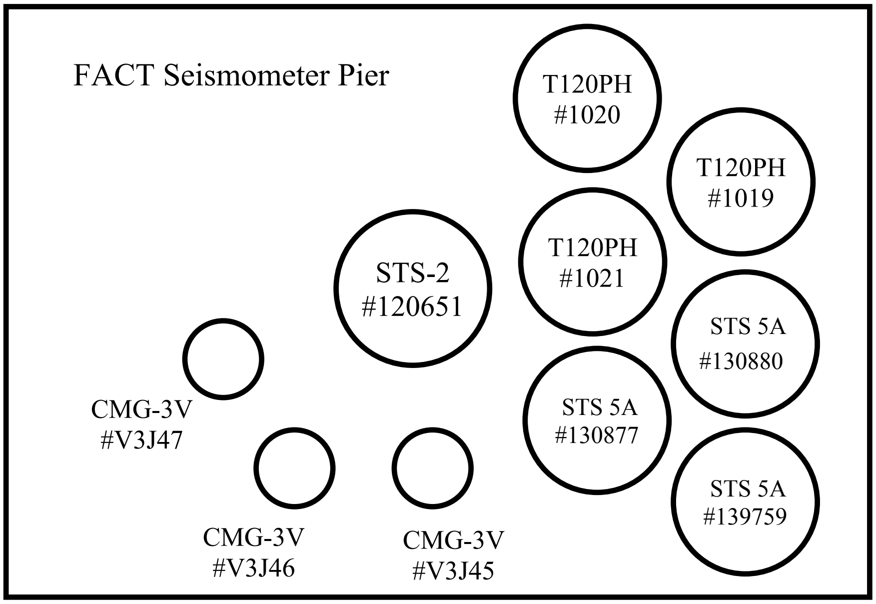


Figure 6 Diagram of installed Seismometers

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 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 SMAD digitizers and other recording equipment present.

Figure 7 GPS Re-broadcaster

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

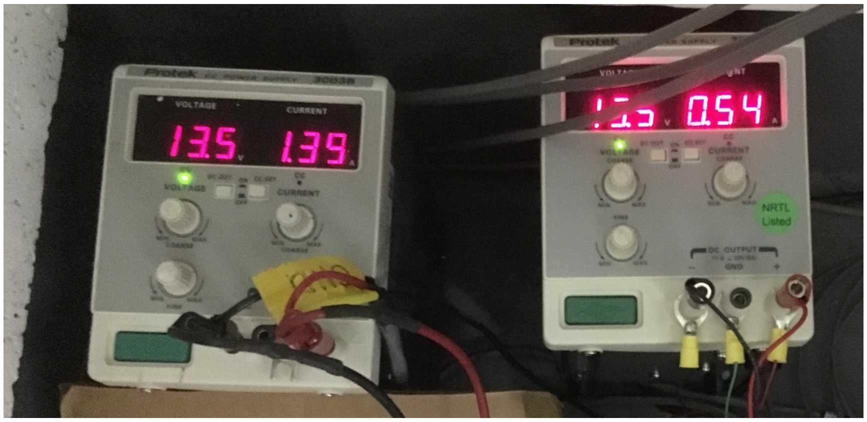


Figure 8 Laboratory Power Supply

The Trillium 120PH seismometers were connected to a Nanometrics Centaur digitizers for recording of the time series data. The seismometer and digitizer channel assignments are contained in the table below.

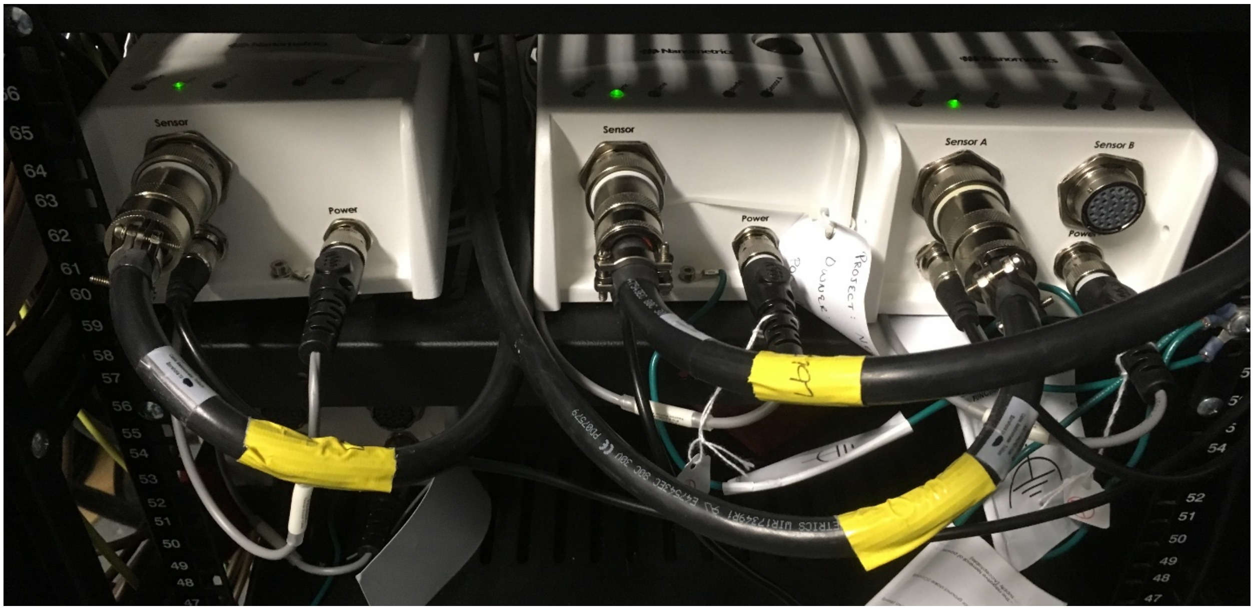


Figure 9 Nanometrics Centaur Digitizers

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 #1030880	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 pressure quantity 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.

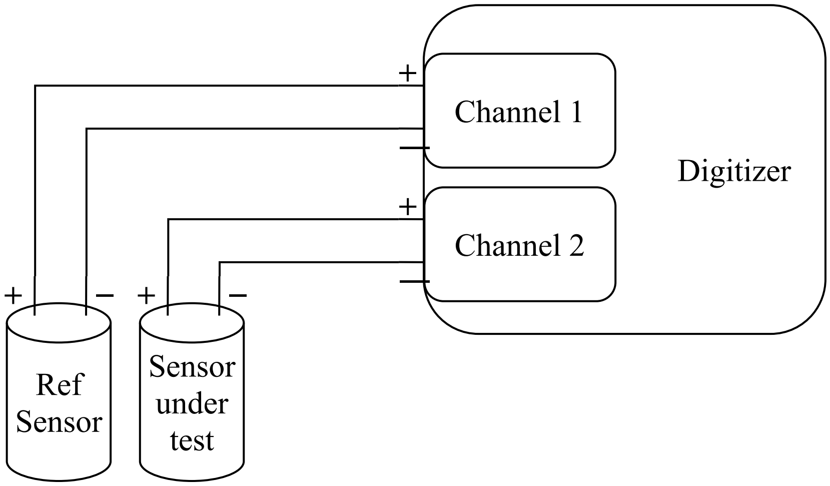


Figure 10 Sensitivity Configuration Diagram

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	Nanometrics T120PH	# 1019, 1020, 1021	1500 V/(m/s)
Sensor Digitizers	Nanometrics Centaur	# N1776, N1787, N1797	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).

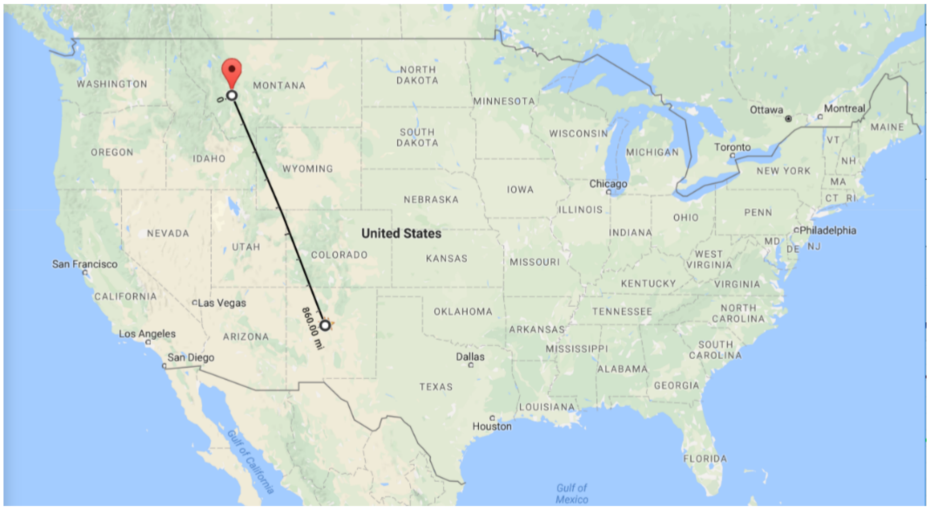
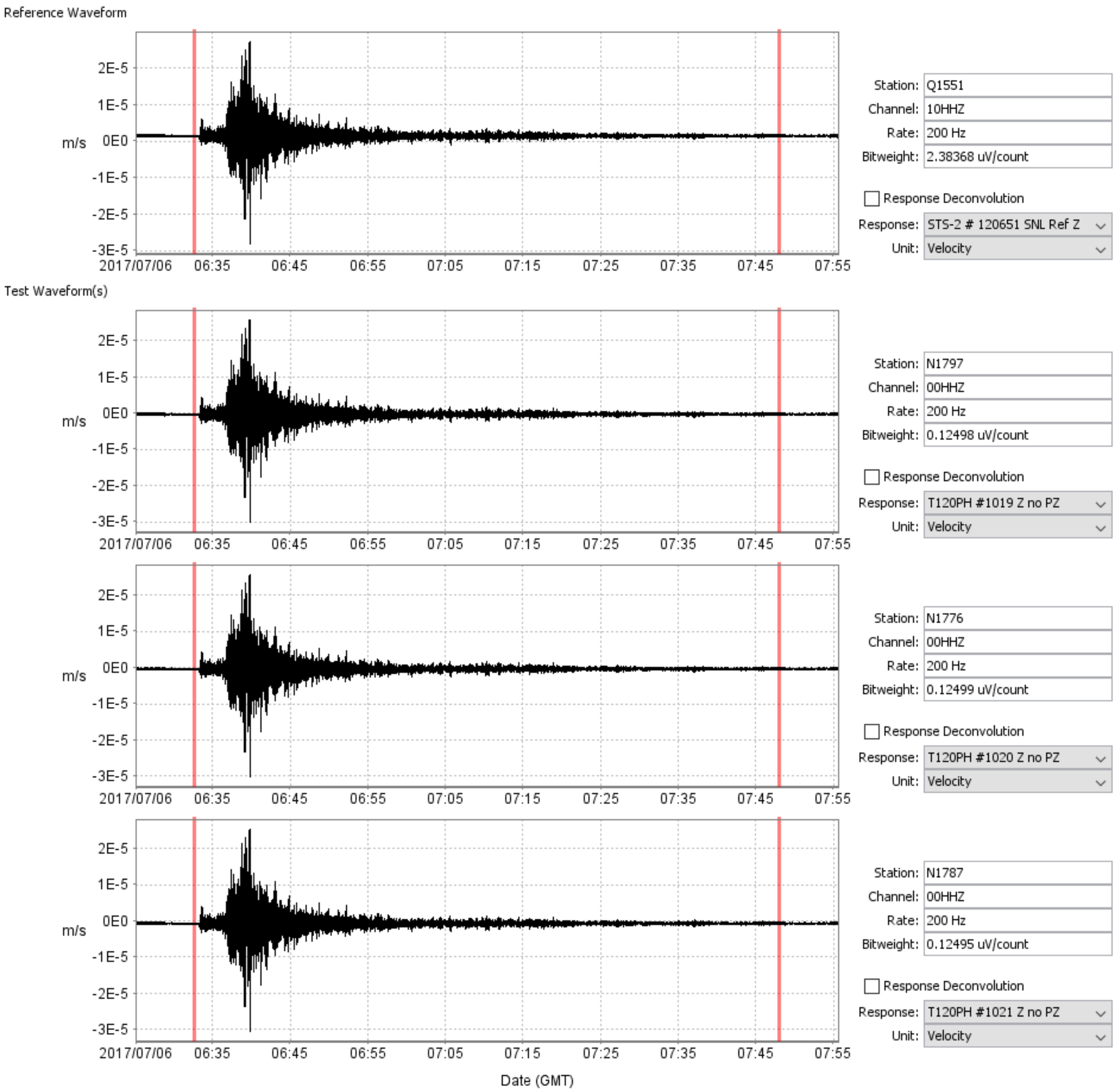


Figure 11 Sensitivity Earthquake Location

These earthquakes were 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 vertical axis only. The horizontal N and E axes are very similar. The window regions bounded by the red lines indicate the segment of data used for analysis.



Station: Q1551
Channel: 10HHZ
Rate: 200 Hz
Bitweight: 2.38368 uV/count
☐ Response Deconvolution
Response: STS-2 # 120651 SNL Ref Z
Unit: Velocity

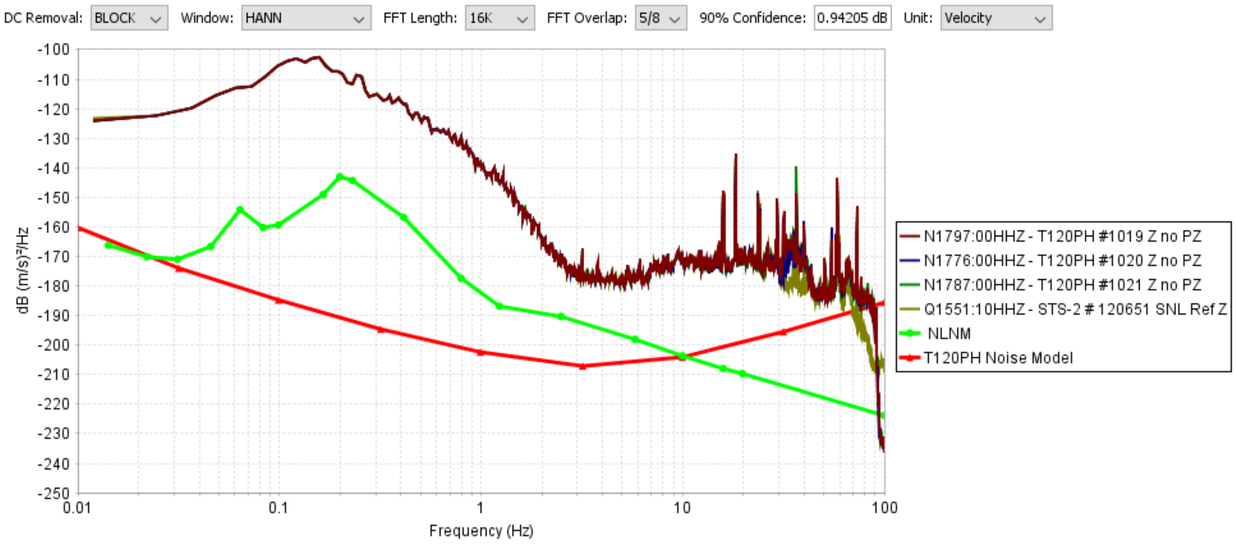
Station: N1797
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1019 Z no PZ
Unit: Velocity

Station: N1776
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1020 Z no PZ
Unit: Velocity

Station: N1787
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12495 uV/count
☐ Response Deconvolution
Response: T120PH #1021 Z no PZ
Unit: Velocity

Figure 12 Sensitivity Time Series

The figures below show the power spectra, coherence, and amplitude response that were computed from the waveform time series for the vertical axis only. Again, the horizontal N and E axes are very similar.



DC Removal: BLOCK Window: HANN FFT Length: 16K FFT Overlap: 5/8 90% Confidence: 0.94205 dB Unit: Velocity

Figure 13 Sensitivity Power Spectra

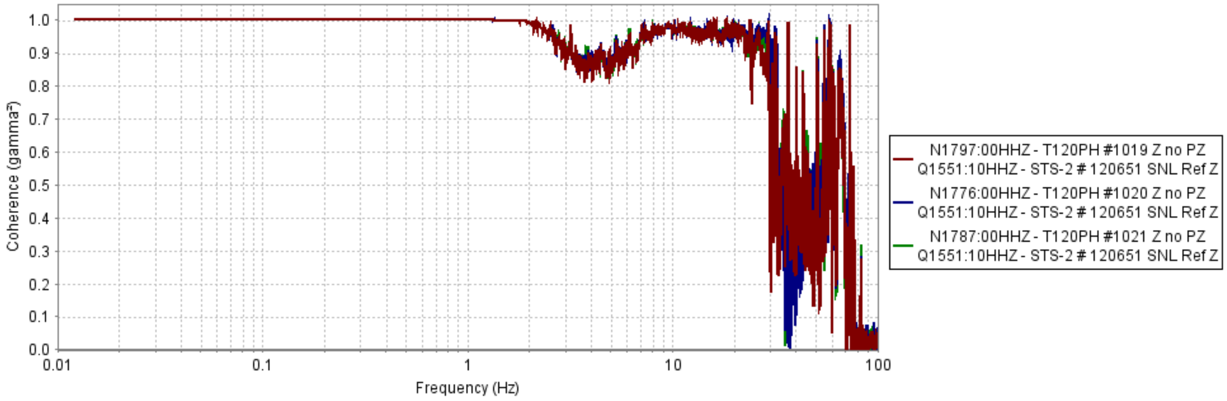


Figure 14 Sensitivity Coherence

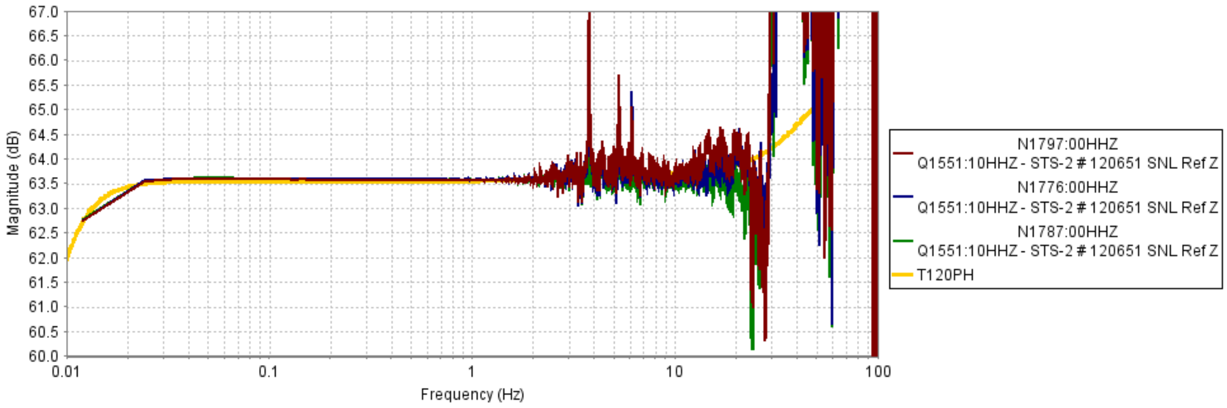


Figure 15 Sensitivity Amplitude Response

Note that the amplitude response curves shown above are consistent with the nominal amplitude response model for a Nanometrics Trillium 120PH, shown in orange, with a sensitivity of 1500

V/(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

		Z		N		E	
Seismometer	Nominal	Sensitivity	%	Sensitivity	%	Sensitivity	%
T120PH #1019	1500 V/(m/s)	1507 V/(m/s)	0.47%	1500 V/(m/s)	0.00%	1506 V/(m/s)	0.40%
T120PH #1020	1500 V/(m/s)	1508 V/(m/s)	0.53%	1502 V/(m/s)	0.13%	1507 V/(m/s)	0.47%
T120PH #1021	1500 V/(m/s)	1508 V/(m/s)	0.53%	1502 V/(m/s)	0.13%	1507 V/(m/s)	0.47%

The measured sensitivities were between 1500 and 1508 V/(m/s). These values differ from the nominal 1500 V/(m/s) by between 0 and 0.53 %. The specification from Nanometrics state that they trim the seismometers to match the nominal response to within 0.5 % of the sensitivity and low frequency corner and within +/- 1 dB (12 %) up to 40 Hz. These measured sensitivities are consistent with that specification.

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

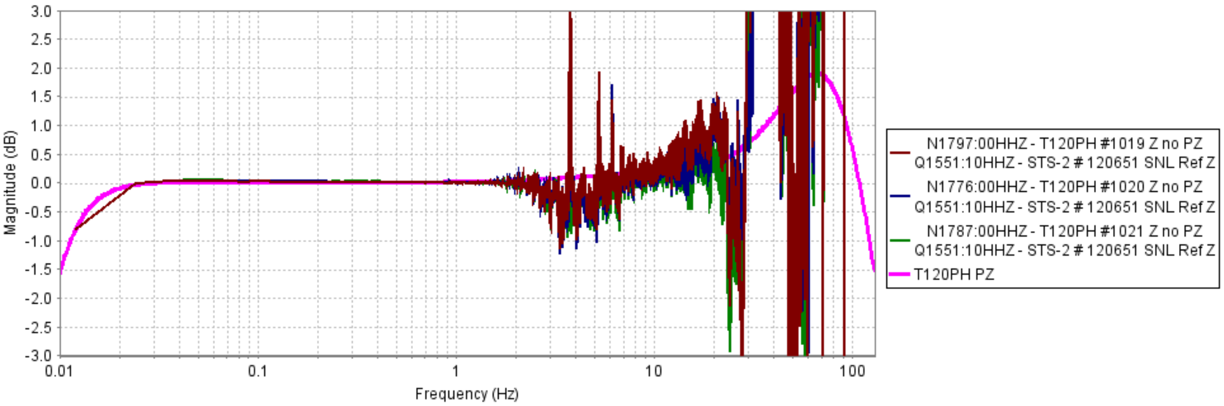


Figure 16 Sensitivity Corrected Amplitude Response

The amplitude response curves are now corrected for the measured sensitivities and show greater agreement with the nominal Nanometrics Trillium 120PH 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.

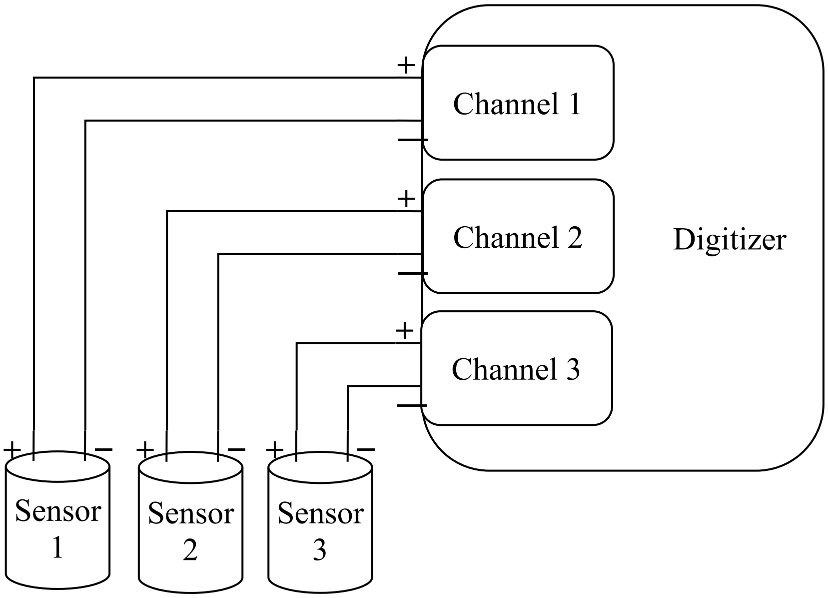


Figure 17 Self-Noise Configuration Diagram

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	Nanometrics T120PH	# 1019, 1020, 1021	1500 V/(m/s)
Sensor Digitizers	Nanometrics Centaur	# N1776, N1787, N1797	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.

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

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.

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

Over frequencies (in Hertz):

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

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:

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

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 collected 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 following series of plots and tables contain a summary of the self-noise levels for all three seismometer axes. A composite set of plots are show side-by-side with different PSD window lengths: a longer window length of 256k for low frequencies (< 0.1 Hz) and a shorter window length of 16k for high frequencies (> 0.1 Hz). The subsequent sections contain more detailed information on each of the axes.

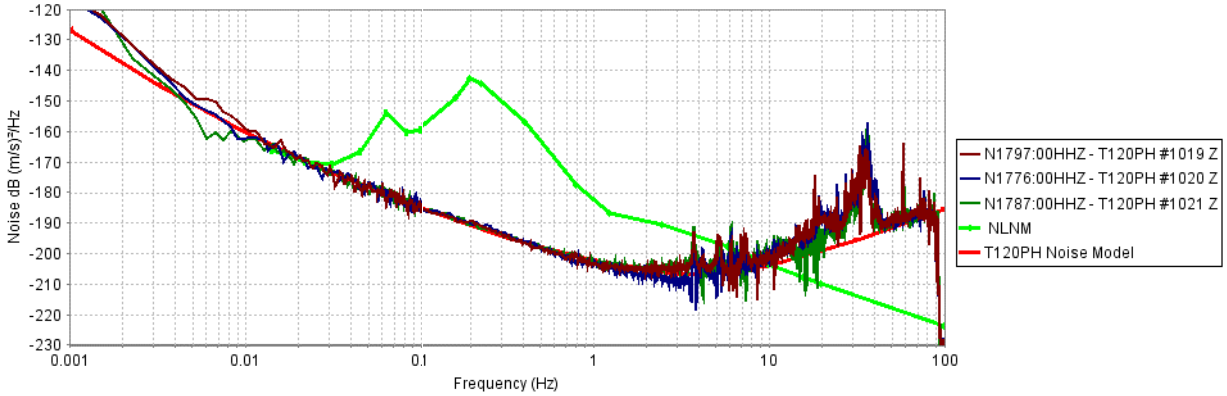


Figure 18 Z Axis Self Noise

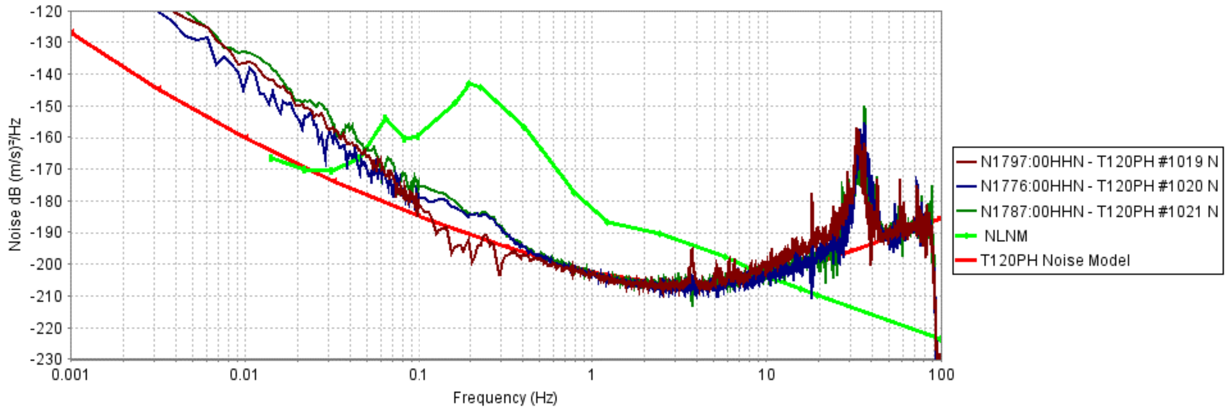


Figure 19 N Axis Self Noise

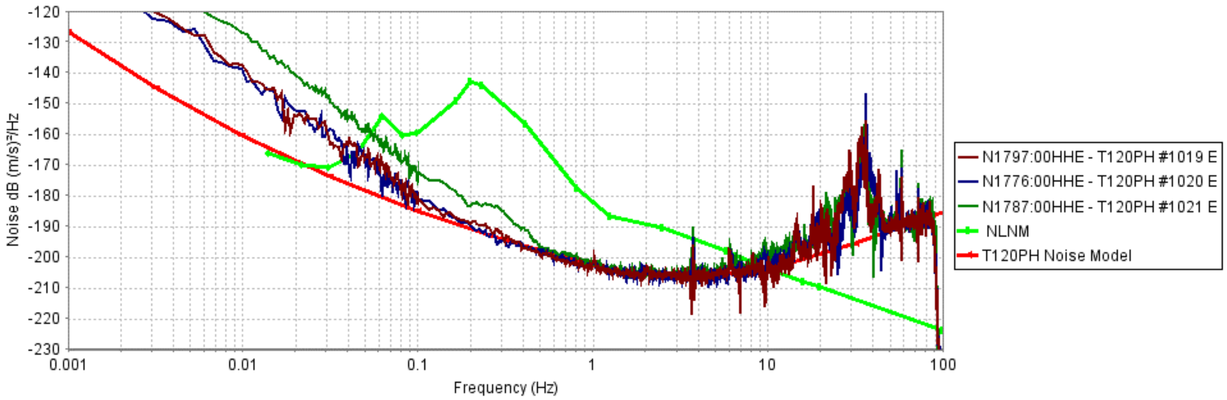


Figure 20 E Axis Self Noise

Note that the apparent change in noise variance at 0.1 Hz in the above plots is due to the different PSD window lengths that were used to process each segment. The spectral estimates of noise on the horizontal channels are higher than on the vertical channel at lower frequencies (< 0.5 Hz). This is likely due to the increased difficulty of aligning seismometer horizontally which reduces signal coherence. At high frequencies (> 10 Hz), some amount of nearby site noise is coupling into the noise estimate, likely due to the seismometers not being perfectly co-located and the pier not being homogeneous.

Overall, the self-noise estimates of the seismometers are consistent with the nominal noise model provided by the manufacturer.

Table 8 Self Noise RMS - Z

	8.3 mHz - 40 Hz	20 mHz - 1 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
T120PH #1019	5.603 nm/s rms	0.439 nm/s rms	0.609 nm/s rms	0.427 nm/s rms
T120PH #1020	8.260 nm/s rms	0.440 nm/s rms	0.594 nm/s rms	0.403 nm/s rms
T120PH #1021	8.833 nm/s rms	0.447 nm/s rms	0.585 nm/s rms	0.384 nm/s rms

Table 9 Self Noise RMS - N

	8.3 mHz - 40 Hz	20 mHz - 1 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
T120PH #1019	16.965 nm/s rms	2.815 nm/s rms	2.841 nm/s rms	0.390 nm/s rms
T120PH #1020	14.428 nm/s rms	1.908 nm/s rms	1.925 nm/s rms	0.262 nm/s rms
T120PH #1021	20.910 nm/s rms	3.847 nm/s rms	3.857 nm/s rms	0.283 nm/s rms

Table 10 Self Noise RMS - E

	8.3 mHz - 40 Hz	20 mHz - 1 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
T120PH #1019	13.515 nm/s rms	2.020 nm/s rms	2.051 nm/s rms	0.357 nm/s rms
T120PH #1020	17.546 nm/s rms	2.050 nm/s rms	2.083 nm/s rms	0.371 nm/s rms
T120PH #1021	36.340 nm/s rms	7.043 nm/s rms	7.055 nm/s rms	0.417 nm/s rms

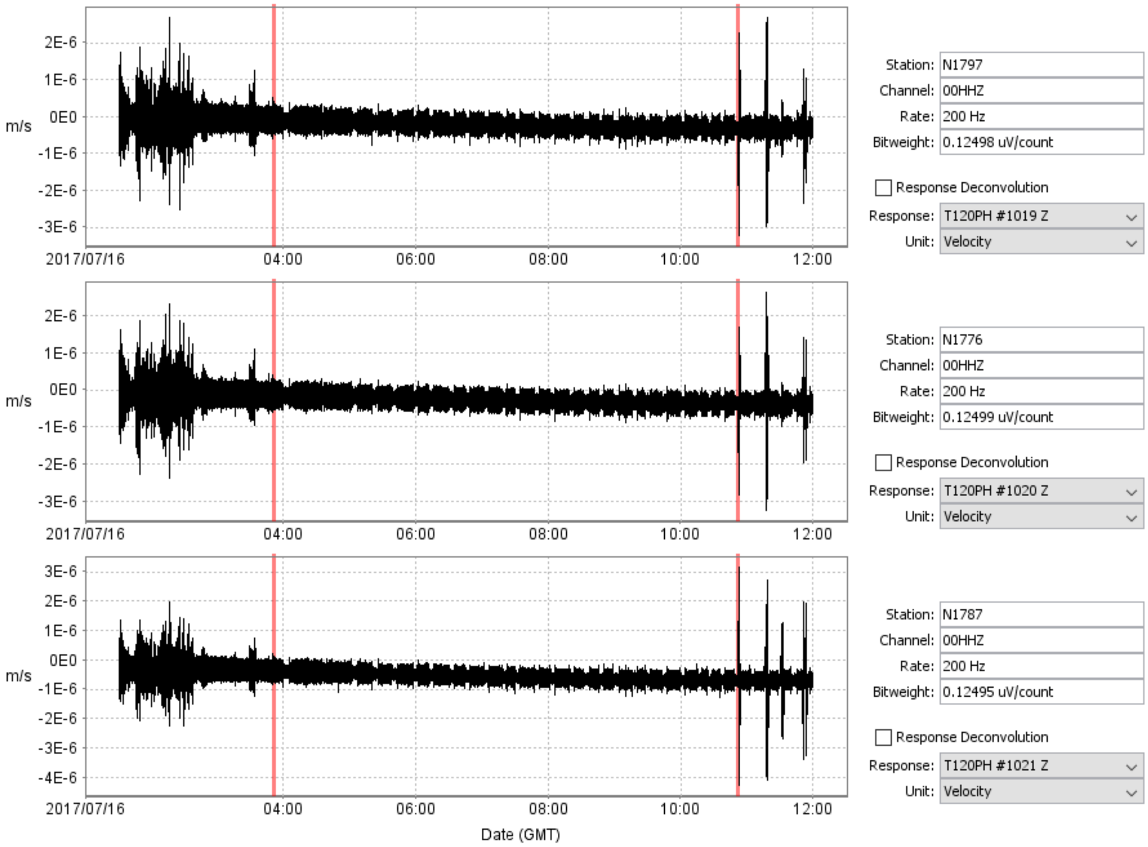
The following table contains the seismometer self-noise values, smoothed with a median filter, expressed as dB relative to 1 $(m/s)^2/Hz$. At frequencies below 0.1 Hz, the spectral uncertainty is 1.6 dB. At frequencies above 0.1 Hz, the spectral uncertainty is 0.4 dB.

Table 11 Self Noise

	Z			N			E		
Frequency	#1019	#1020	#1021	#1019	#1020	#1021	#1019	#1020	#1021
0.001 Hz	-114.7 dB	-115.5 dB	-119.2 dB	-99.3 dB	-99.8 dB	-101.2 dB	-98.0 dB	-93.0 dB	-82.5 dB
0.00125 Hz	-121.3 dB	-120.9 dB	-127.7 dB	-106.5 dB	-108.7 dB	-96.2 dB	-106.0 dB	-106.3 dB	-94.3 dB
0.0016 Hz	-123.8 dB	-121.8 dB	-131.5 dB	-106.4 dB	-112.4 dB	-98.2 dB	-106.8 dB	-106.6 dB	-96.9 dB
0.002 Hz	-125.6 dB	-126.9 dB	-134.7 dB	-106.4 dB	-112.4 dB	-100.4 dB	-106.5 dB	-108.8 dB	-95.2 dB
0.0025 Hz	-136.5 dB	-134.3 dB	-137.1 dB	-115.3 dB	-115.6 dB	-111.8 dB	-119.3 dB	-119.3 dB	-103.3 dB
0.00315 Hz	-139.2 dB	-140.5 dB	-143.2 dB	-117.5 dB	-119.8 dB	-114.7 dB	-118.9 dB	-117.0 dB	-106.3 dB
0.004 Hz	-144.2 dB	-144.8 dB	-148.0 dB	-120.1 dB	-118.9 dB	-116.4 dB	-123.2 dB	-125.8 dB	-113.5 dB
0.005 Hz	-147.2 dB	-151.5 dB	-153.6 dB	-124.0 dB	-128.4 dB	-123.9 dB	-127.3 dB	-129.0 dB	-114.9 dB
0.0063 Hz	-152.1 dB	-154.6 dB	-157.1 dB	-125.9 dB	-131.6 dB	-127.5 dB	-130.5 dB	-133.2 dB	-119.4 dB
0.008 Hz	-154.4 dB	-157.3 dB	-161.0 dB	-132.2 dB	-136.5 dB	-131.3 dB	-137.2 dB	-134.9 dB	-122.6 dB
0.010 Hz	-158.7 dB	-161.8 dB	-163.0 dB	-137.9 dB	-139.6 dB	-133.4 dB	-137.5 dB	-137.8 dB	-127.9 dB
0.0125 Hz	-162.3 dB	-163.8 dB	-164.7 dB	-140.2 dB	-142.7 dB	-135.4 dB	-142.5 dB	-145.1 dB	-130.7 dB
0.016 Hz	-165.2 dB	-167.5 dB	-167.3 dB	-143.9 dB	-147.9 dB	-141.8 dB	-145.9 dB	-148.4 dB	-135.3 dB
0.020 Hz	-168.8 dB	-168.6 dB	-169.6 dB	-150.5 dB	-152.9 dB	-148.5 dB	-149.7 dB	-153.0 dB	-140.5 dB
0.025 Hz	-171.5 dB	-172.8 dB	-172.0 dB	-152.8 dB	-153.0 dB	-149.6 dB	-153.1 dB	-154.8 dB	-144.9 dB
0.0315 Hz	-174.1 dB	-173.9 dB	-174.0 dB	-157.7 dB	-159.6 dB	-154.3 dB	-159.1 dB	-158.7 dB	-148.7 dB
0.040 Hz	-176.9 dB	-176.1 dB	-175.7 dB	-162.3 dB	-164.6 dB	-156.2 dB	-162.1 dB	-163.7 dB	-153.2 dB
0.050 Hz	-178.8 dB	-179.1 dB	-179.3 dB	-166.3 dB	-169.2 dB	-164.2 dB	-166.0 dB	-166.7 dB	-158.3 dB
0.063 Hz	-181.5 dB	-180.3 dB	-179.9 dB	-170.8 dB	-172.8 dB	-169.9 dB	-170.8 dB	-172.0 dB	-163.0 dB
0.080 Hz	-183.4 dB	-182.7 dB	-183.0 dB	-176.9 dB	-177.0 dB	-172.6 dB	-175.1 dB	-176.7 dB	-167.6 dB
0.100 Hz	-184.8 dB	-184.3 dB	-184.3 dB	-180.4 dB	-179.3 dB	-174.9 dB	-180.3 dB	-180.1 dB	-171.5 dB
0.125 Hz	-186.8 dB	-186.4 dB	-186.1 dB	-186.0 dB	-180.0 dB	-176.9 dB	-184.3 dB	-183.1 dB	-175.0 dB
0.160 Hz	-188.5 dB	-187.7 dB	-188.4 dB	-195.5 dB	-181.7 dB	-179.7 dB	-186.5 dB	-187.1 dB	-178.2 dB
0.200 Hz	-189.8 dB	-190.0 dB	-190.2 dB	-195.5 dB	-184.3 dB	-183.9 dB	-188.8 dB	-189.2 dB	-182.7 dB
0.250 Hz	-191.7 dB	-191.0 dB	-192.1 dB	-194.2 dB	-184.6 dB	-184.3 dB	-189.9 dB	-192.5 dB	-183.1 dB
0.315 Hz	-194.5 dB	-193.5 dB	-194.3 dB	-197.4 dB	-190.2 dB	-189.5 dB	-193.9 dB	-195.2 dB	-185.9 dB
0.400 Hz	-196.8 dB	-196.1 dB	-196.1 dB	-197.6 dB	-194.5 dB	-194.6 dB	-197.2 dB	-196.4 dB	-190.8 dB
0.500 Hz	-198.2 dB	-198.3 dB	-198.1 dB	-198.8 dB	-197.4 dB	-197.0 dB	-199.1 dB	-198.1 dB	-196.6 dB
0.630 Hz	-200.3 dB	-200.5 dB	-199.9 dB	-200.7 dB	-200.1 dB	-199.4 dB	-200.6 dB	-200.3 dB	-198.6 dB
0.800 Hz	-201.4 dB	-202.6 dB	-200.6 dB	-202.2 dB	-201.9 dB	-201.3 dB	-202.3 dB	-202.1 dB	-200.3 dB
1.000 Hz	-203.5 dB	-203.7 dB	-202.9 dB	-203.5 dB	-203.2 dB	-203.1 dB	-203.2 dB	-202.9 dB	-201.7 dB
1.250 Hz	-204.3 dB	-204.9 dB	-203.9 dB	-204.8 dB	-204.7 dB	-204.3 dB	-204.8 dB	-204.5 dB	-203.6 dB
1.600 Hz	-205.0 dB	-206.1 dB	-204.6 dB	-206.2 dB	-205.9 dB	-205.4 dB	-205.5 dB	-205.7 dB	-204.5 dB
2.000 Hz	-205.2 dB	-207.1 dB	-204.7 dB	-206.7 dB	-206.6 dB	-206.2 dB	-206.0 dB	-205.3 dB	-204.4 dB
2.500 Hz	-205.2 dB	-208.2 dB	-204.6 dB	-207.0 dB	-207.4 dB	-206.0 dB	-206.1 dB	-206.4 dB	-205.3 dB
3.150 Hz	-204.9 dB	-208.9 dB	-204.6 dB	-206.7 dB	-207.6 dB	-206.0 dB	-206.2 dB	-206.6 dB	-205.7 dB
4.000 Hz	-203.1 dB	-204.6 dB	-202.9 dB	-205.5 dB	-207.5 dB	-206.5 dB	-206.6 dB	-205.7 dB	-203.8 dB
5.000 Hz	-203.2 dB	-207.2 dB	-203.9 dB	-206.2 dB	-207.5 dB	-205.9 dB	-205.7 dB	-206.7 dB	-205.3 dB
6.300 Hz	-205.5 dB	-203.4 dB	-201.8 dB	-204.5 dB	-206.1 dB	-205.8 dB	-205.0 dB	-205.0 dB	-203.3 dB
8.000 Hz	-202.1 dB	-204.3 dB	-203.1 dB	-204.0 dB	-205.2 dB	-204.5 dB	-204.1 dB	-204.8 dB	-203.2 dB
10.000 Hz	-201.9 dB	-201.8 dB	-200.6 dB	-200.9 dB	-203.7 dB	-203.2 dB	-204.3 dB	-202.2 dB	-199.1 dB
12.500 Hz	-199.3 dB	-198.9 dB	-198.6 dB	-198.7 dB	-202.2 dB	-202.2 dB	-202.4 dB	-200.8 dB	-197.8 dB
16.000 Hz	-193.9 dB	-195.4 dB	-199.3 dB	-195.5 dB	-200.2 dB	-199.4 dB	-198.3 dB	-196.5 dB	-196.1 dB
20.000 Hz	-189.6 dB	-188.7 dB	-194.0 dB	-191.9 dB	-197.3 dB	-198.0 dB	-194.4 dB	-190.2 dB	-191.6 dB
25.000 Hz	-190.7 dB	-189.2 dB	-192.7 dB	-188.7 dB	-193.9 dB	-194.6 dB	-190.8 dB	-193.3 dB	-185.2 dB
31.500 Hz	-178.1 dB	-181.4 dB	-182.5 dB	-177.5 dB	-182.3 dB	-179.7 dB	-175.7 dB	-184.2 dB	-179.4 dB
40.000 Hz	-186.4 dB	-178.7 dB	-186.8 dB	-185.9 dB	-177.4 dB	-178.4 dB	-184.0 dB	-175.6 dB	-183.1 dB
50.000 Hz	-189.3 dB	-190.1 dB	-190.4 dB	-190.6 dB	-190.8 dB	-190.0 dB	-190.1 dB	-190.0 dB	-189.4 dB
63.000 Hz	-187.9 dB	-188.4 dB	-188.6 dB	-188.9 dB	-189.0 dB	-188.8 dB	-188.7 dB	-188.7 dB	-188.3 dB
80.000 Hz	-187.3 dB	-187.1 dB	-186.6 dB	-187.6 dB	-187.6 dB	-187.4 dB	-187.4 dB	-187.6 dB	-186.2 dB

3.2.4.1 Z Axis

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.


Station: N1797
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1019 Z
Unit: Velocity

Station: N1776
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1020 Z
Unit: Velocity

Station: N1787
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12495 uV/count
☐ Response Deconvolution
Response: T120PH #1021 Z
Unit: Velocity

Figure 21 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.

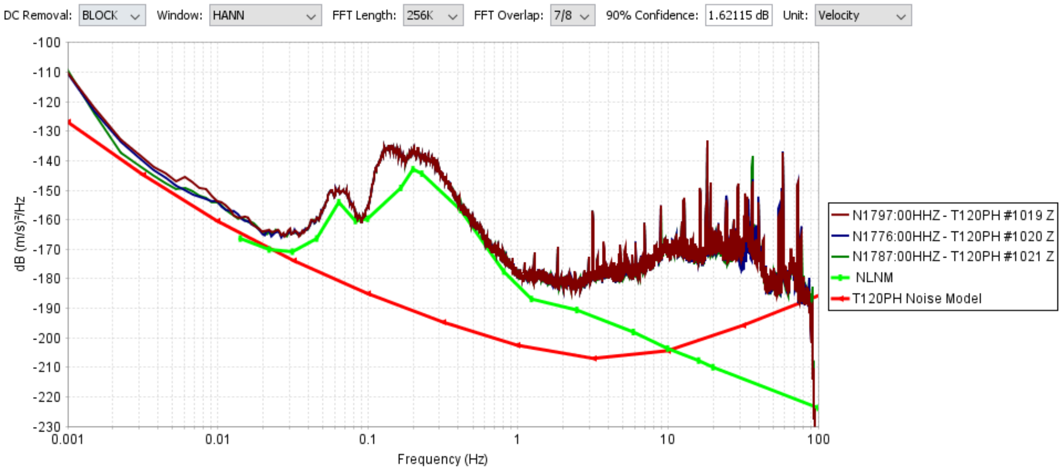

DC Removal: BLOCK
Window: HANN
FFT Length: 256K
FFT Overlap: 7/8
90% Confidence: 1.62115 dB
Unit: Velocity

Figure 22 Self Noise Raw Power Spectra

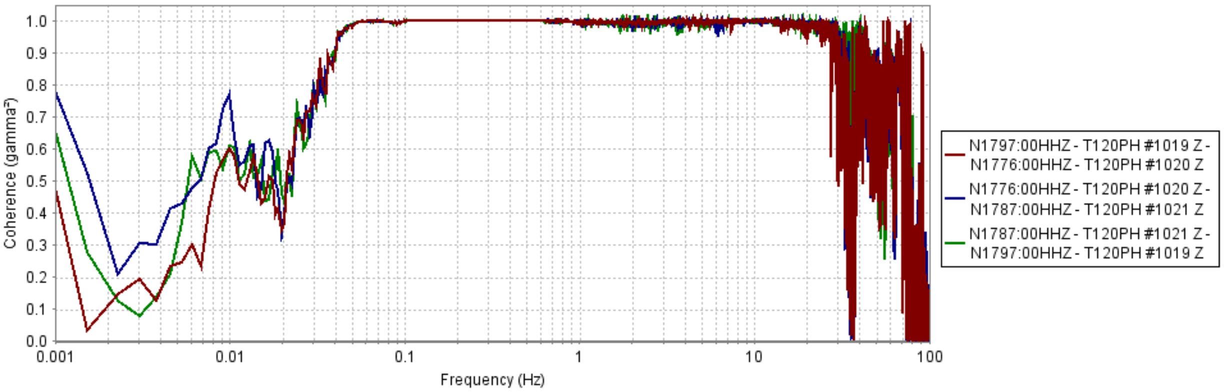


Figure 23 Self Noise Coherence

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 Trillium 120PH noise model are overlaid for comparison.

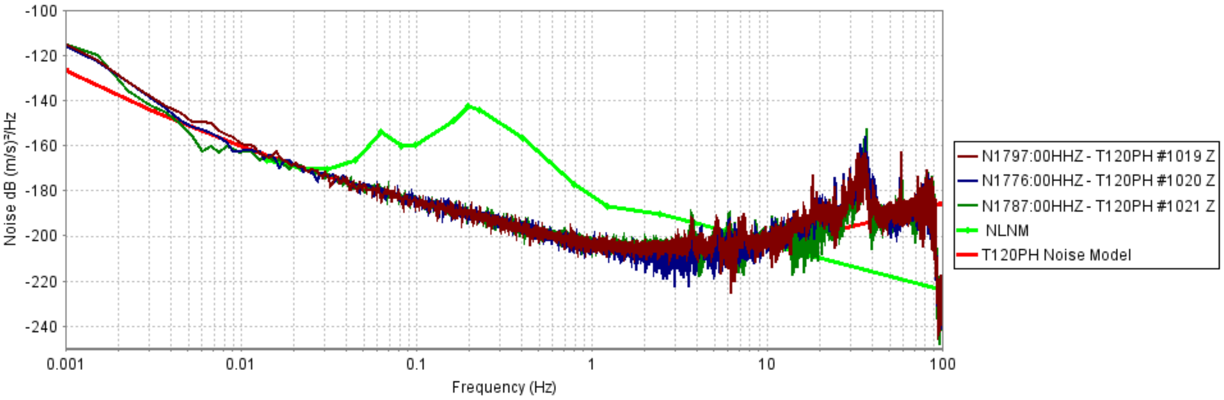


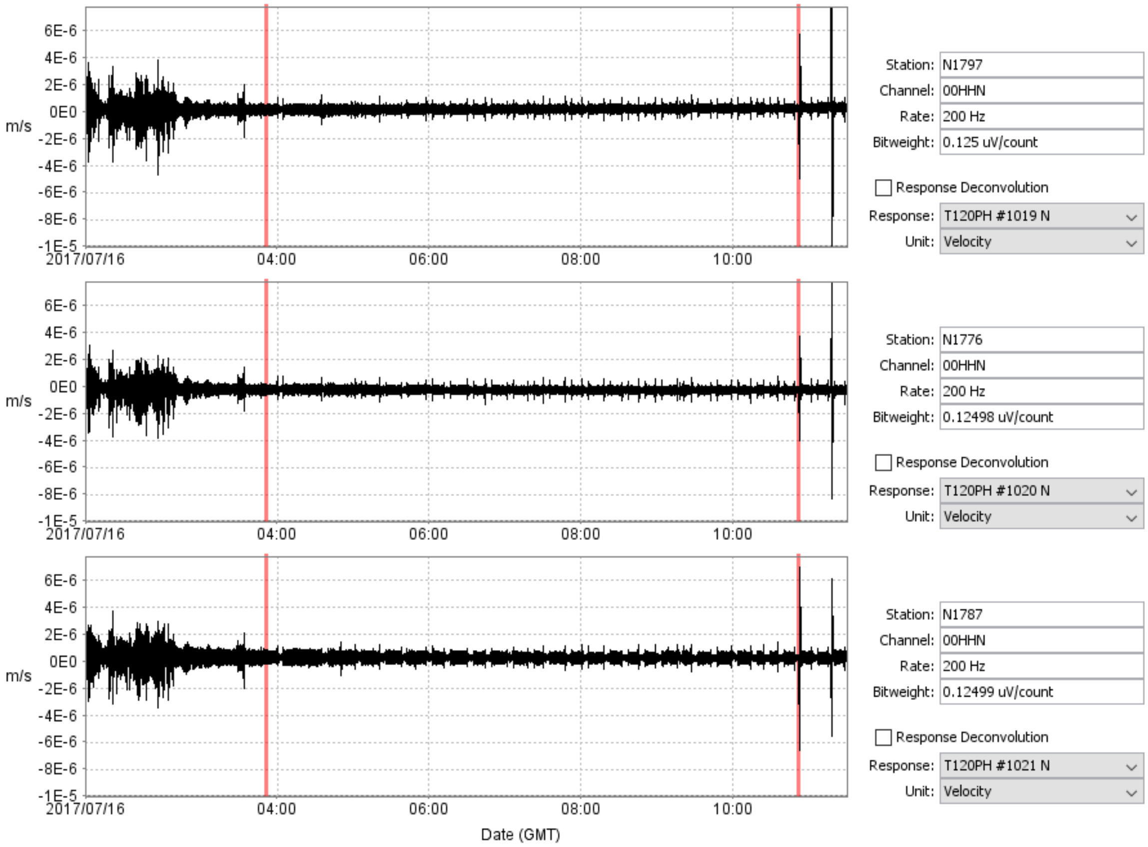
Figure 24 Self Noise

We observe that there is good signal coherence, even when recording just quiet background, between 0.05 and 25 Hz. Coherence is lost below 0.05 Hz due to the sensor self-noise rising above the level of the recorded background. Coherence is likely lost above 25 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. There is some scatter in the estimate of the self-noise at higher frequencies, > 10 Hz, due to the levels of site-noise present.

3.2.4.2 N Axis

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.



Station: N1797
Channel: 00HHN
Rate: 200 Hz
Bitweight: 0.125 uV/count
☐ Response Deconvolution
Response: T120PH #1019 N
Unit: Velocity

Station: N1776
Channel: 00HHN
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1020 N
Unit: Velocity

Station: N1787
Channel: 00HHN
Rate: 200 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1021 N
Unit: Velocity

Figure 25 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.

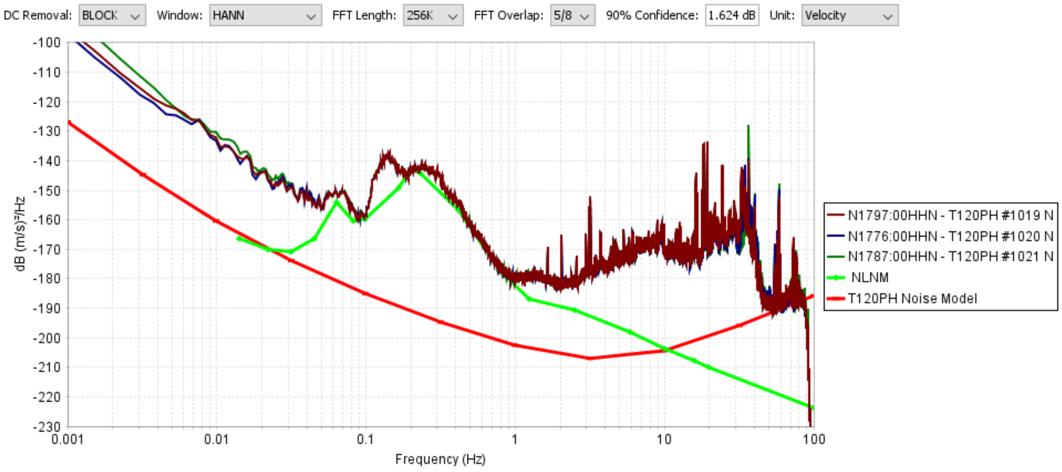

DC Removal: BLOCK
Window: HANN
FFT Length: 256K
FFT Overlap: 5/8
90% Confidence: 1.624 dB
Unit: Velocity

Figure 26 Self Noise Raw Power Spectra

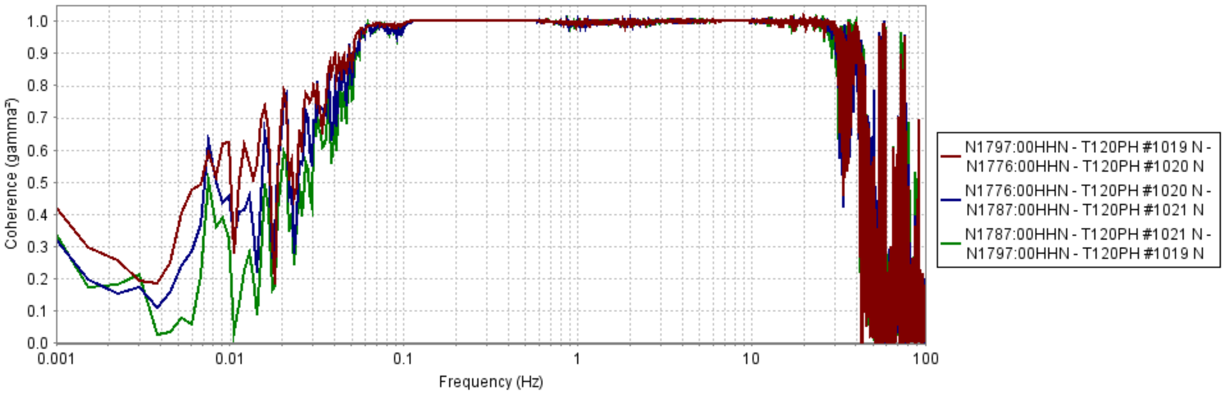


Figure 27 Self Noise Coherence

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 Trillium 120PH noise model are overlaid for comparison.

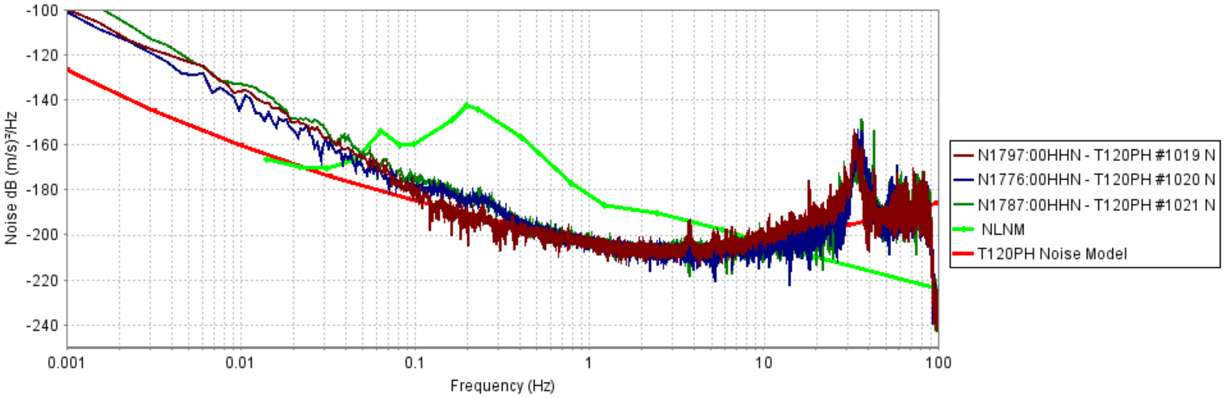


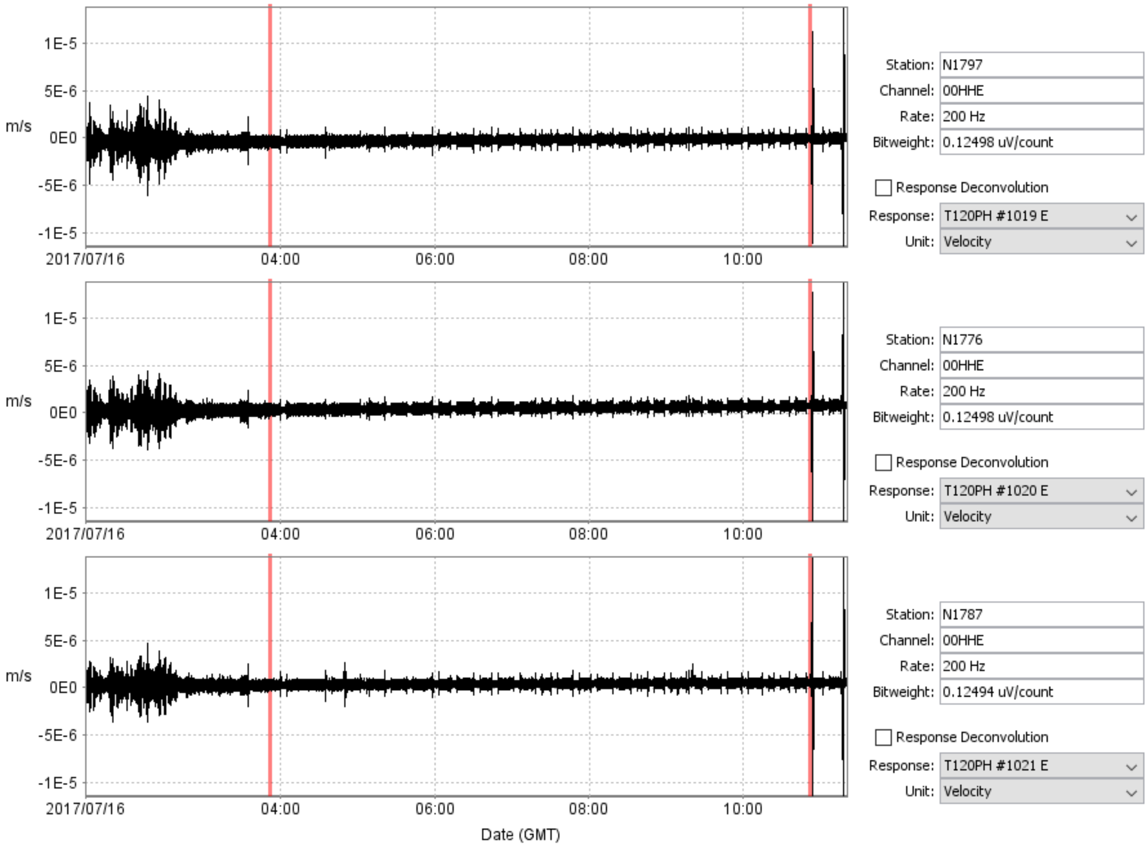
Figure 28 Self Noise

We observe that there is good signal coherence, even when recording just quiet background, between 0.06 and 25 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 25 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, > 20 Hz, due to the levels of site-noise present.

3.2.4.3 E Axis

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.



Station: N1797
Channel: 00HHE
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1019 E
Unit: Velocity

Station: N1776
Channel: 00HHE
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1020 E
Unit: Velocity

Station: N1787
Channel: 00HHE
Rate: 200 Hz
Bitweight: 0.12494 uV/count
☐ Response Deconvolution
Response: T120PH #1021 E
Unit: Velocity

Figure 29 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.

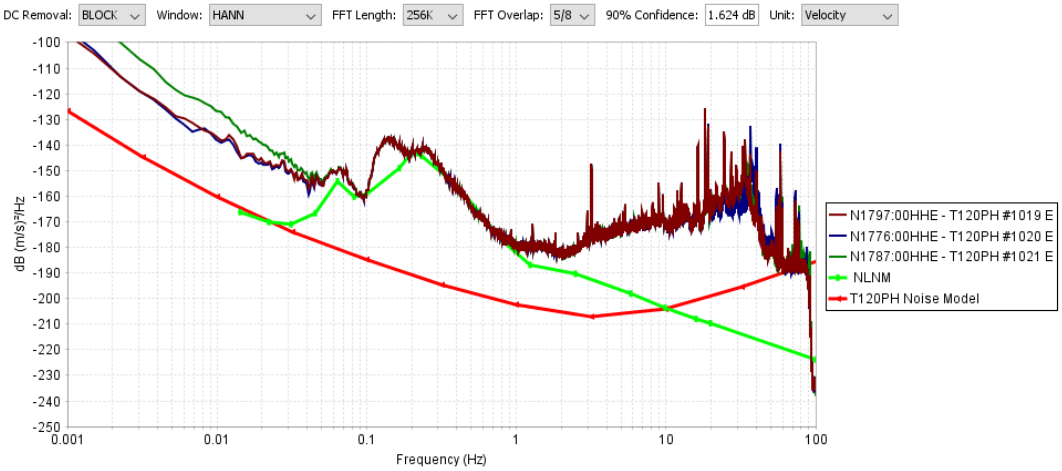

DC Removal: BLOCK Window: HANN FFT Length: 256K FFT Overlap: 5/8 90% Confidence: 1.624 dB Unit: Velocity

Figure 30 Self Noise Raw Power Spectra

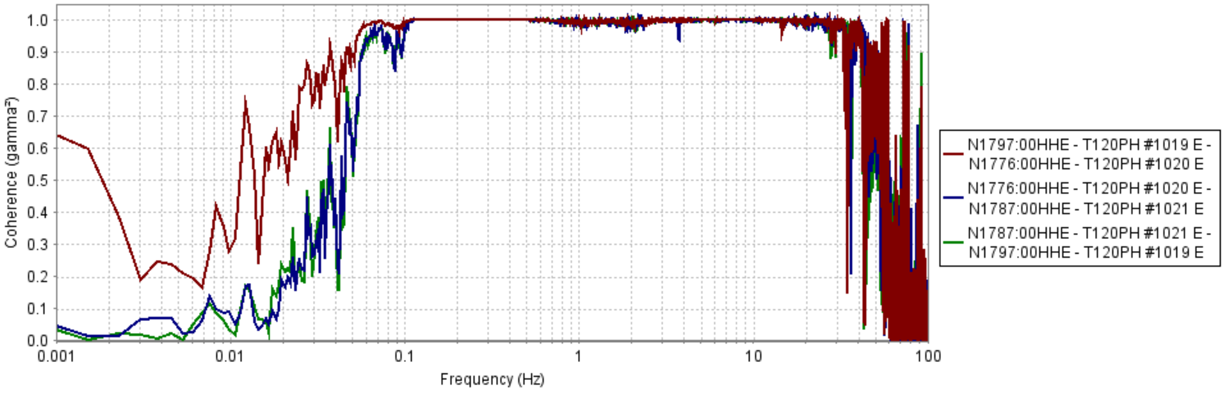


Figure 31 Self Noise Coherence

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 Trillium 120PH noise model are overlaid for comparison.

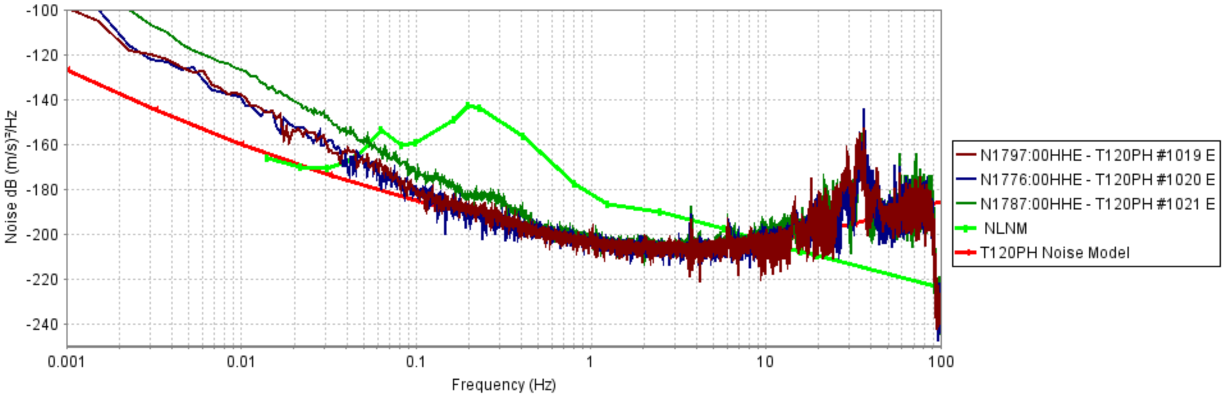


Figure 32 Self Noise

We observe that there is good signal coherence, even when recording just quiet background, between 0.1 and 30 Hz. Coherence is lost below 0.1 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, > 20 Hz, due to the levels of site-noise present.

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 application 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 12 Dynamic Range - Z

	8.3 mHz - 40 Hz	20 mHz - 1 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
T120PH #1019	124.48 dB	146.60 dB	143.76 dB	146.84 dB
T120PH #1020	121.10 dB	146.57 dB	143.97 dB	147.35 dB
T120PH #1021	120.52 dB	146.44 dB	144.10 dB	147.77 dB

Table 13 Dynamic Range - N

	8.3 mHz - 40 Hz	20 mHz - 1 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
T120PH #1019	114.90 dB	130.50 dB	130.42 dB	147.66 dB
T120PH #1020	116.29 dB	133.86 dB	133.79 dB	151.10 dB
T120PH #1021	113.07 dB	127.77 dB	127.75 dB	150.44 dB

Table 14 Dynamic Range - E

	8.3 mHz - 40 Hz	20 mHz - 1 Hz	20 mHz - 16 Hz	0.5 Hz - 16 Hz
T120PH #1019	116.84 dB	133.35 dB	133.22 dB	148.41 dB
T120PH #1020	114.56 dB	133.21 dB	133.08 dB	148.06 dB
T120PH #1021	108.24 dB	122.49 dB	122.48 dB	147.05 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 122.5 dB and 144 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, relative to the sensitivity at 1 Hz in V/Pa, 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.

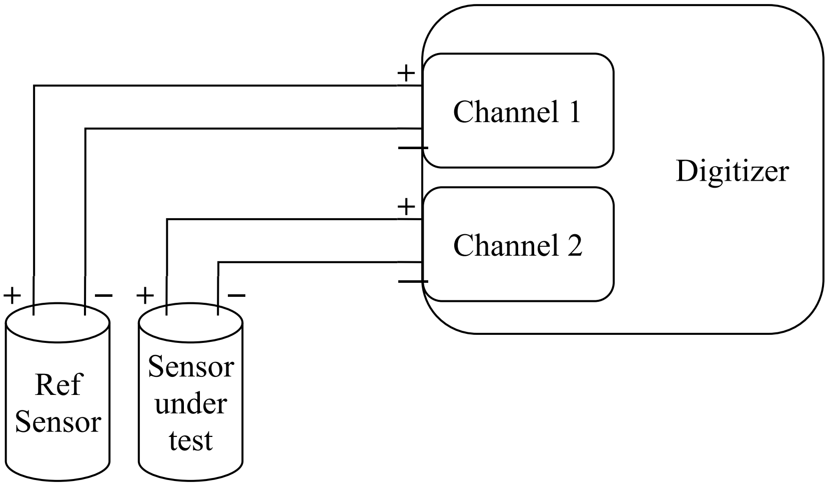


Figure 33 Frequency Response Configuration Diagram

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 15 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	Nanometrics T120PH	# 1019, 1020, 1021	1500 V/(m/s)
Sensor Digitizers	Nanometrics Centaur	# N1776, N1787, N1797	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 16 Frequency Response Earthquakes

Frequency Range	Date / Time (UTC)	Magnitude	Location	Distance
< 0.1 Hz	July 17, 2017, 23:44	7.7	Eastern Russia	6600 km
0.1 – 1 Hz	June 6, 2017, 06:30	5.8	Montana	1384 km
> 1 Hz	July 14, 2017, 13:46	4.2	Oklahoma	890 km

The following figures and tables contains the composite seismometer response values, averaged from the PSD, expressed as dB of amplitude relative to each seismometers sensitivity at 1 Hz and degrees of phase.

The resulting response that were measured are very similar to the nominal response model. The only difference occurs at high frequencies (> 10 Hz) where the coherence to the reference is beginning to experience some degradation indicating that the response estimate has less confidence.

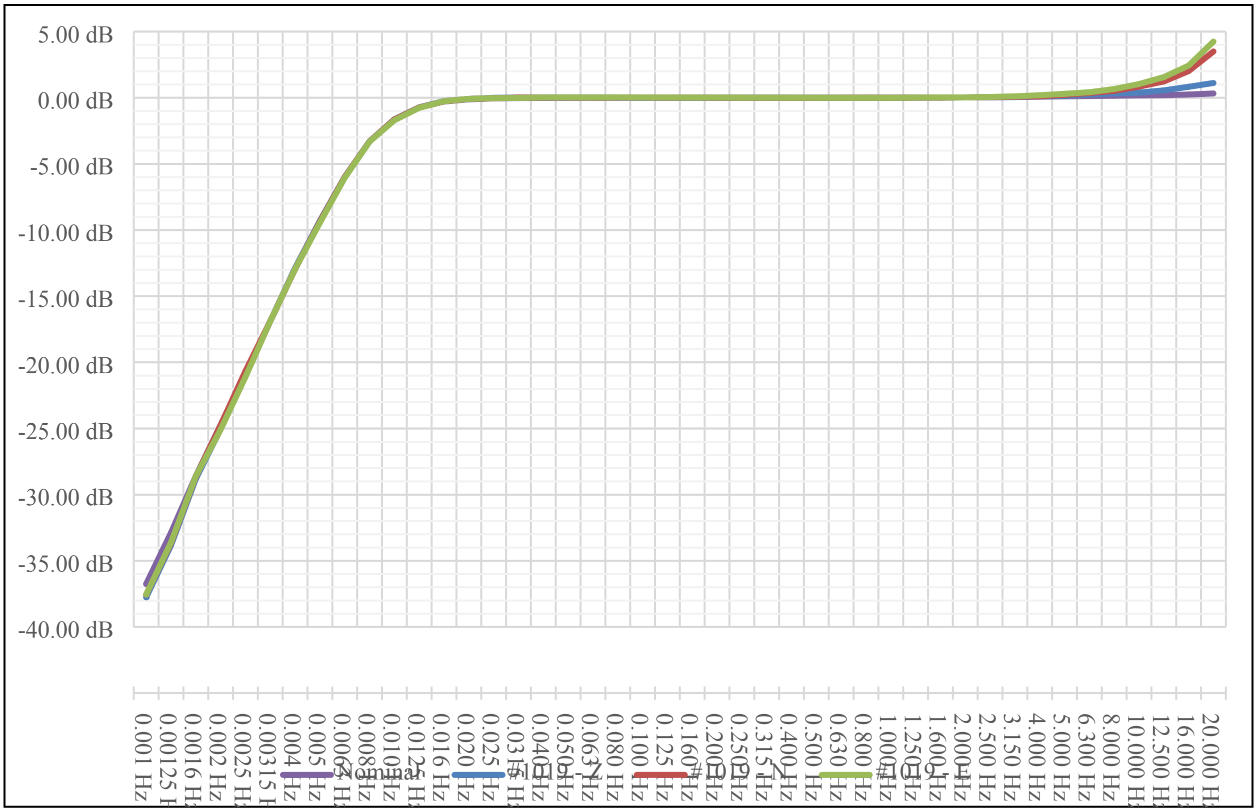


Figure 34 Amplitude Response - #1019

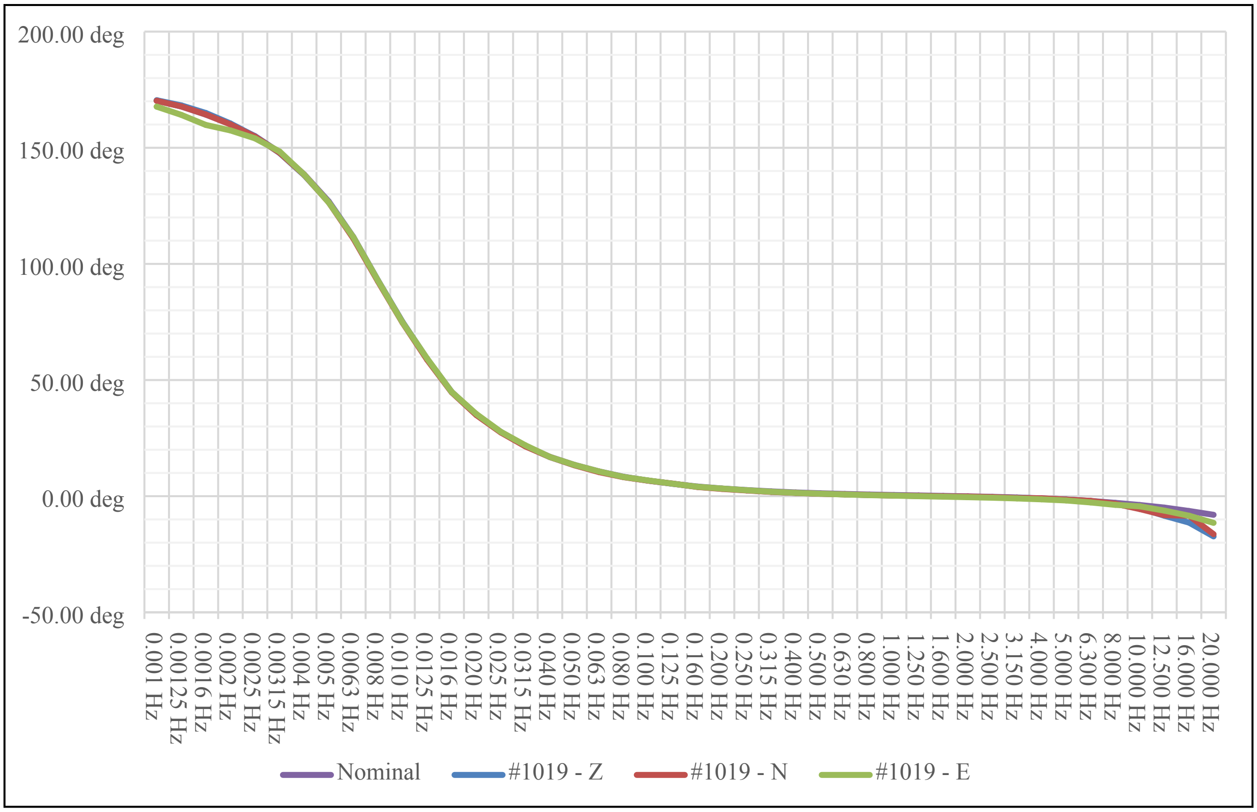


Figure 35 Phase Response - #1019

Table 17 Frequency Response - #1019

	Nominal		Z		N		E	
Frequency	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0.001 Hz	-36.75 dB	170.24 deg	-37.76 dB	170.45 deg	-37.56 dB	170.23 deg	-37.55 dB	167.70 deg
0.00125 Hz	-32.88 dB	167.76 deg	-33.84 dB	168.24 deg	-33.67 dB	167.79 deg	-33.61 dB	164.16 deg
0.0016 Hz	-28.59 dB	164.26 deg	-28.81 dB	164.97 deg	-28.65 dB	164.32 deg	-28.61 dB	159.82 deg
0.002 Hz	-24.72 dB	160.20 deg	-25.04 dB	160.45 deg	-24.75 dB	160.05 deg	-25.08 dB	157.47 deg
0.0025 Hz	-20.86 dB	155.00 deg	-20.95 dB	154.89 deg	-20.66 dB	154.75 deg	-21.10 dB	154.05 deg
0.00315 Hz	-16.90 dB	148.03 deg	-16.88 dB	147.76 deg	-16.89 dB	147.88 deg	-16.89 dB	148.39 deg
0.004 Hz	-12.88 dB	138.53 deg	-12.88 dB	138.21 deg	-12.96 dB	138.36 deg	-12.94 dB	138.43 deg
0.005 Hz	-9.30 dB	126.89 deg	-9.32 dB	126.65 deg	-9.37 dB	126.47 deg	-9.44 dB	126.46 deg
0.0063 Hz	-5.98 dB	111.59 deg	-6.00 dB	111.41 deg	-6.00 dB	110.96 deg	-6.05 dB	111.49 deg
0.008 Hz	-3.29 dB	92.91 deg	-3.30 dB	92.86 deg	-3.30 dB	92.52 deg	-3.31 dB	92.85 deg
0.010 Hz	-1.64 dB	74.99 deg	-1.63 dB	74.98 deg	-1.65 dB	74.71 deg	-1.70 dB	74.84 deg
0.0125 Hz	-0.74 dB	59.01 deg	-0.72 dB	59.14 deg	-0.74 dB	58.78 deg	-0.76 dB	59.28 deg
0.016 Hz	-0.28 dB	44.88 deg	-0.25 dB	44.86 deg	-0.28 dB	44.75 deg	-0.26 dB	44.89 deg
0.020 Hz	-0.12 dB	35.13 deg	-0.09 dB	35.12 deg	-0.09 dB	34.95 deg	-0.09 dB	35.42 deg
0.025 Hz	-0.05 dB	27.64 deg	0.00 dB	27.66 deg	-0.04 dB	27.44 deg	-0.03 dB	27.71 deg
0.0315 Hz	-0.02 dB	21.67 deg	0.01 dB	21.64 deg	0.01 dB	21.45 deg	-0.01 dB	21.91 deg
0.040 Hz	-0.01 dB	16.93 deg	0.03 dB	16.83 deg	0.01 dB	16.85 deg	0.02 dB	16.87 deg
0.050 Hz	-0.01 dB	13.47 deg	0.03 dB	13.35 deg	0.02 dB	13.29 deg	0.02 dB	13.45 deg
0.063 Hz	-0.01 dB	10.65 deg	0.03 dB	10.55 deg	0.01 dB	10.36 deg	0.02 dB	10.65 deg
0.080 Hz	-0.01 dB	8.36 deg	0.03 dB	8.24 deg	0.02 dB	8.18 deg	0.02 dB	8.28 deg
0.100 Hz	-0.01 dB	6.68 deg	0.02 dB	6.72 deg	0.02 dB	6.67 deg	0.02 dB	6.77 deg
0.125 Hz	-0.01 dB	5.33 deg	0.02 dB	5.37 deg	0.01 dB	5.41 deg	0.01 dB	5.36 deg
0.160 Hz	-0.01 dB	4.15 deg	0.02 dB	4.02 deg	0.02 dB	3.96 deg	0.01 dB	4.06 deg
0.200 Hz	-0.01 dB	3.31 deg	0.01 dB	3.23 deg	0.01 dB	3.13 deg	0.01 dB	3.29 deg
0.250 Hz	-0.01 dB	2.63 deg	0.01 dB	2.55 deg	0.01 dB	2.47 deg	0.00 dB	2.57 deg
0.315 Hz	-0.01 dB	2.07 deg	0.01 dB	1.88 deg	0.00 dB	1.83 deg	0.01 dB	1.92 deg
0.400 Hz	-0.01 dB	1.61 deg	0.01 dB	1.43 deg	0.00 dB	1.40 deg	0.00 dB	1.43 deg
0.500 Hz	-0.01 dB	1.25 deg	0.00 dB	1.09 deg	0.00 dB	1.04 deg	0.00 dB	1.07 deg
0.630 Hz	-0.01 dB	0.96 deg	0.00 dB	0.78 deg	0.00 dB	0.77 deg	0.00 dB	0.73 deg
0.800 Hz	0.00 dB	0.70 deg	0.00 dB	0.51 deg	0.01 dB	0.50 deg	0.00 dB	0.45 deg
1.000 Hz	0.00 dB	0.50 deg	0.00 dB	0.30 deg	0.00 dB	0.28 deg	0.00 dB	0.25 deg
1.250 Hz	0.00 dB	0.31 deg	0.02 dB	0.12 deg	0.01 dB	0.13 deg	0.01 dB	0.00 deg
1.600 Hz	0.01 dB	0.12 deg	0.02 dB	-0.05 deg	0.01 dB	-0.05 deg	0.02 dB	-0.21 deg
2.000 Hz	0.02 dB	-0.07 deg	0.02 dB	-0.27 deg	0.03 dB	-0.16 deg	0.03 dB	-0.43 deg
2.500 Hz	0.04 dB	-0.28 deg	0.04 dB	-0.43 deg	0.05 dB	-0.39 deg	0.06 dB	-0.66 deg
3.150 Hz	0.06 dB	-0.56 deg	0.06 dB	-0.66 deg	0.08 dB	-0.76 deg	0.11 dB	-0.97 deg
4.000 Hz	0.08 dB	-0.94 deg	0.10 dB	-0.99 deg	0.11 dB	-0.92 deg	0.19 dB	-1.36 deg
5.000 Hz	0.11 dB	-1.41 deg	0.14 dB	-1.43 deg	0.22 dB	-1.45 deg	0.30 dB	-1.84 deg
6.300 Hz	0.13 dB	-2.04 deg	0.24 dB	-2.18 deg	0.36 dB	-2.03 deg	0.42 dB	-2.69 deg
8.000 Hz	0.15 dB	-2.86 deg	0.33 dB	-3.40 deg	0.52 dB	-3.27 deg	0.66 dB	-3.73 deg
10.000 Hz	0.17 dB	-3.80 deg	0.39 dB	-5.16 deg	0.84 dB	-5.54 deg	1.03 dB	-4.37 deg
12.500 Hz	0.20 dB	-4.91 deg	0.56 dB	-8.42 deg	1.23 dB	-8.17 deg	1.56 dB	-6.21 deg
16.000 Hz	0.24 dB	-6.37 deg	0.83 dB	-11.36 deg	2.02 dB	-8.39 deg	2.43 dB	-8.40 deg
20.000 Hz	0.32 dB	-8.01 deg	1.12 dB	-17.31 deg	3.50 dB	-16.36 deg	4.24 dB	-11.48 deg

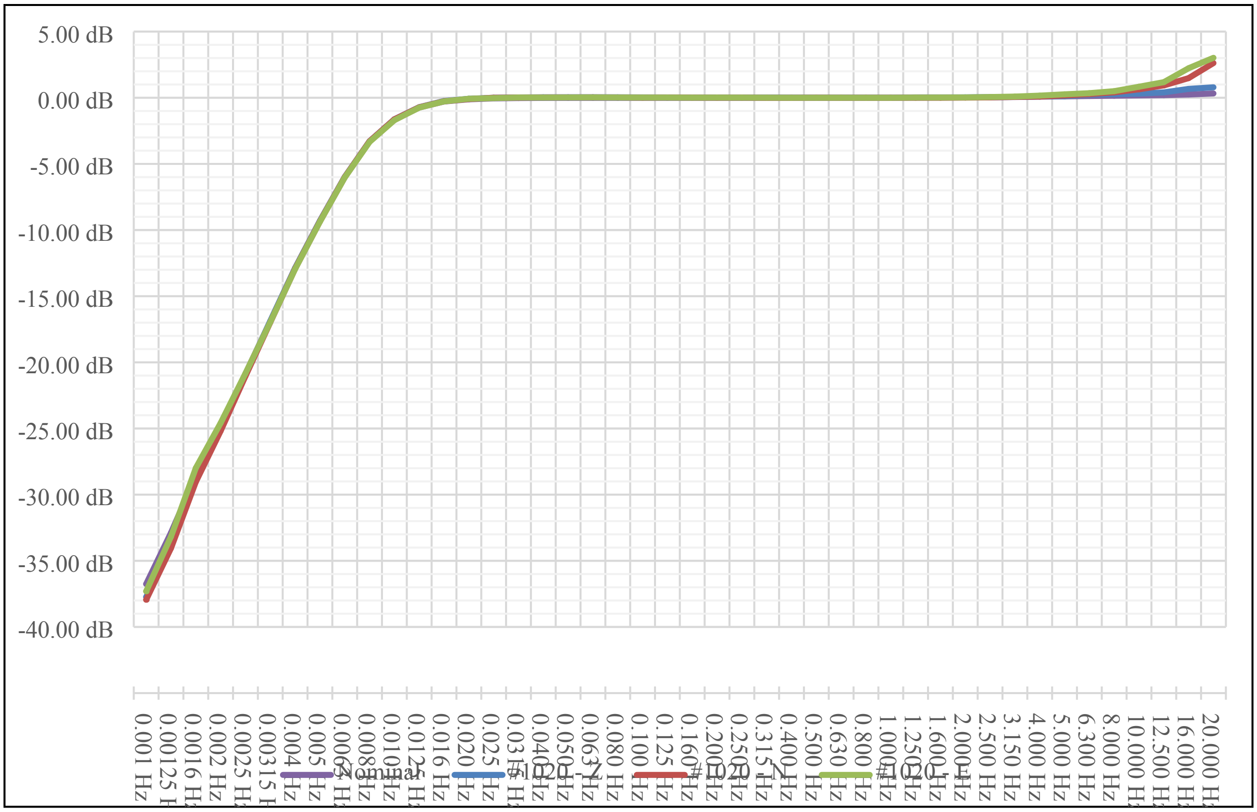


Figure 36 Amplitude Response - #1020

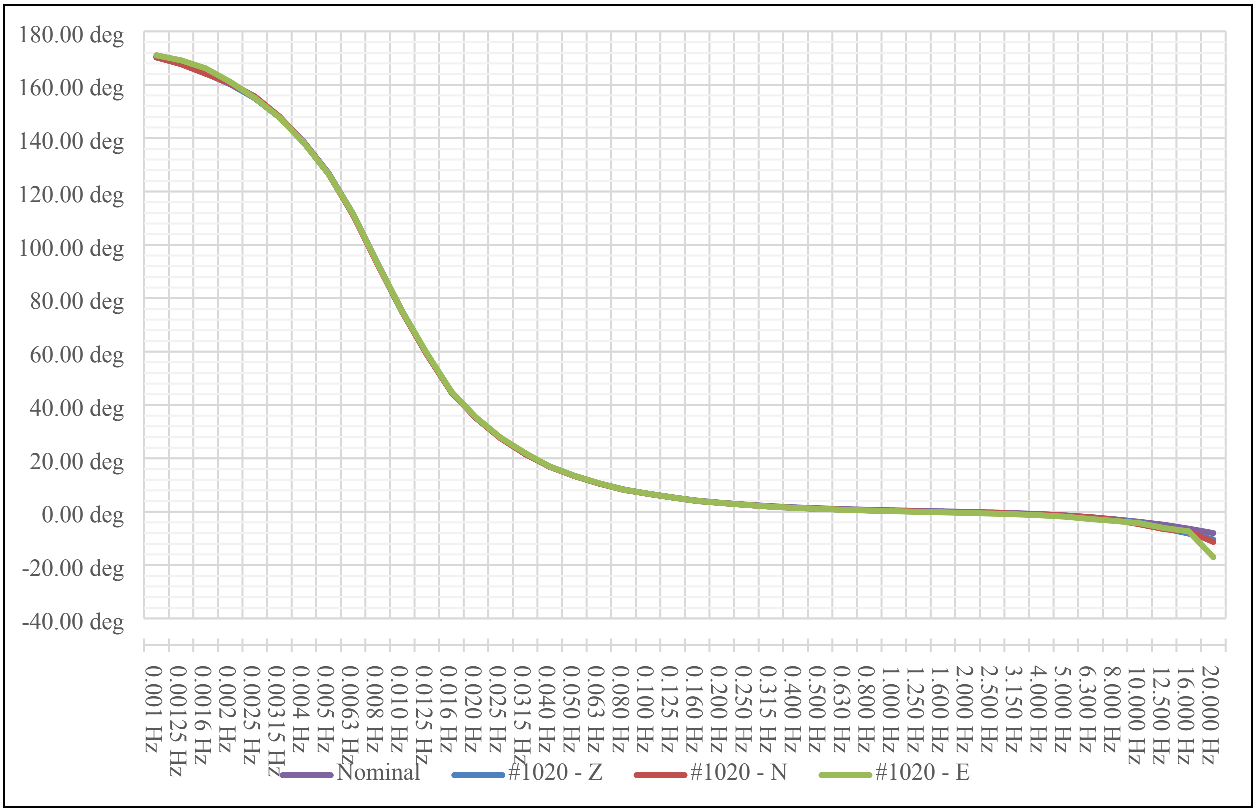


Figure 37 Phase Response - #1020

Table 18 Frequency Response - #1020

	Nominal		Z		N		E	
Frequency	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0.001 Hz	-36.75 dB	170.24 deg	-37.74 dB	170.48 deg	-37.94 dB	170.34 deg	-37.30 dB	171.03 deg
0.00125 Hz	-32.88 dB	167.76 deg	-33.80 dB	168.31 deg	-34.05 dB	167.71 deg	-33.17 dB	169.16 deg
0.0016 Hz	-28.59 dB	164.26 deg	-28.77 dB	165.08 deg	-29.04 dB	164.15 deg	-27.99 dB	166.16 deg
0.002 Hz	-24.72 dB	160.20 deg	-25.01 dB	160.53 deg	-25.18 dB	160.61 deg	-24.59 dB	161.09 deg
0.0025 Hz	-20.86 dB	155.00 deg	-20.93 dB	154.93 deg	-21.04 dB	155.62 deg	-20.83 dB	155.06 deg
0.00315 Hz	-16.90 dB	148.03 deg	-16.88 dB	147.80 deg	-16.98 dB	148.12 deg	-16.96 dB	147.79 deg
0.004 Hz	-12.88 dB	138.53 deg	-12.87 dB	138.25 deg	-12.92 dB	138.33 deg	-12.95 dB	138.25 deg
0.005 Hz	-9.30 dB	126.89 deg	-9.32 dB	126.69 deg	-9.35 dB	126.60 deg	-9.37 dB	126.59 deg
0.0063 Hz	-5.98 dB	111.59 deg	-6.00 dB	111.47 deg	-6.01 dB	111.19 deg	-6.03 dB	111.59 deg
0.008 Hz	-3.29 dB	92.91 deg	-3.30 dB	92.91 deg	-3.29 dB	92.62 deg	-3.34 dB	92.92 deg
0.010 Hz	-1.64 dB	74.99 deg	-1.63 dB	75.05 deg	-1.63 dB	74.78 deg	-1.70 dB	75.03 deg
0.0125 Hz	-0.74 dB	59.01 deg	-0.71 dB	59.18 deg	-0.72 dB	58.97 deg	-0.75 dB	59.35 deg
0.016 Hz	-0.28 dB	44.88 deg	-0.25 dB	44.92 deg	-0.27 dB	44.72 deg	-0.28 dB	44.96 deg
0.020 Hz	-0.12 dB	35.13 deg	-0.08 dB	35.20 deg	-0.10 dB	35.12 deg	-0.07 dB	35.34 deg
0.025 Hz	-0.05 dB	27.64 deg	0.00 dB	27.67 deg	0.00 dB	27.52 deg	-0.03 dB	27.78 deg
0.0315 Hz	-0.02 dB	21.67 deg	0.02 dB	21.67 deg	0.01 dB	21.64 deg	0.02 dB	22.00 deg
0.040 Hz	-0.01 dB	16.93 deg	0.04 dB	16.87 deg	0.03 dB	16.81 deg	0.02 dB	16.92 deg
0.050 Hz	-0.01 dB	13.47 deg	0.04 dB	13.39 deg	0.03 dB	13.38 deg	0.02 dB	13.48 deg
0.063 Hz	-0.01 dB	10.65 deg	0.04 dB	10.57 deg	0.03 dB	10.58 deg	0.03 dB	10.69 deg
0.080 Hz	-0.01 dB	8.36 deg	0.04 dB	8.27 deg	0.03 dB	8.19 deg	0.02 dB	8.28 deg
0.100 Hz	-0.01 dB	6.68 deg	0.03 dB	6.75 deg	0.01 dB	6.74 deg	0.02 dB	6.75 deg
0.125 Hz	-0.01 dB	5.33 deg	0.03 dB	5.37 deg	0.02 dB	5.34 deg	0.01 dB	5.34 deg
0.160 Hz	-0.01 dB	4.15 deg	0.02 dB	4.06 deg	0.01 dB	3.99 deg	0.01 dB	4.05 deg
0.200 Hz	-0.01 dB	3.31 deg	0.02 dB	3.26 deg	0.01 dB	3.27 deg	0.01 dB	3.24 deg
0.250 Hz	-0.01 dB	2.63 deg	0.02 dB	2.56 deg	0.01 dB	2.55 deg	0.01 dB	2.56 deg
0.315 Hz	-0.01 dB	2.07 deg	0.02 dB	1.91 deg	0.00 dB	1.94 deg	0.01 dB	1.89 deg
0.400 Hz	-0.01 dB	1.61 deg	0.01 dB	1.44 deg	0.00 dB	1.43 deg	0.00 dB	1.42 deg
0.500 Hz	-0.01 dB	1.25 deg	0.01 dB	1.08 deg	0.00 dB	1.08 deg	0.00 dB	1.07 deg
0.630 Hz	-0.01 dB	0.96 deg	0.01 dB	0.77 deg	0.00 dB	0.78 deg	0.00 dB	0.70 deg
0.800 Hz	0.00 dB	0.70 deg	0.01 dB	0.50 deg	0.00 dB	0.50 deg	0.00 dB	0.44 deg
1.000 Hz	0.00 dB	0.50 deg	0.00 dB	0.30 deg	0.00 dB	0.28 deg	0.00 dB	0.22 deg
1.250 Hz	0.00 dB	0.31 deg	0.03 dB	0.06 deg	0.00 dB	0.11 deg	0.01 dB	-0.06 deg
1.600 Hz	0.01 dB	0.12 deg	0.03 dB	-0.05 deg	0.00 dB	-0.13 deg	0.02 dB	-0.23 deg
2.000 Hz	0.02 dB	-0.07 deg	0.03 dB	-0.35 deg	0.01 dB	-0.30 deg	0.03 dB	-0.47 deg
2.500 Hz	0.04 dB	-0.28 deg	0.04 dB	-0.50 deg	0.03 dB	-0.45 deg	0.05 dB	-0.69 deg
3.150 Hz	0.06 dB	-0.56 deg	0.06 dB	-0.73 deg	0.07 dB	-0.74 deg	0.09 dB	-0.98 deg
4.000 Hz	0.08 dB	-0.94 deg	0.10 dB	-1.06 deg	0.09 dB	-0.94 deg	0.16 dB	-1.36 deg
5.000 Hz	0.11 dB	-1.41 deg	0.12 dB	-1.58 deg	0.17 dB	-1.48 deg	0.26 dB	-1.87 deg
6.300 Hz	0.13 dB	-2.04 deg	0.24 dB	-2.16 deg	0.28 dB	-2.02 deg	0.35 dB	-2.74 deg
8.000 Hz	0.15 dB	-2.86 deg	0.27 dB	-3.20 deg	0.41 dB	-3.09 deg	0.50 dB	-3.46 deg
10.000 Hz	0.17 dB	-3.80 deg	0.31 dB	-3.91 deg	0.64 dB	-4.72 deg	0.83 dB	-4.32 deg
12.500 Hz	0.20 dB	-4.91 deg	0.40 dB	-6.24 deg	0.93 dB	-6.53 deg	1.18 dB	-6.10 deg
16.000 Hz	0.24 dB	-6.37 deg	0.67 dB	-8.19 deg	1.48 dB	-7.42 deg	2.23 dB	-7.36 deg
20.000 Hz	0.32 dB	-8.01 deg	0.79 dB	-10.42 deg	2.62 dB	-11.31 deg	3.02 dB	-17.02 deg

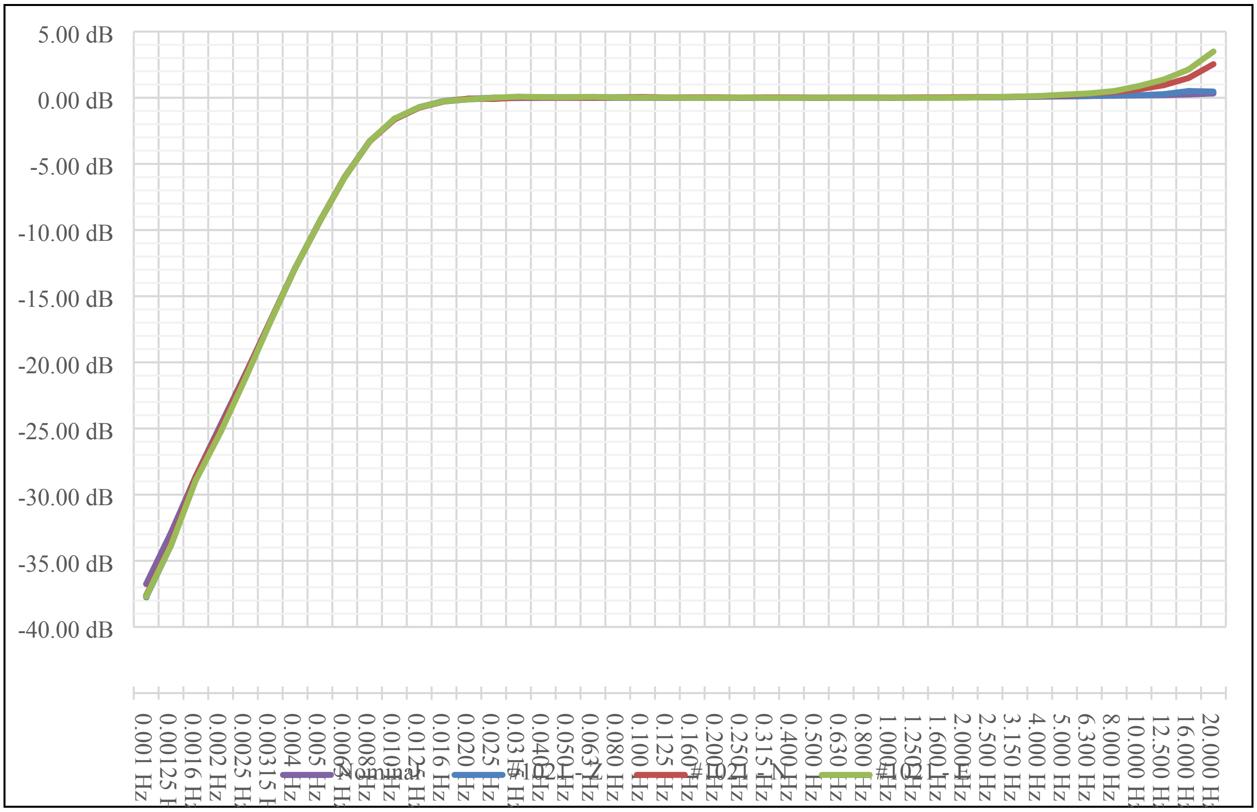


Figure 38 Amplitude Response - #1021

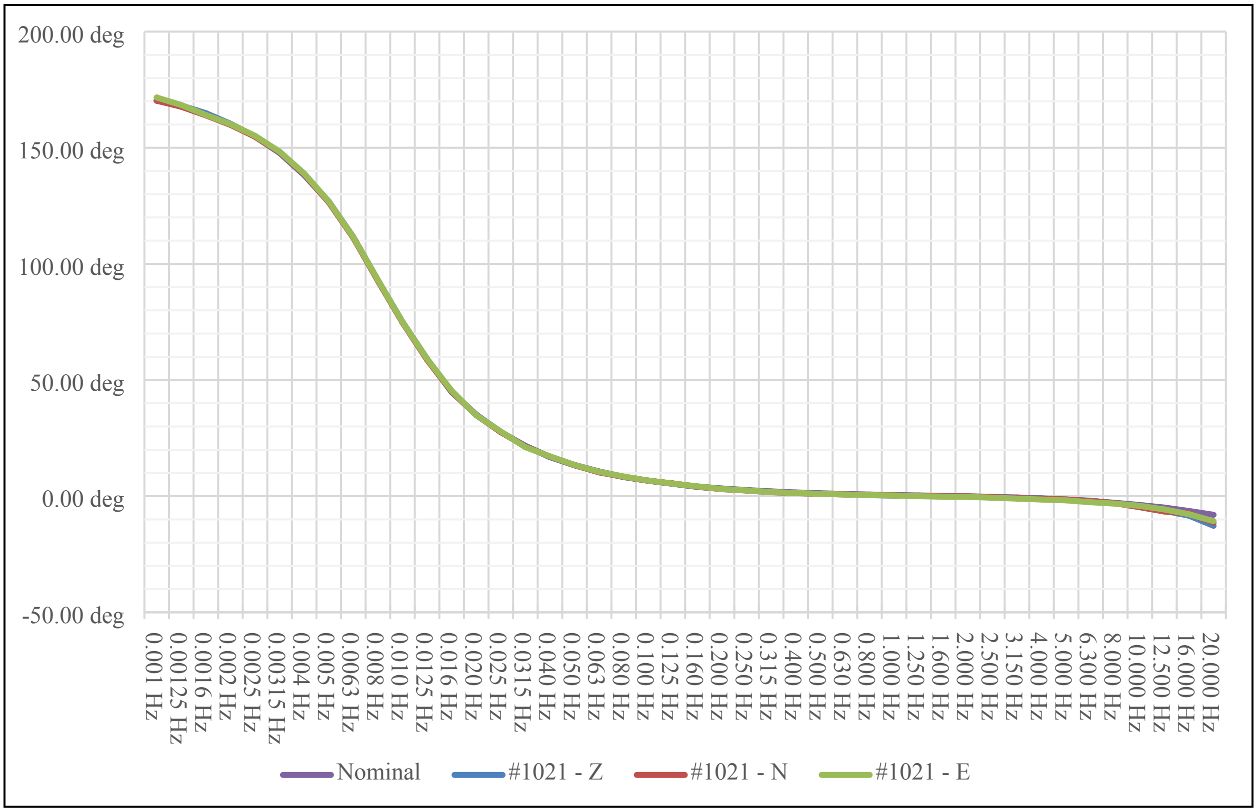


Figure 39 Phase Response - #1021

Table 19 Frequency Response - #1021

	Nominal		Z		N		E	
Frequency	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0.001 Hz	-36.75 dB	170.24 deg	-37.76 dB	170.44 deg	-37.62 dB	170.34 deg	-37.70 dB	171.63 deg
0.00125 Hz	-32.88 dB	167.76 deg	-33.84 dB	168.20 deg	-33.68 dB	167.66 deg	-33.84 dB	168.40 deg
0.0016 Hz	-28.59 dB	164.26 deg	-28.82 dB	164.89 deg	-28.65 dB	163.94 deg	-28.90 dB	164.12 deg
0.002 Hz	-24.72 dB	160.20 deg	-25.04 dB	160.34 deg	-24.97 dB	159.86 deg	-25.27 dB	160.17 deg
0.0025 Hz	-20.86 dB	155.00 deg	-20.95 dB	154.79 deg	-20.95 dB	154.76 deg	-21.21 dB	155.14 deg
0.00315 Hz	-16.90 dB	148.03 deg	-16.88 dB	147.76 deg	-16.88 dB	148.02 deg	-16.96 dB	148.34 deg
0.004 Hz	-12.88 dB	138.53 deg	-12.87 dB	138.21 deg	-12.89 dB	138.47 deg	-12.89 dB	138.92 deg
0.005 Hz	-9.30 dB	126.89 deg	-9.32 dB	126.64 deg	-9.34 dB	126.54 deg	-9.32 dB	126.88 deg
0.0063 Hz	-5.98 dB	111.59 deg	-6.00 dB	111.40 deg	-6.00 dB	111.20 deg	-6.01 dB	111.50 deg
0.008 Hz	-3.29 dB	92.91 deg	-3.29 dB	92.85 deg	-3.32 dB	92.73 deg	-3.30 dB	93.08 deg
0.010 Hz	-1.64 dB	74.99 deg	-1.62 dB	74.98 deg	-1.64 dB	74.78 deg	-1.58 dB	75.03 deg
0.0125 Hz	-0.74 dB	59.01 deg	-0.71 dB	59.13 deg	-0.75 dB	58.69 deg	-0.71 dB	59.09 deg
0.016 Hz	-0.28 dB	44.88 deg	-0.24 dB	44.84 deg	-0.27 dB	45.02 deg	-0.26 dB	45.40 deg
0.020 Hz	-0.12 dB	35.13 deg	-0.08 dB	35.09 deg	-0.06 dB	34.88 deg	-0.13 dB	34.86 deg
0.025 Hz	-0.05 dB	27.64 deg	0.01 dB	27.64 deg	-0.09 dB	27.56 deg	0.00 dB	27.85 deg
0.0315 Hz	-0.02 dB	21.67 deg	0.02 dB	21.61 deg	0.02 dB	21.36 deg	0.08 dB	21.10 deg
0.040 Hz	-0.01 dB	16.93 deg	0.04 dB	16.79 deg	0.01 dB	17.03 deg	0.05 dB	17.16 deg
0.050 Hz	-0.01 dB	13.47 deg	0.04 dB	13.31 deg	0.02 dB	13.32 deg	0.04 dB	13.46 deg
0.063 Hz	-0.01 dB	10.65 deg	0.04 dB	10.52 deg	0.00 dB	10.25 deg	0.07 dB	10.51 deg
0.080 Hz	-0.01 dB	8.36 deg	0.04 dB	8.22 deg	0.03 dB	8.33 deg	0.02 dB	8.46 deg
0.100 Hz	-0.01 dB	6.68 deg	0.03 dB	6.71 deg	0.05 dB	6.64 deg	0.01 dB	6.74 deg
0.125 Hz	-0.01 dB	5.33 deg	0.03 dB	5.37 deg	0.02 dB	5.50 deg	0.02 dB	5.43 deg
0.160 Hz	-0.01 dB	4.15 deg	0.03 dB	3.99 deg	0.03 dB	4.07 deg	0.00 dB	4.24 deg
0.200 Hz	-0.01 dB	3.31 deg	0.03 dB	3.21 deg	0.03 dB	3.03 deg	0.00 dB	3.08 deg
0.250 Hz	-0.01 dB	2.63 deg	0.02 dB	2.53 deg	0.01 dB	2.45 deg	0.02 dB	2.48 deg
0.315 Hz	-0.01 dB	2.07 deg	0.02 dB	1.87 deg	0.03 dB	1.73 deg	-0.01 dB	1.76 deg
0.400 Hz	-0.01 dB	1.61 deg	0.02 dB	1.41 deg	0.02 dB	1.34 deg	-0.01 dB	1.39 deg
0.500 Hz	-0.01 dB	1.25 deg	0.01 dB	1.07 deg	0.00 dB	1.01 deg	0.01 dB	1.00 deg
0.630 Hz	-0.01 dB	0.96 deg	0.01 dB	0.78 deg	0.01 dB	0.76 deg	0.00 dB	0.74 deg
0.800 Hz	0.00 dB	0.70 deg	0.01 dB	0.48 deg	0.02 dB	0.52 deg	0.00 dB	0.44 deg
1.000 Hz	0.00 dB	0.50 deg	0.00 dB	0.28 deg	0.00 dB	0.33 deg	0.01 dB	0.30 deg
1.250 Hz	0.00 dB	0.31 deg	0.02 dB	0.10 deg	0.03 dB	0.08 deg	0.00 dB	-0.01 deg
1.600 Hz	0.01 dB	0.12 deg	0.02 dB	-0.06 deg	0.03 dB	-0.08 deg	-0.01 dB	-0.21 deg
2.000 Hz	0.02 dB	-0.07 deg	0.02 dB	-0.26 deg	0.04 dB	-0.06 deg	0.01 dB	-0.31 deg
2.500 Hz	0.04 dB	-0.28 deg	0.03 dB	-0.49 deg	0.05 dB	-0.39 deg	0.04 dB	-0.66 deg
3.150 Hz	0.06 dB	-0.56 deg	0.06 dB	-0.75 deg	0.07 dB	-0.84 deg	0.08 dB	-1.04 deg
4.000 Hz	0.08 dB	-0.94 deg	0.08 dB	-1.01 deg	0.12 dB	-1.09 deg	0.13 dB	-1.45 deg
5.000 Hz	0.11 dB	-1.41 deg	0.10 dB	-1.58 deg	0.17 dB	-1.44 deg	0.24 dB	-1.80 deg
6.300 Hz	0.13 dB	-2.04 deg	0.13 dB	-1.93 deg	0.31 dB	-2.11 deg	0.33 dB	-2.59 deg
8.000 Hz	0.15 dB	-2.86 deg	0.19 dB	-3.12 deg	0.43 dB	-3.05 deg	0.51 dB	-3.22 deg
10.000 Hz	0.17 dB	-3.80 deg	0.19 dB	-4.17 deg	0.64 dB	-4.75 deg	0.89 dB	-4.18 deg
12.500 Hz	0.20 dB	-4.91 deg	0.27 dB	-6.30 deg	0.95 dB	-6.60 deg	1.38 dB	-5.71 deg
16.000 Hz	0.24 dB	-6.37 deg	0.51 dB	-8.38 deg	1.49 dB	-7.43 deg	2.14 dB	-7.75 deg
20.000 Hz	0.32 dB	-8.01 deg	0.47 dB	-12.74 deg	2.54 dB	-11.37 deg	3.50 dB	-10.76 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 the 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).

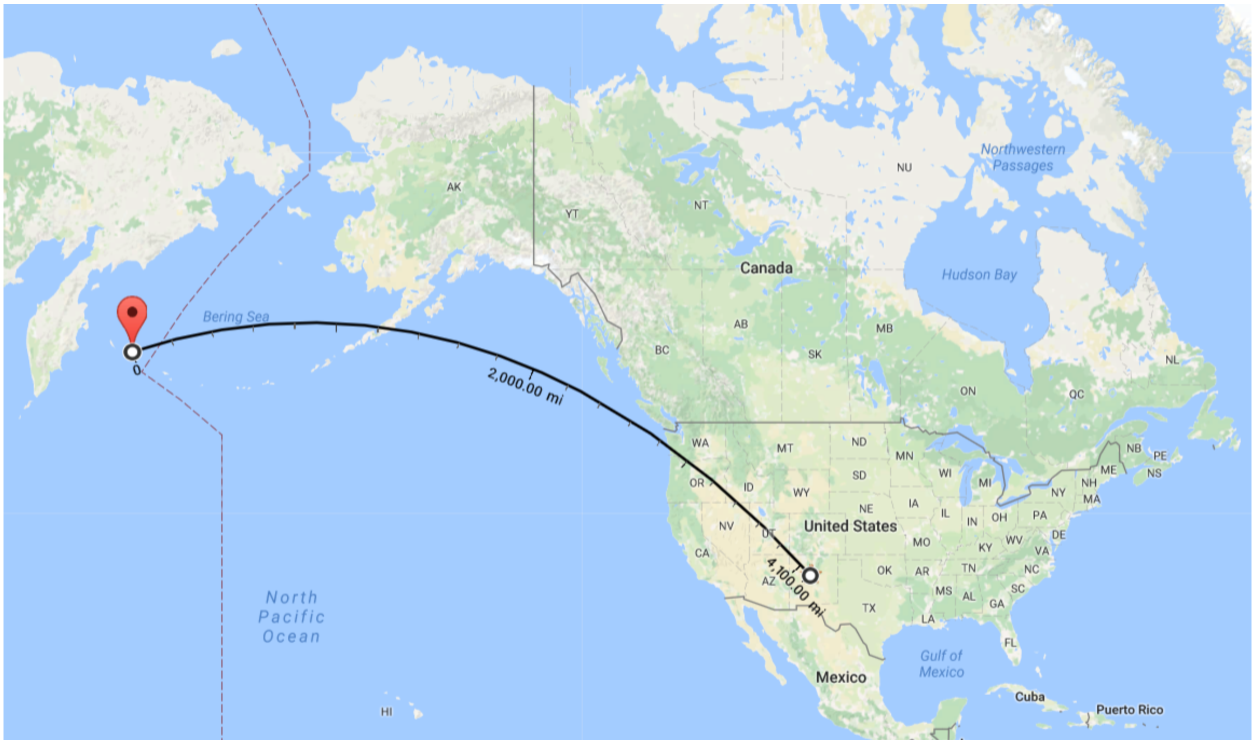
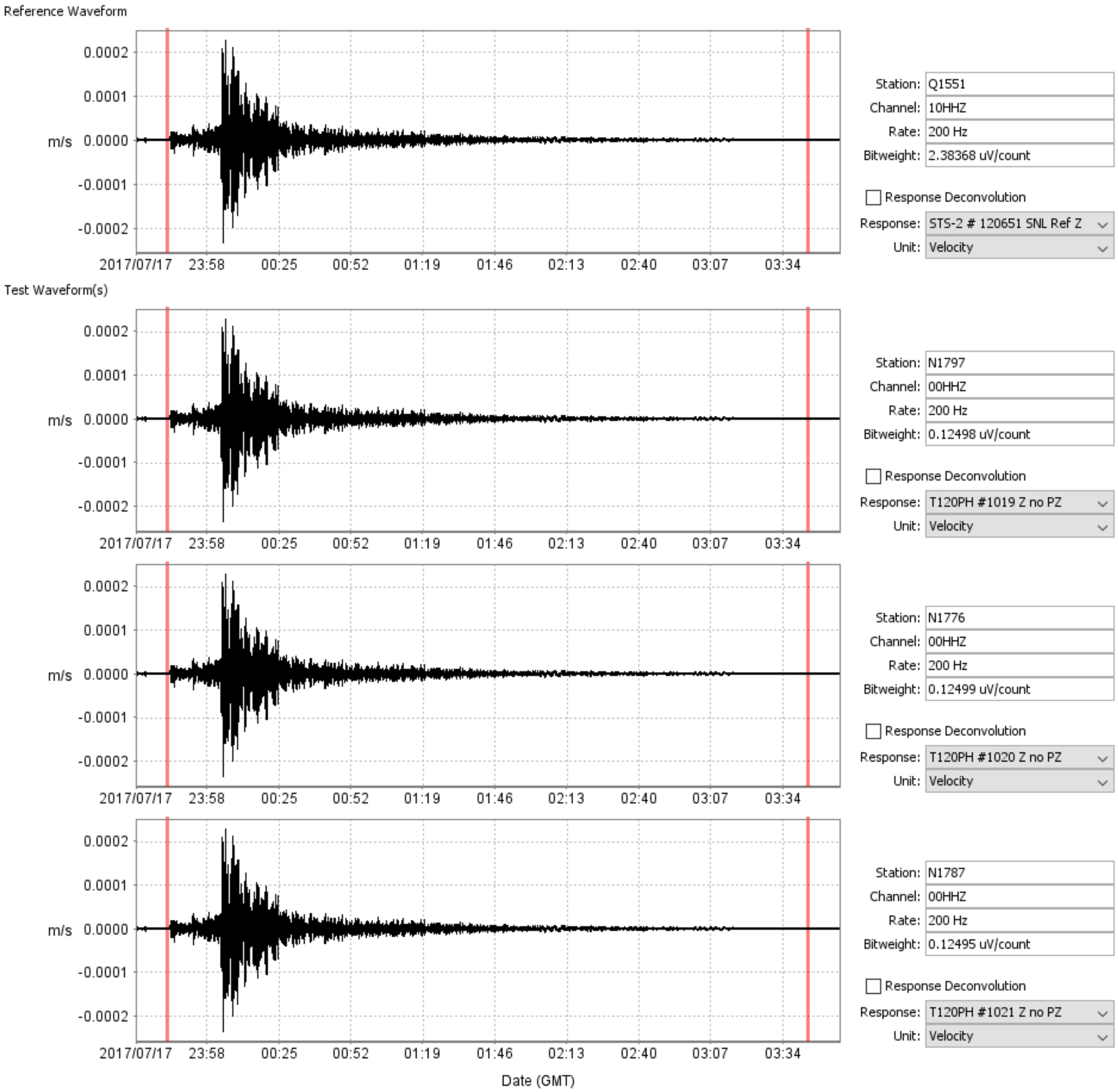


Figure 40 Sensitivity Earthquake Location

These 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. Only the vertical channel is shown as the two horizontal channels are nearly identical. The window regions bounded by the red lines indicate the segment of data used for analysis.



Station: Q1551
Channel: 10HHZ
Rate: 200 Hz
Bitweight: 2.38368 uV/count
☐ Response Deconvolution
Response: STS-2 # 120651 SNL Ref Z
Unit: Velocity

Station: N1797
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1019 Z no PZ
Unit: Velocity

Station: N1776
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1020 Z no PZ
Unit: Velocity

Station: N1787
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12495 uV/count
☐ Response Deconvolution
Response: T120PH #1021 Z no PZ
Unit: Velocity

Figure 41 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.

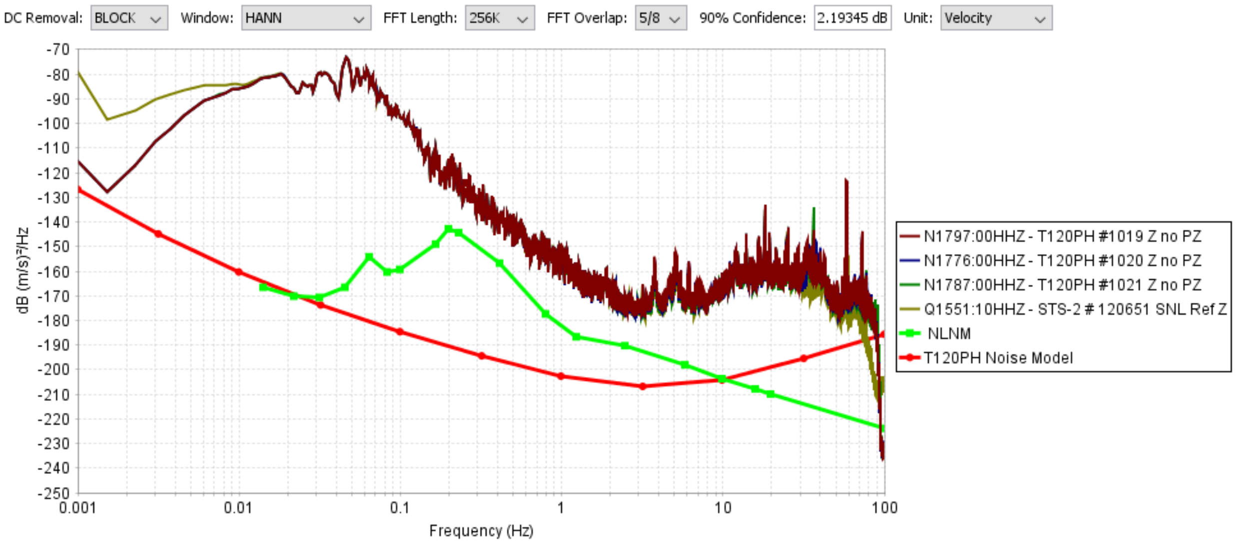

DC Removal: BLOCK Window: HANN FFT Length: 256K FFT Overlap: 5/8 90% Confidence: 2.19345 dB Unit: Velocity

Figure 42 Low Frequency Response Power Spectra

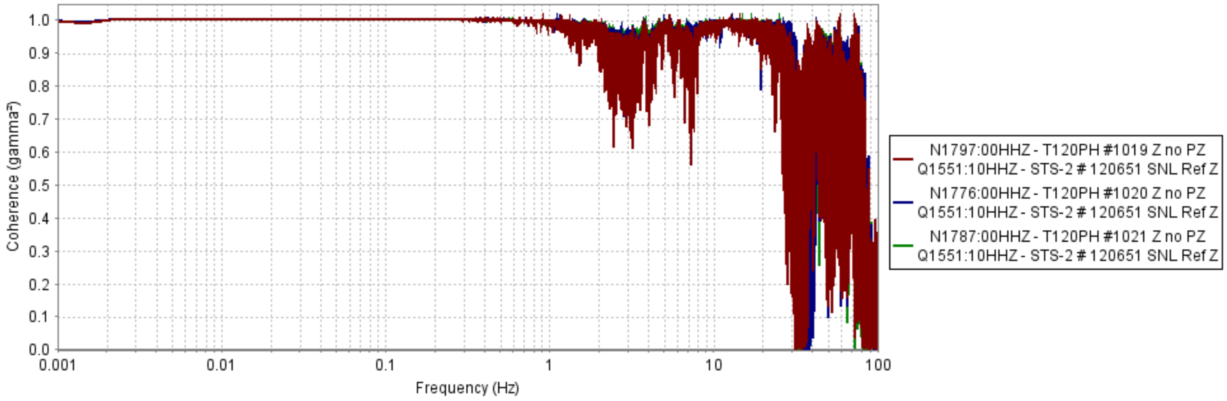


Figure 43 Low Frequency Response Coherence

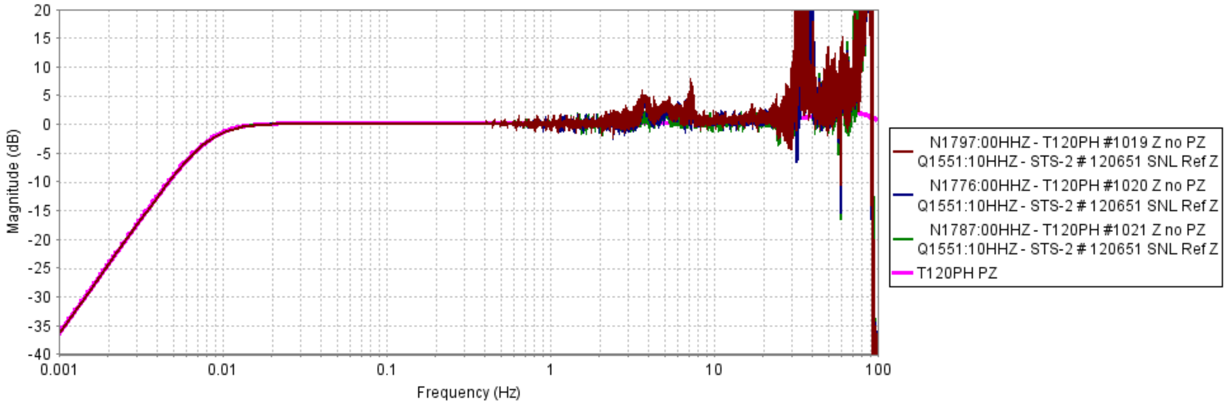


Figure 44 Low Frequency Amplitude Response

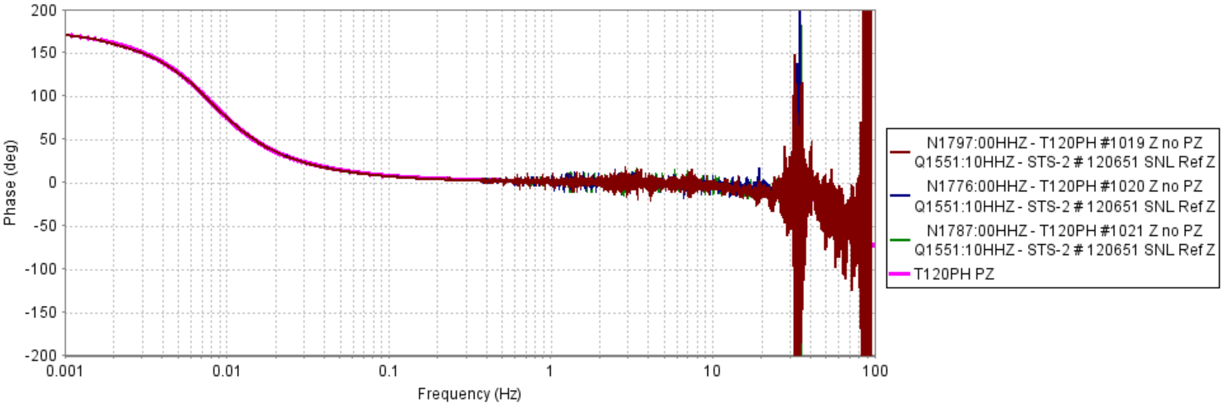


Figure 45 Low Frequency Phase Response

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 0.001 and 1 Hz. Across this pass-band the amplitude and phase response match very closely with the nominal response model, shown with a purple 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).

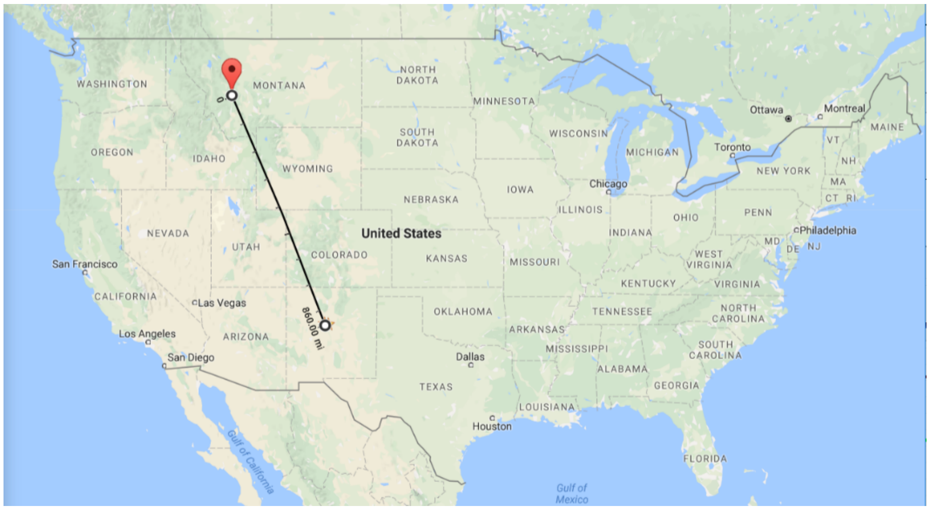
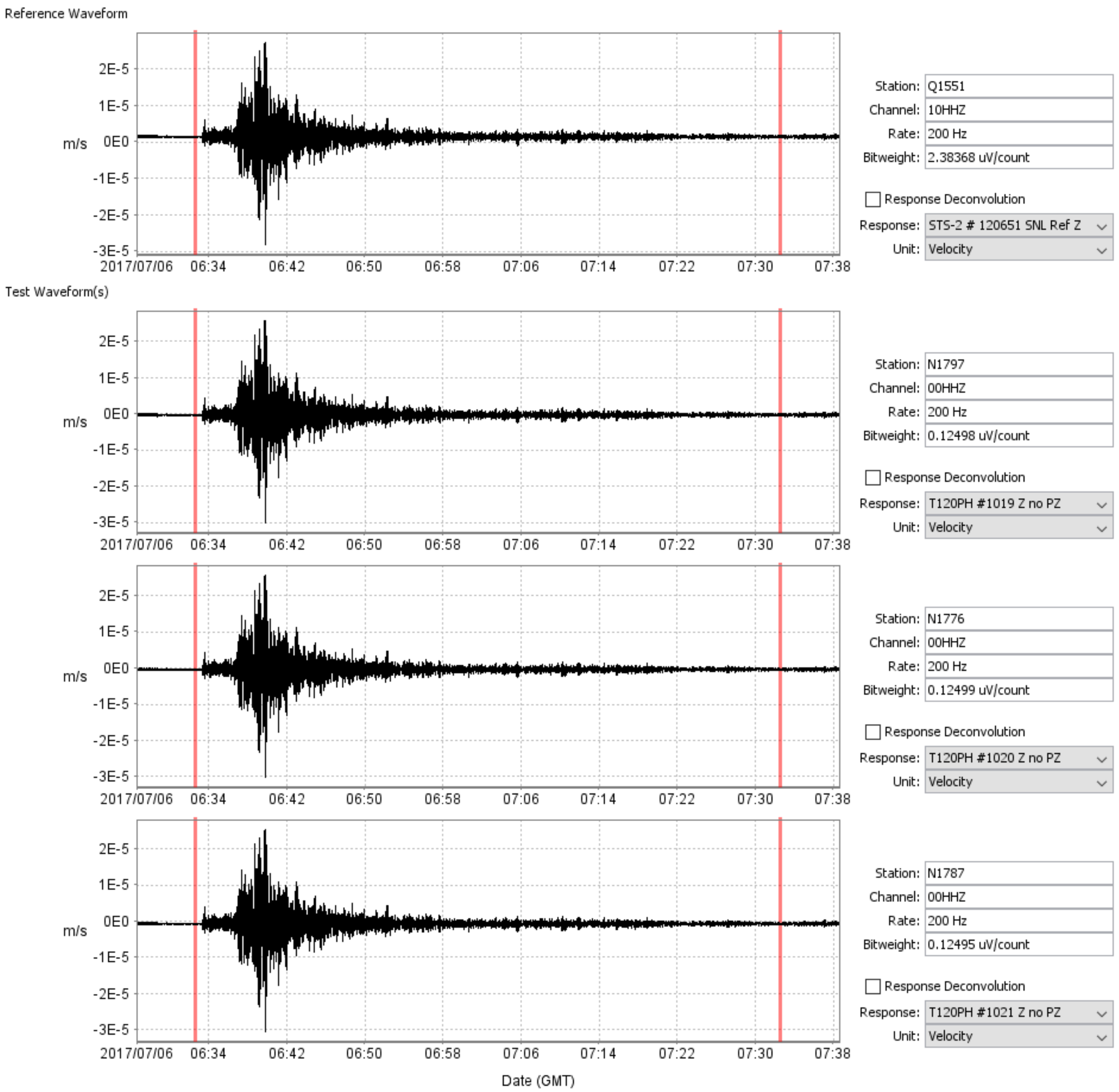


Figure 46 Sensitivity Earthquake Location

These earthquakes were 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. Only the vertical channel is shown as the two horizontal channels are nearly identical. The window regions bounded by the red lines indicate the segment of data used for analysis.



Station: Q1551
Channel: 10HHZ
Rate: 200 Hz
Bitweight: 2.38368 uV/count
☐ Response Deconvolution
Response: STS-2 # 120651 SNL Ref Z
Unit: Velocity

Station: N1797
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1019 Z no PZ
Unit: Velocity

Station: N1776
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1020 Z no PZ
Unit: Velocity

Station: N1787
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12495 uV/count
☐ Response Deconvolution
Response: T120PH #1021 Z no PZ
Unit: Velocity

Figure 47 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.

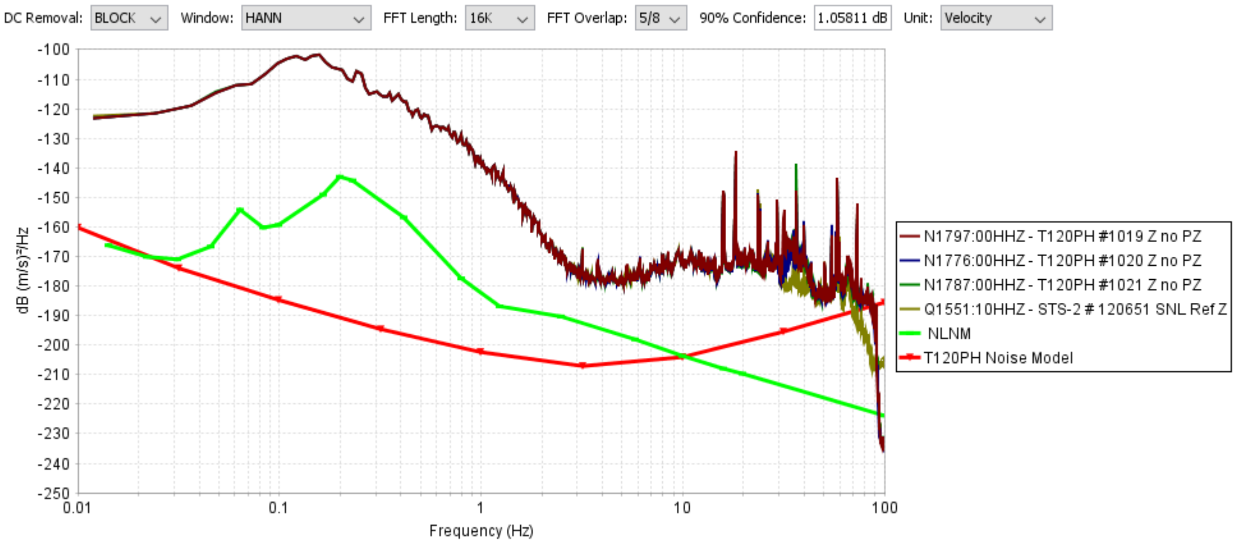

DC Removal: BLOCK Window: HANN FFT Length: 16K FFT Overlap: 5/8 90% Confidence: 1.05811 dB Unit: Velocity

Figure 48 Mid Frequency Response Power Spectra

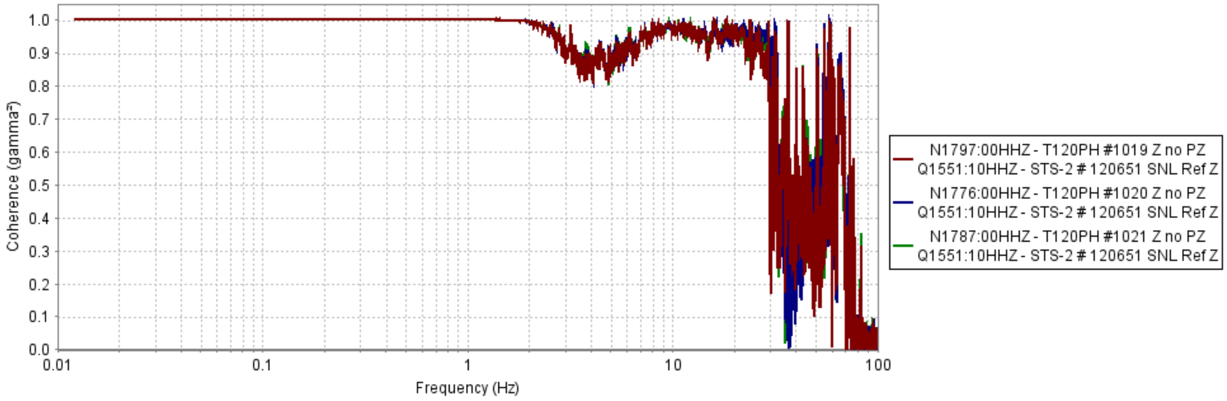


Figure 49 Mid Frequency Response Coherence

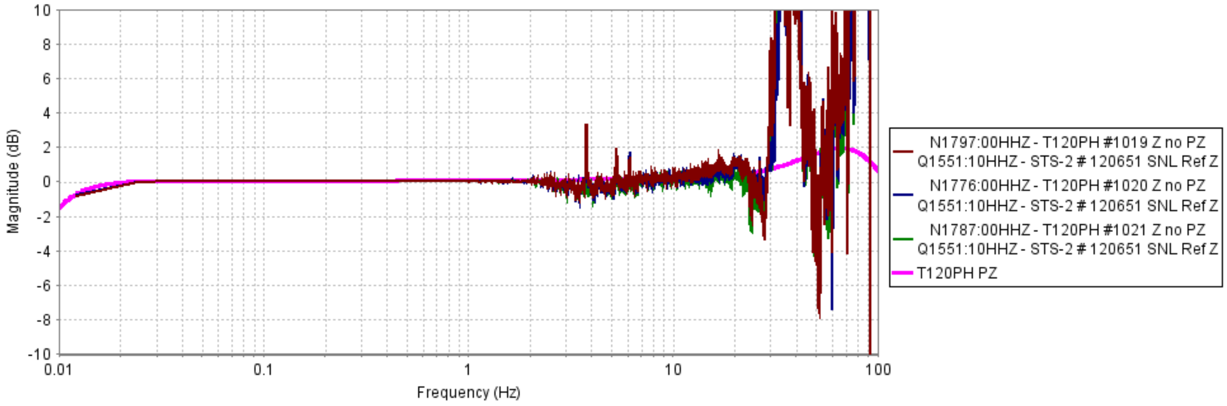


Figure 50 Mid Frequency Amplitude Response

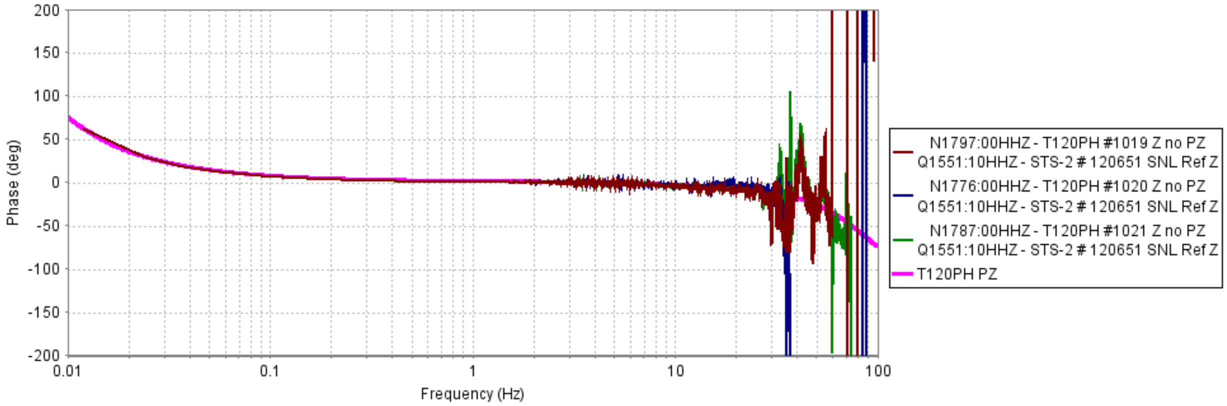


Figure 51 Mid Frequency Phase Response

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 response model, shown with a purple 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).

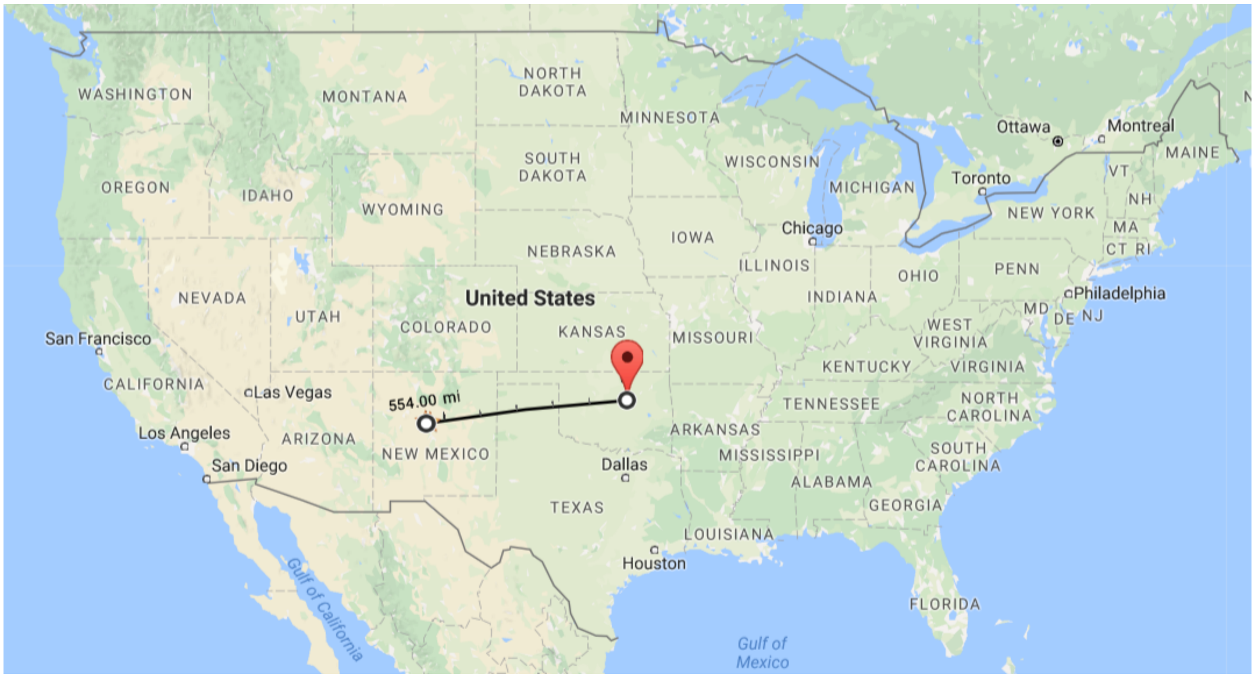
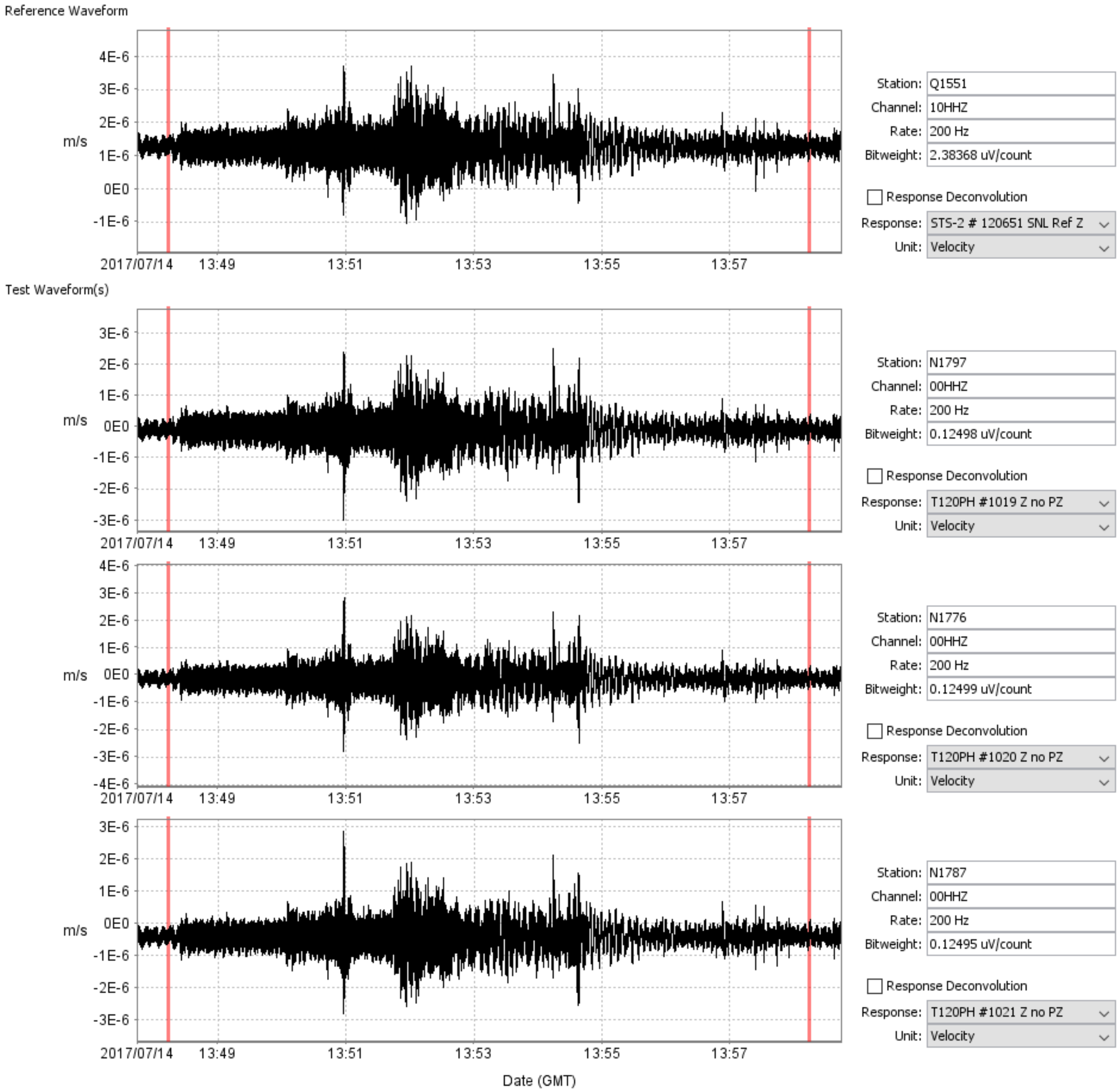


Figure 52 High Frequency Earthquake Location

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. Only the vertical channel is shown as the two horizontal channels are nearly identical. The window regions bounded by the red lines indicate the segment of data used for analysis.



Station: Q1551
Channel: 10HHZ
Rate: 200 Hz
Bitweight: 2.38368 uV/count
☐ Response Deconvolution
Response: STS-2 # 120651 SNL Ref Z
Unit: Velocity

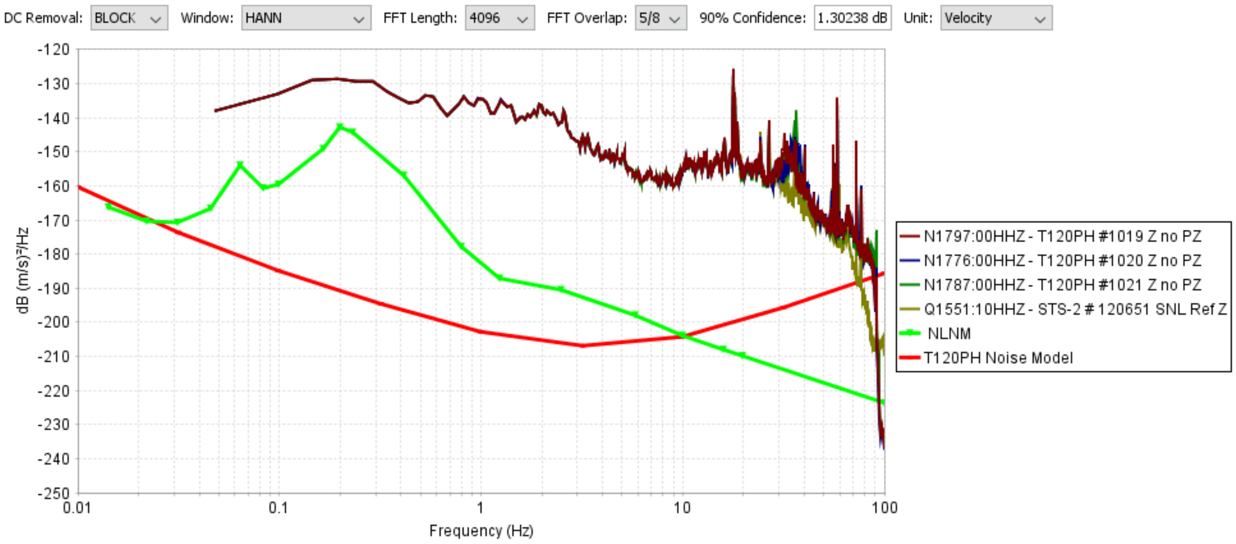
Station: N1797
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: T120PH #1019 Z no PZ
Unit: Velocity

Station: N1776
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1020 Z no PZ
Unit: Velocity

Station: N1787
Channel: 00HHZ
Rate: 200 Hz
Bitweight: 0.12495 uV/count
☐ Response Deconvolution
Response: T120PH #1021 Z no PZ
Unit: Velocity

Figure 53 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.



DC Removal: BLOCK Window: HANN FFT Length: 4096 FFT Overlap: 5/8 90% Confidence: 1.30238 dB Unit: Velocity

Figure 54 High Frequency Response Power Spectra

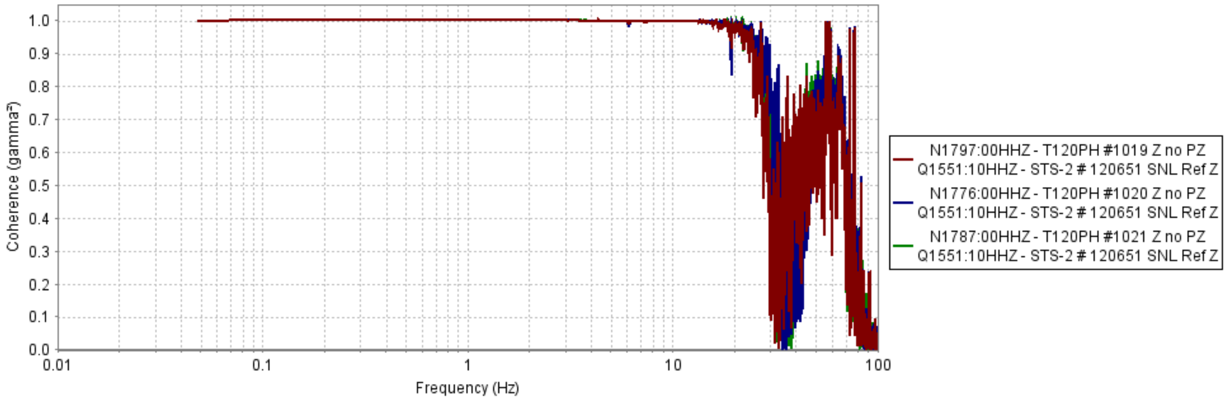


Figure 55 High Frequency Response Coherence

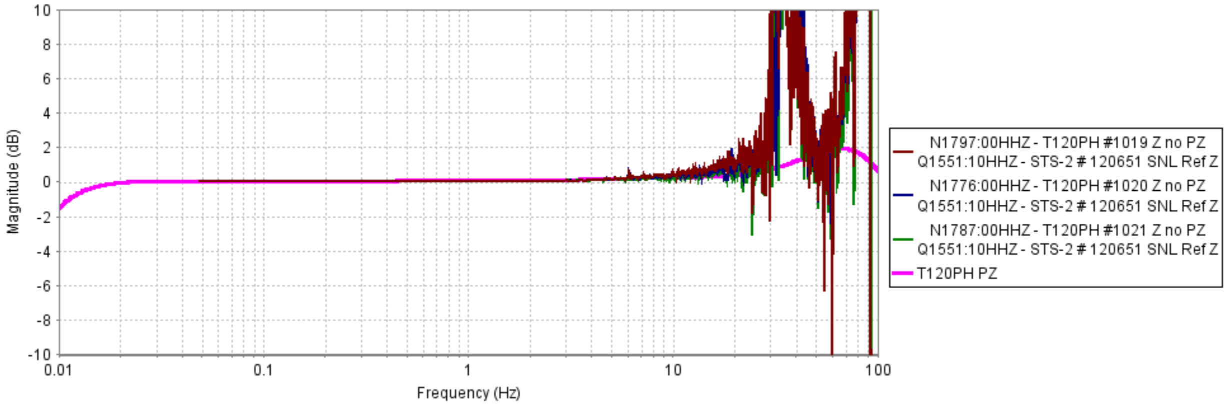


Figure 56 High Frequency Amplitude Response

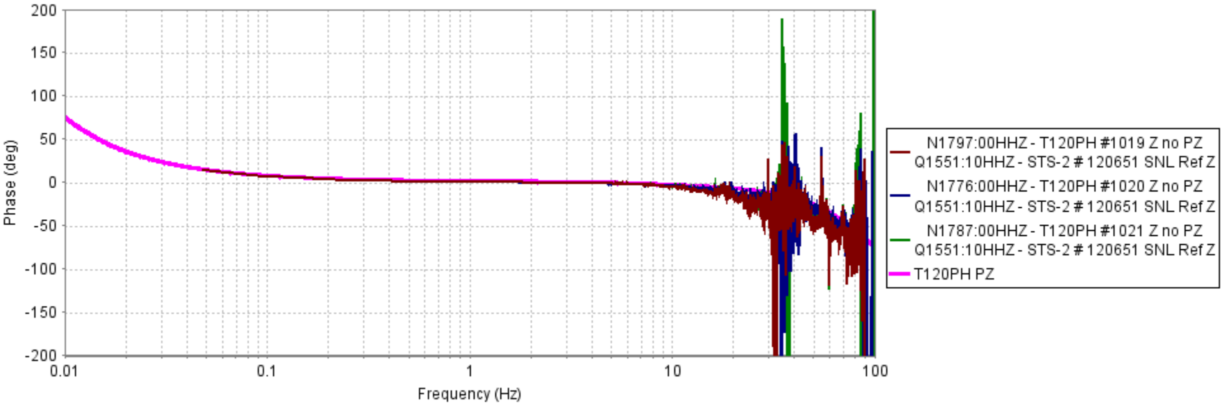


Figure 57 High Frequency Phase Response

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 20 Hz. Across this pass-band the amplitude and phase response match very closely with the nominal response model, shown with a purple 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.

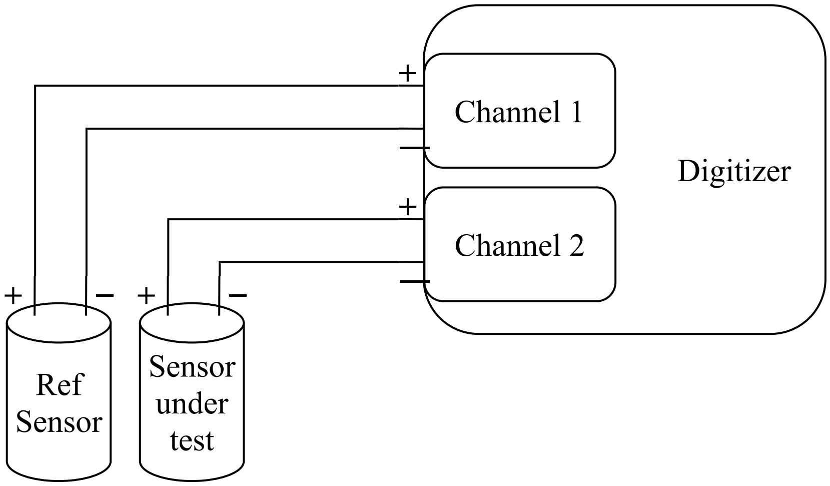


Figure 58 Passband Configuration Diagram

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 20 Passband 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	Nanometrics T120PH	# 1019, 1020, 1021	1500 V/(m/s)
Sensor Digitizers	Nanometrics Centaur	# N1776, N1787, N1797	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:

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

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.

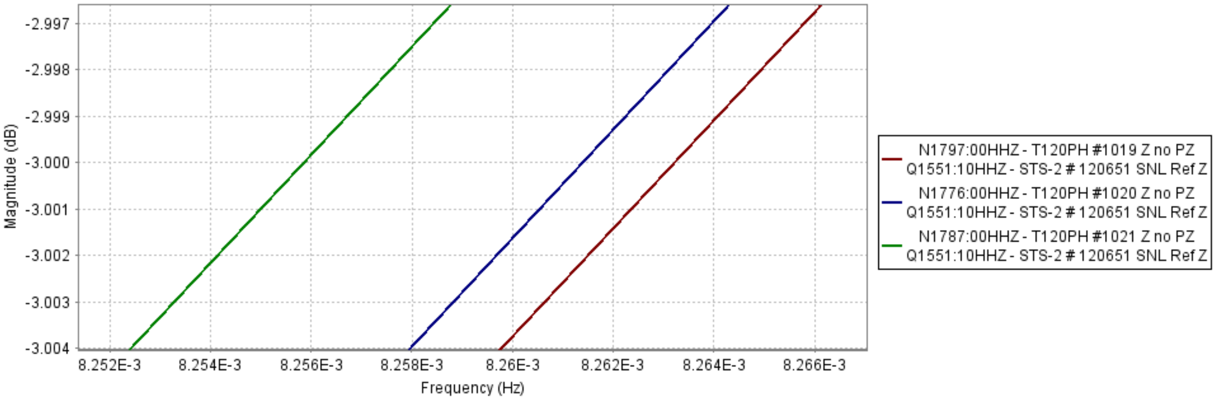


Figure 59 Passband Z Low Frequency

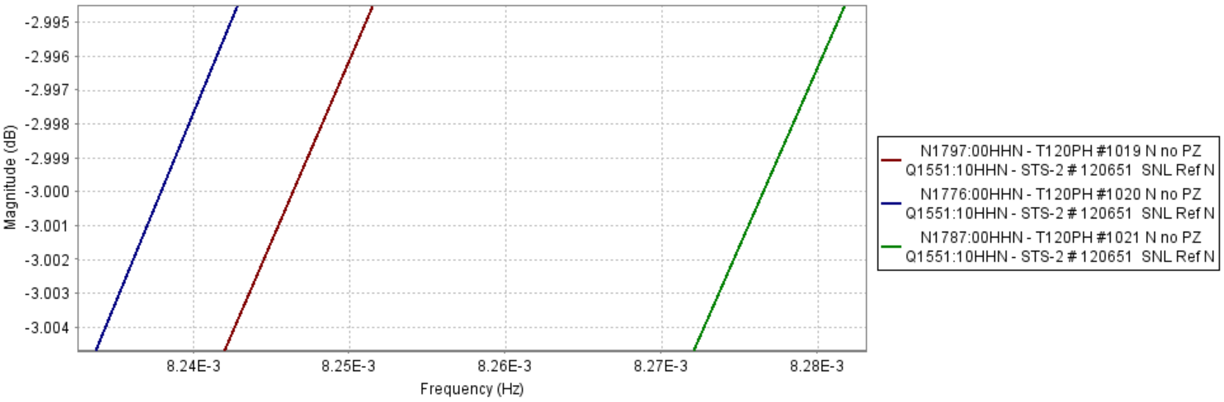


Figure 60 Passband N Low Frequency

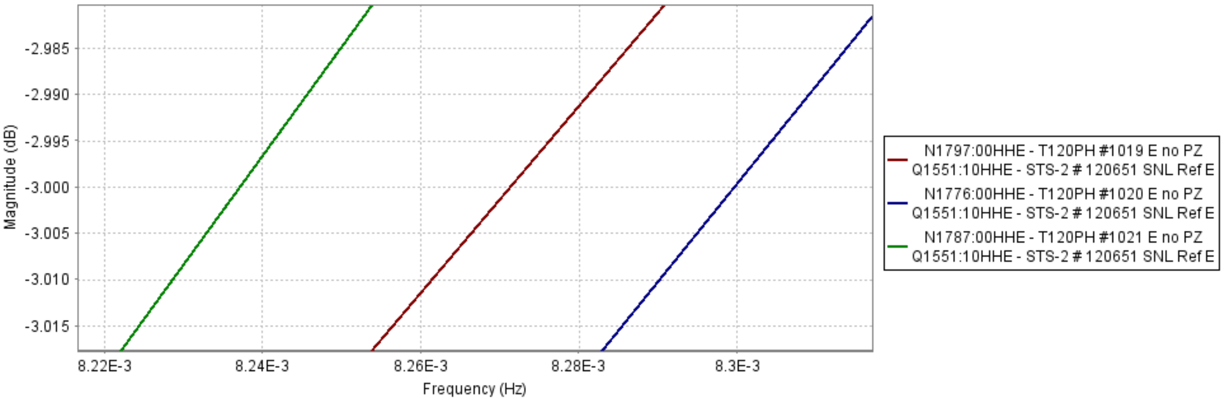


Figure 61 Passband E Low Frequency

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

Table 21 Passband

	Chanel	Low Frequency	High Frequency
Nominal		0.00833 Hz (120 sec)	150 Hz
T120PH #1019	Z	8.26 mHz	> 20 Hz
	N	8.25 mHz	> 20 Hz
	E	8.27 mHz	> 20 Hz
T120PH #1020	Z	8.26 mHz	> 20 Hz
	N	8.24 mHz	> 20 Hz
	E	8.30 mHz	> 20 Hz
T120PH #1021	Z	8.26 mHz	> 20 Hz
	N	8.28 mHz	> 20 Hz

We can observe that the low frequency corner was lower than the nominal 120 second, or 0.00833 Hz, corner specified for the Trillium 120PH. Actual values ranged between 0.00824 and 0.00830 Hz. Due to the data available, it is difficult to evaluate outside of the region in which there is coherence (< 20 Hz). However, it appears that the high frequency corner exceeds the 20 Hz limit of the coherence in this evaluation.

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 to the seismometers.

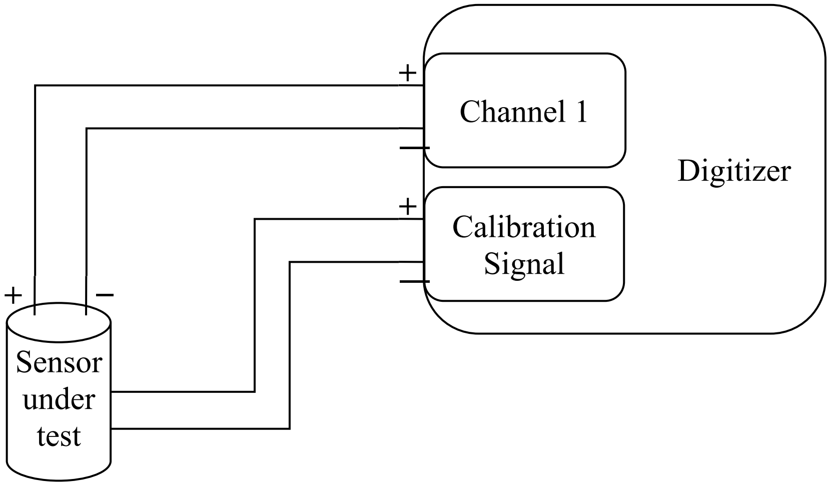


Figure 62 Calibrator Sensitivity Configuration Diagram

Table 22 Calibrator Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Sensor under test	Nanometrics T120PH	# 1019, 1020, 1021	1500 V/(m/s)
Sensor Digitizers	Nanometrics Centaur	# N1776, N1787, N1797	200 Hz, 40 Vpp

The digitizer is configured to generate a 1 Hz sinusoid for 30 seconds.

3.6.3 Analysis

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

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

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

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

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

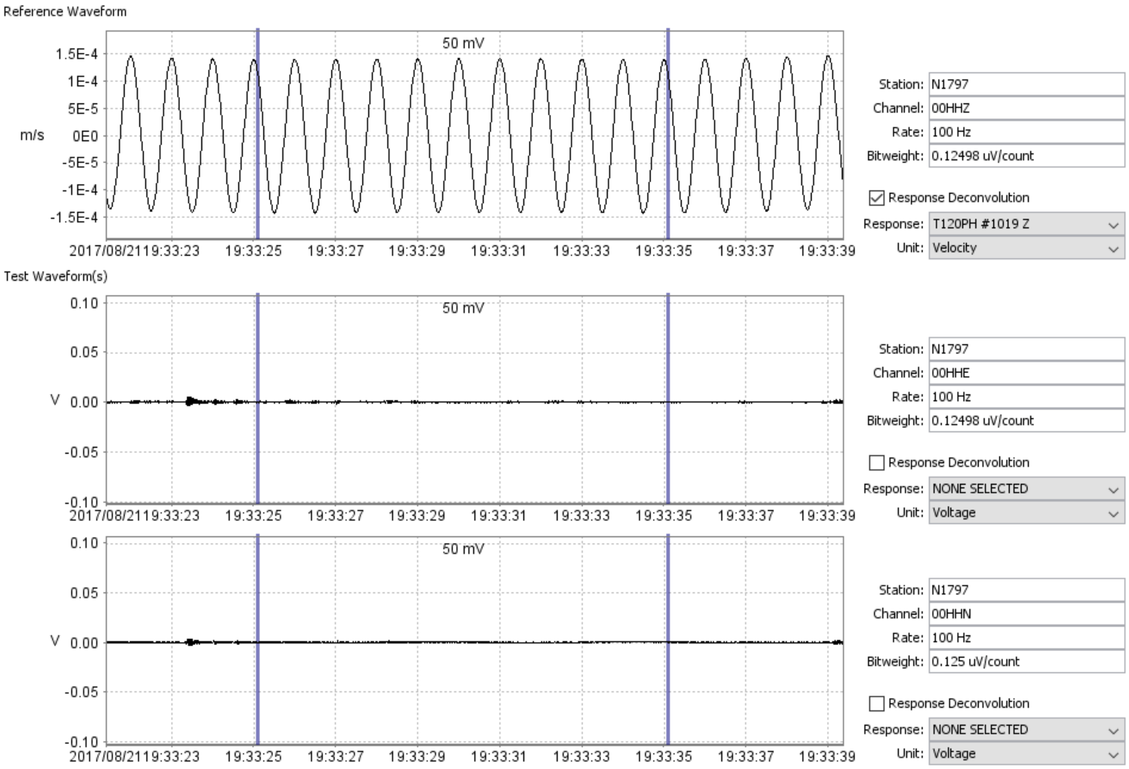
The Nanometrics Centaur digitizers have limited calibration capabilities at this time. It is necessary to pre-generate a waveform file that is loaded onto the digitizer. Thus, any arbitrary waveform may be used to perform a calibration by playing back the waveform file out the calibration line using the Centaur digitizer webpage. Scheduling and automation of calibration signals is not available. As configured from the manufacturer, the Centaur digitizers only have a calibration waveform file for a sinusoid with a duration of 30 seconds, frequency of 1 Hz, and peak amplitude of 5 Volts.

A 100x output attenuation was used when generating the calibration signal as it was determined that this was necessary to prevent clipping on the seismometer output. It was also determined that the Centaur digitizers do not provide a looped back recording of the calibration signal that is being injected into the seismometer. Therefore, it is assumed from the configuration settings that the amplitude of the sinusoid was 0.05 Volts (5 Volts divided by the 100x attenuation). Examination of the results would seem to indicate that the 0.05 Volt amplitude is specified per different leg. Therefore, peak amplitude would actually be 0.1 Volts.

The calibration signal is injected equally into the three U, V, and W seismometer components. Due to the transformation that is applied internal to the seismometer, ideally this should result in the calibration signal being generated entirely on the Z axis with no signal on the horizontal X or Y axes.

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.

Due to the short duration of the calibration signal and the uncertainty associated with the output amplitude, the test was repeated 4 times for each seismometer and the results averaged from the outcomes. The results in each of the repeated tests were nearly identical.


Reference Waveform

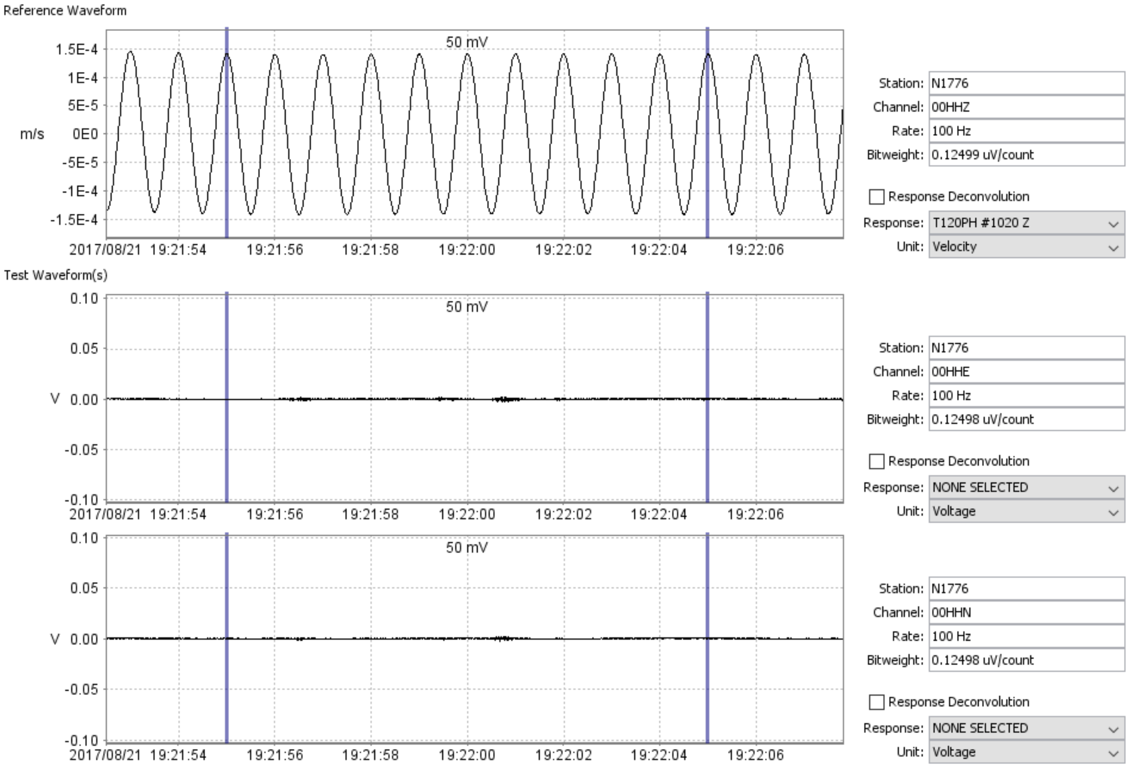
Station: N1797
Channel: 00HHZ
Rate: 100 Hz
Bitweight: 0.12498 uV/count
☑ Response Deconvolution
Response: T120PH #1019 Z
Unit: Velocity

Test Waveform(s)

Station: N1797
Channel: 00HHE
Rate: 100 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: NONE SELECTED
Unit: Voltage

Station: N1797
Channel: 00HHN
Rate: 100 Hz
Bitweight: 0.125 uV/count
☐ Response Deconvolution
Response: NONE SELECTED
Unit: Voltage

Figure 63 Calibrator Sensitivity Time Series - #1019


Reference Waveform

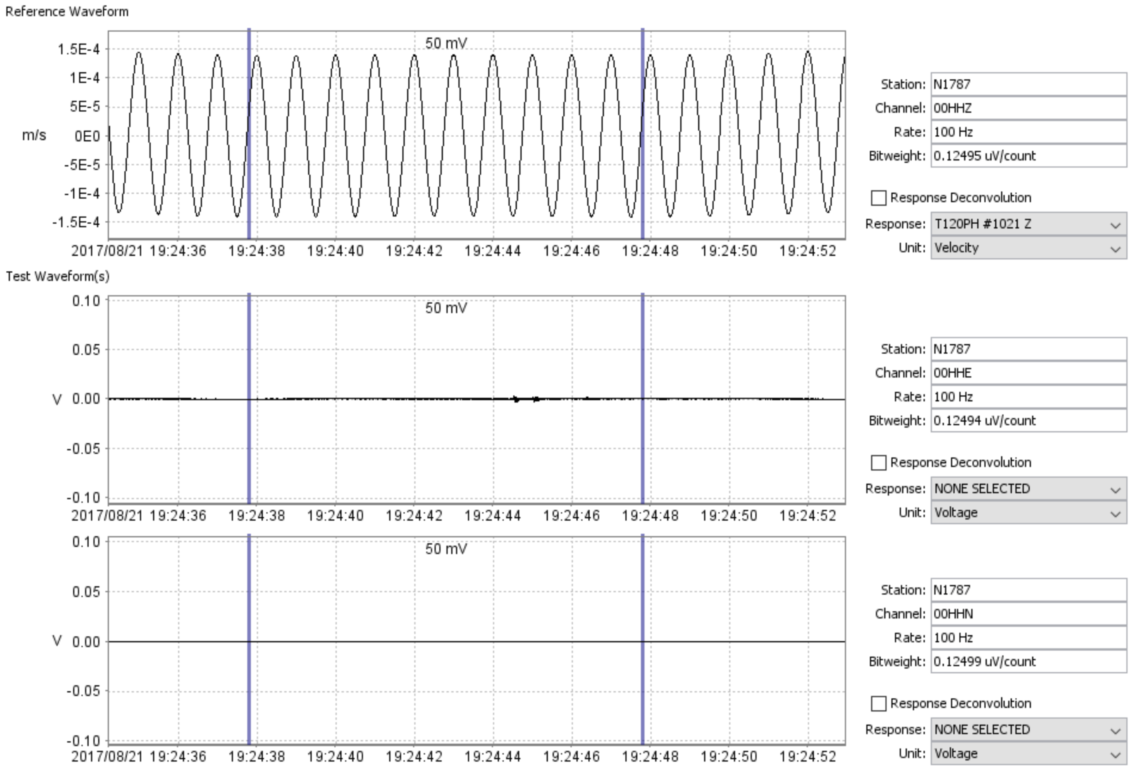
Station: N1776
Channel: 00HHZ
Rate: 100 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: T120PH #1020 Z
Unit: Velocity

Test Waveform(s)

Station: N1776
Channel: 00HHE
Rate: 100 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: NONE SELECTED
Unit: Voltage

Station: N1776
Channel: 00HHN
Rate: 100 Hz
Bitweight: 0.12498 uV/count
☐ Response Deconvolution
Response: NONE SELECTED
Unit: Voltage

Figure 64 Calibrator Sensitivity Time Series - #1020



Station: N1787
Channel: 00HHZ
Rate: 100 Hz
Bitweight: 0.12495 uV/count
☐ Response Deconvolution
Response: T120PH #1021 Z
Unit: Velocity

Station: N1787
Channel: 00HHE
Rate: 100 Hz
Bitweight: 0.12494 uV/count
☐ Response Deconvolution
Response: NONE SELECTED
Unit: Voltage

Station: N1787
Channel: 00HHN
Rate: 100 Hz
Bitweight: 0.12499 uV/count
☐ Response Deconvolution
Response: NONE SELECTED
Unit: Voltage

Figure 65 Calibrator Sensitivity Time Series - #1021

The following table contains the computed calibration sensitivities for the vertical channels

Table 23 Calibrator Sensitivity

	T120PH #1019	T120PH #1020	T120PH #1021
Input Voltage (Vin)	0.1000 V	0.1000 V	0.1000 V
Input Frequency (f)	1.0 Hz	1.0 Hz	1.0 Hz
Output Voltage (Vout)	0.2121 V	0.2127 V	0.2108 V
Seismometer Sensitivity (Gseis)	1507 V/(m/s)	1508 V/(m/s)	1508 V/(m/s)
Output Velocity	1.407E-4 m/s	1.410E-4 m/s	1.398E-4 m/s
Calibrator Sensitivity (Gcalib)	113.08 V/(m/s2)	112.86 V/(m/s2)	113.84 V/(m/s2)

For a simultaneous calibration of all three U, V, and W axes, the resulting vertical calibrator sensitivities were determined to be between 112.86 V/(m/s^2) and 113.84 V/(m/s^2). However, it was unverified what the actual calibration signal was that was injected into the seismometers. This analysis assumes that the 5 V amplitude and 100x attenuation programmed into the Centaur digitizer was correct.

The Trillium 120 manual states that the U, V, and W nominal calibrator sensitivities are 0.01 (m/s^2)/V or 100 V/(m/s^2). These values differ from the nominal by as much as 14%.

4 SUMMARY

Sensitivity
The Trillium 120PH seismometers were found to have sensitivities at 1 Hz of between 1500 and 1508 V/(m/s). These values differ by between 0 % and 0.53 % of the nominal 1500 V/(m/s) and are within the +/- 0.5% tolerance quoted by Nanometrics.

Self-Noise
All three Trillium 120PH seismometers exhibited self-noise levels that are consistent with the manufacturer's nominal noise model for the vertical axis. The horizontal axis appeared to exhibit elevated noise levels at frequencies below 0.5 Hz, especially on #1021, which could be an installation issue. 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 122.5 and 144 dB.

Frequency Response Verification
The seismometers were found to have a frequency response that closely matched the manufacturers nominal response model. Above 5 Hz, the amplitude response appears to be higher than expected from the nominal response model and the phase response appears to be lower.

Passband
All three seismometers were found to have a low frequency limit consistent with the nominal 0.00833 Hz. Due to the limitation of the data available, the high frequency corner was found to exceed a minimum of 20 Hz.

Calibrator Sensitivity
The vertical seismometer calibrator sensitivities were measured to be between 112.86 V/(m/s^2) and 113.84 V/(m/s^2).

REFERENCES

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

2. 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.

3. Kinemetrics, *STS-5A Borehole Sensor System Datasheet*, 04-26-2017.

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

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

6. 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.

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

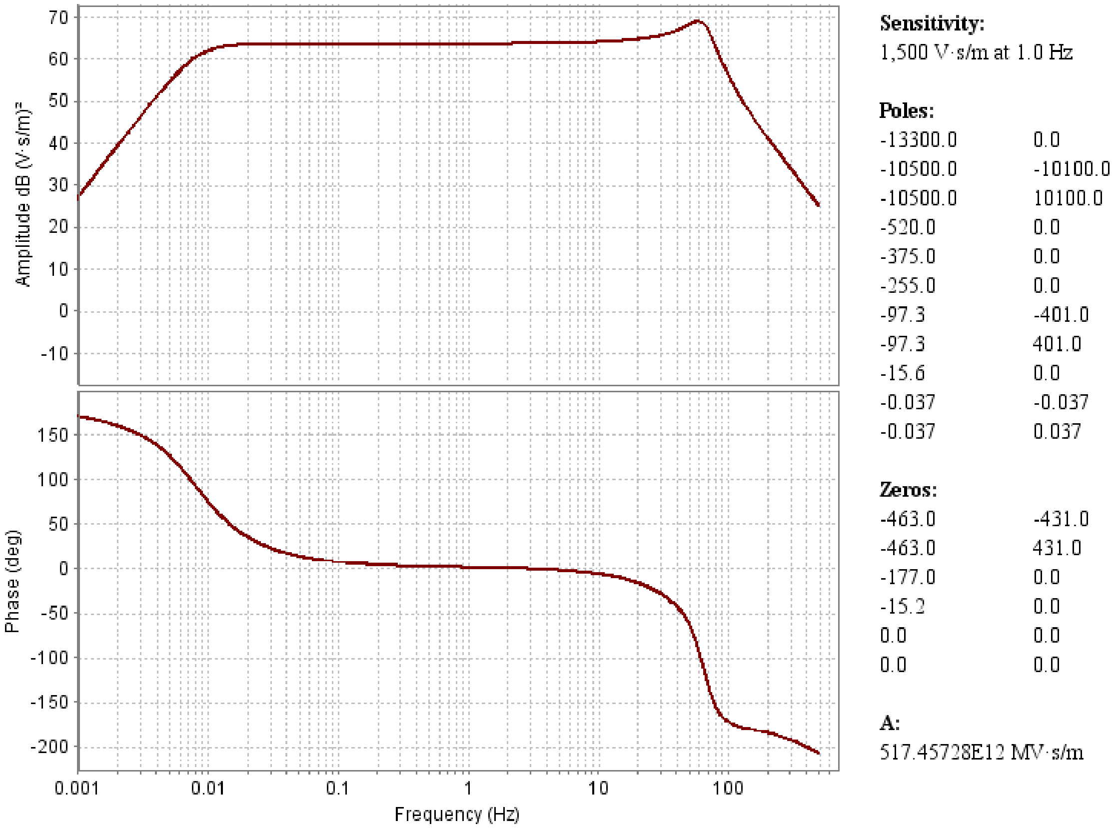
8. Merchant, B. John, and Darren M. Hart (2011), *Component Evaluation Testing and Analysis Algorithms*, SAND2011-8265.

9. 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

Kinemetrics STS-2 #120651 SNL Reference Response

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



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

-13300.0	0.0
-10500.0	-10100.0
-10500.0	10100.0
-520.0	0.0
-375.0	0.0
-255.0	0.0
-97.3	-401.0
-97.3	401.0
-15.6	0.0
-0.037	-0.037
-0.037	0.037

Zeros:

-463.0	-431.0
-463.0	431.0
-177.0	0.0
-15.2	0.0
0.0	0.0
0.0	0.0

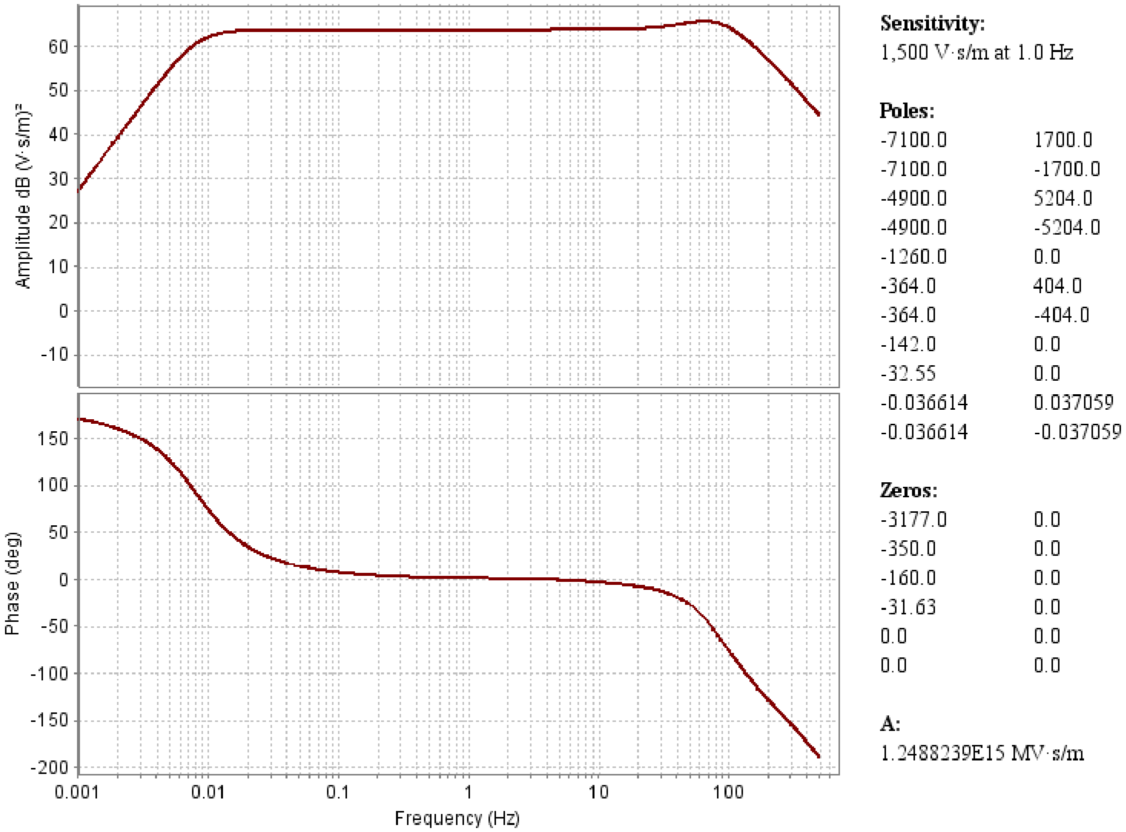
A:
517.45728E12 MV·s/m

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)

Nanometrics Trillium 120PH Response

The Trillium 120PH poles and zeros, provided by Nanometrics, along with the sensitivity of 1500 V/(m/s) are shown below.



Sensitivity:
1,500 V·s/m at 1.0 Hz

Poles:

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

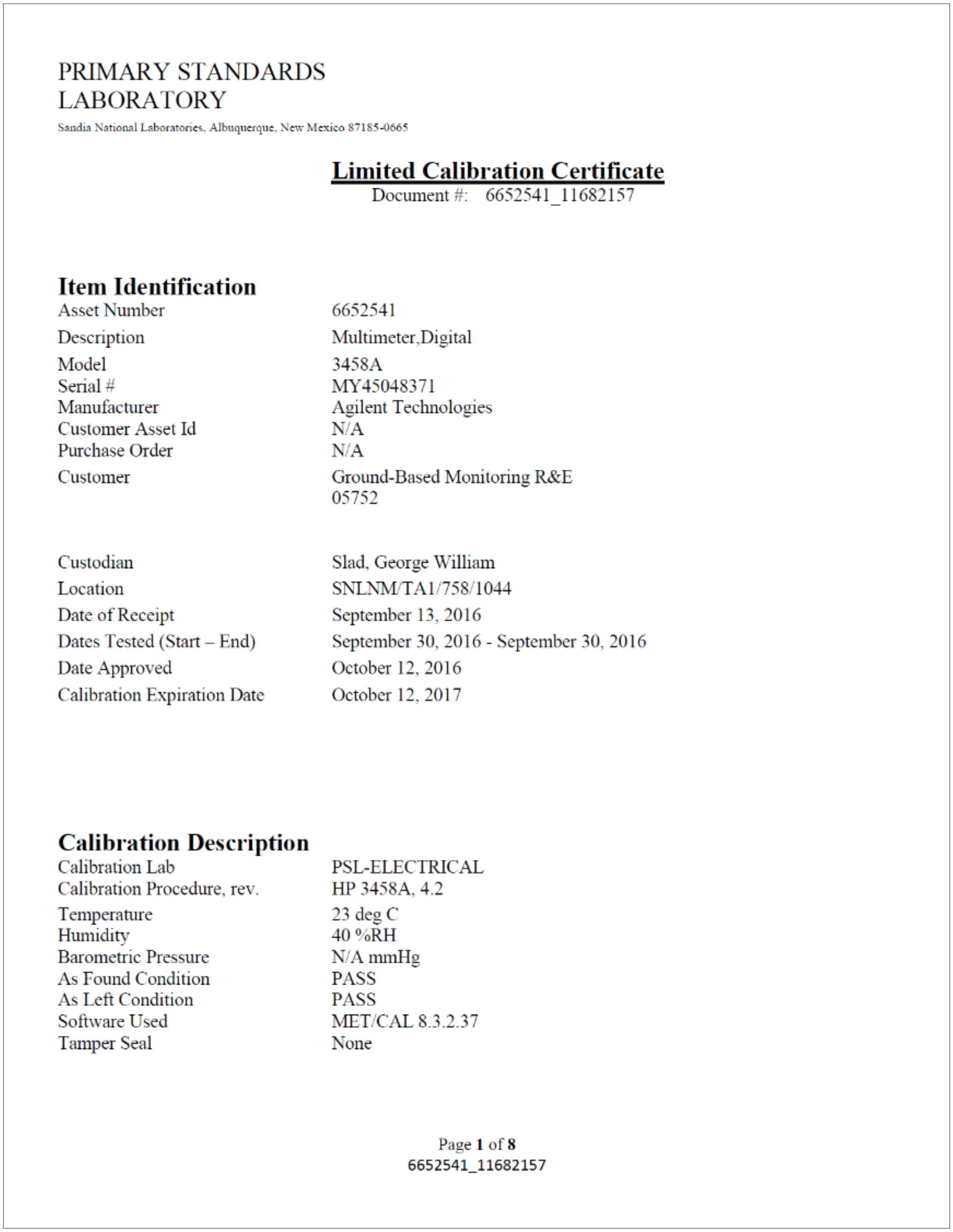
Zeros:

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

A:
1.2488239E15 MV·s/m

APPENDIX B: CALIBRATION SHEETS

Agilent 3458A # MY45048371



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

Limited Calibration Certificate

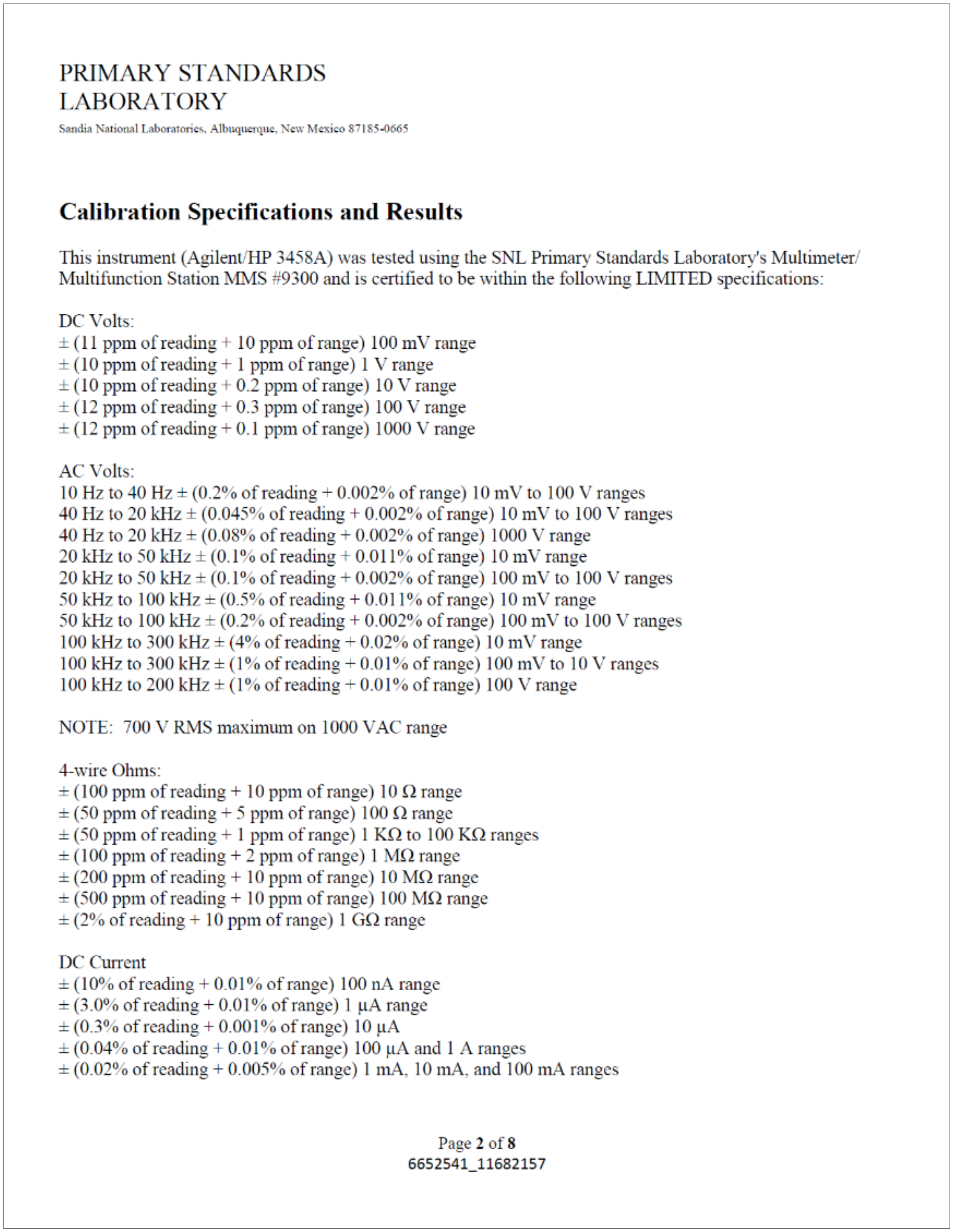
Document #: 6652541_11682157

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



PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Specifications and Results

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

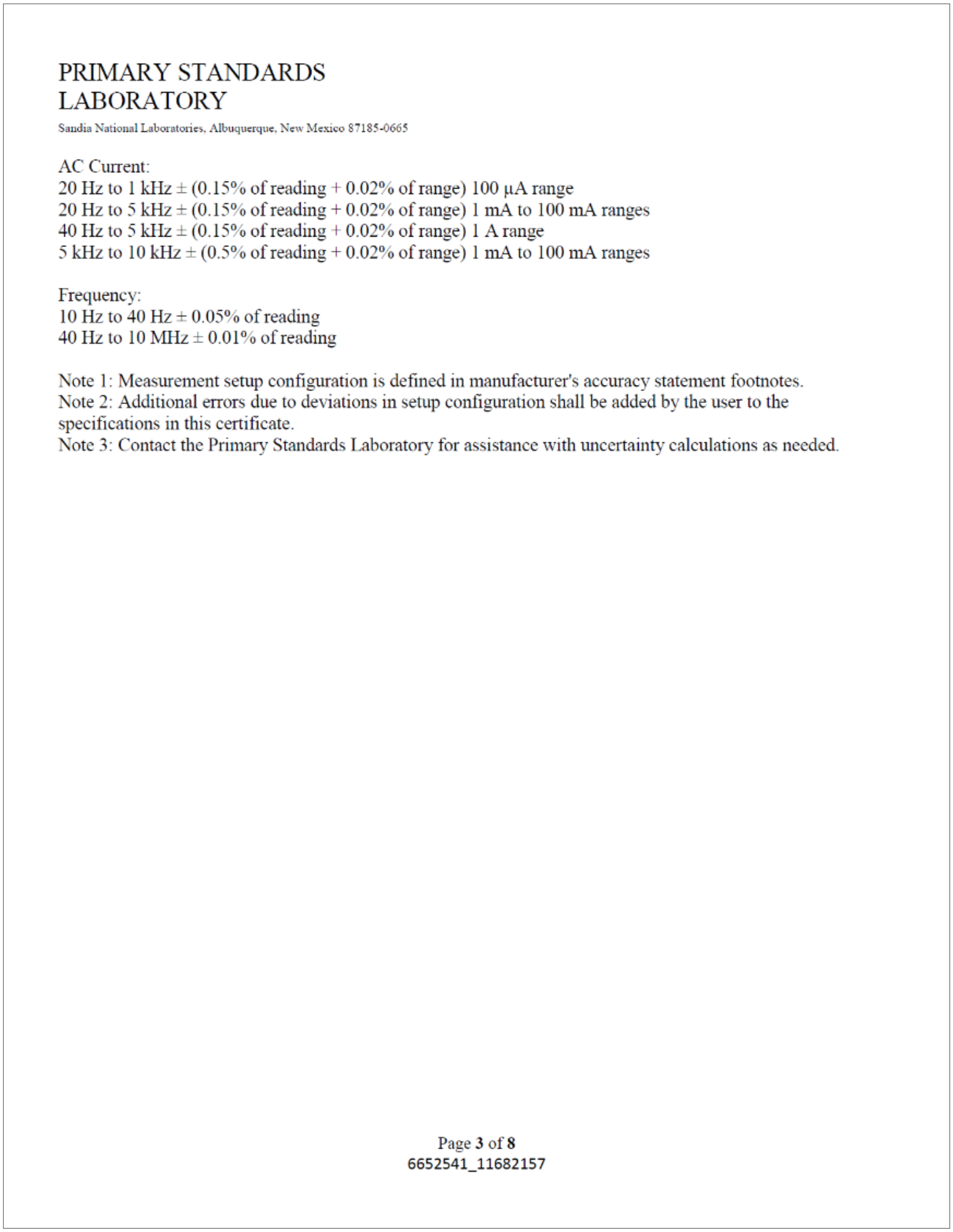
DC Volts:
± (11 ppm of reading + 10 ppm of range) 100 mV range
± (10 ppm of reading + 1 ppm of range) 1 V range
± (10 ppm of reading + 0.2 ppm of range) 10 V range
± (12 ppm of reading + 0.3 ppm of range) 100 V range
± (12 ppm of reading + 0.1 ppm of range) 1000 V range

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

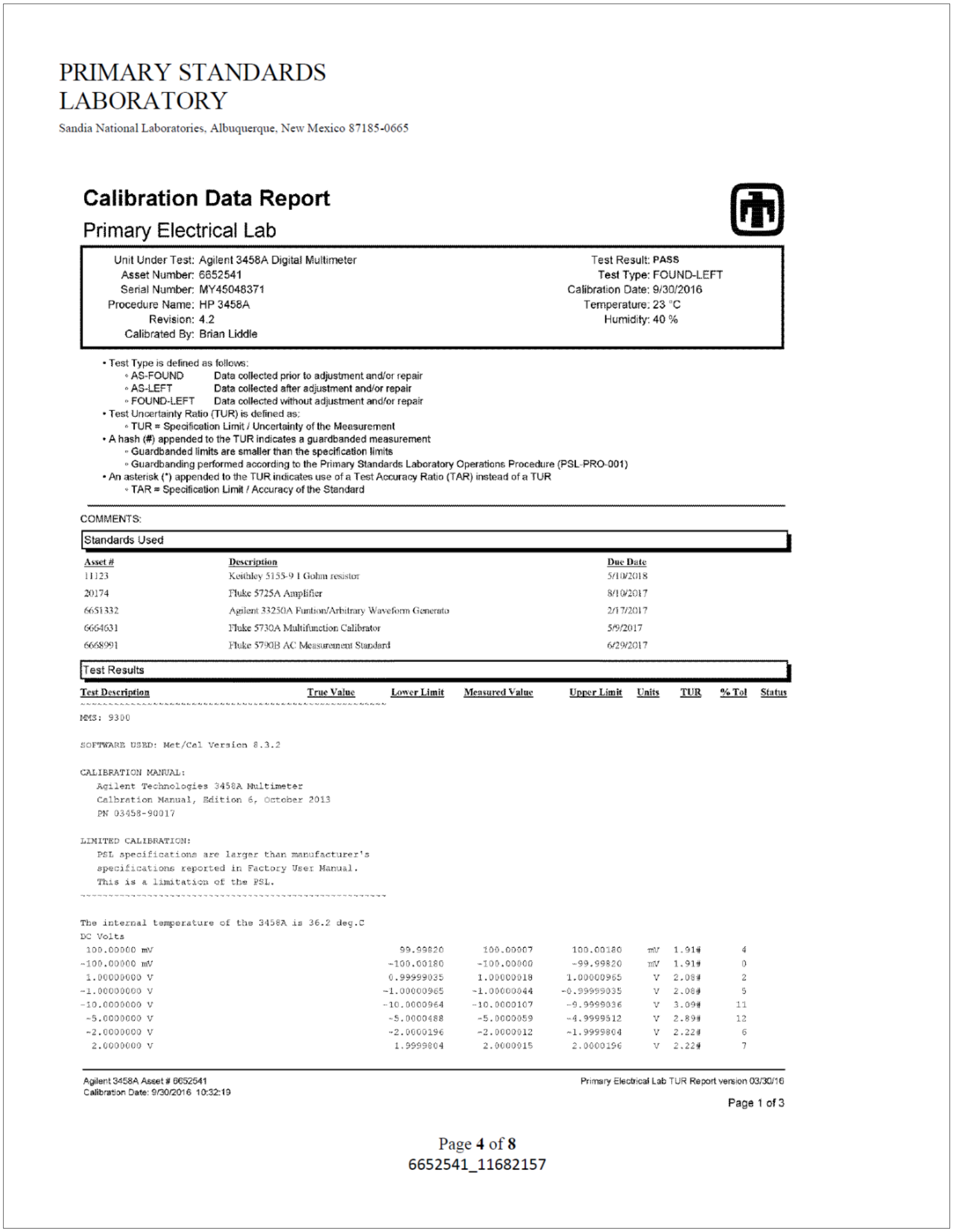
DC Current
± (10% of reading + 0.01% of range) 100 nA range
± (3.0% of reading + 0.01% of range) 1 µA range
± (0.3% of reading + 0.001% of range) 10 µA
± (0.04% of reading + 0.01% of range) 100 µA and 1 A ranges
± (0.02% of reading + 0.005% of range) 1 mA, 10 mA, and 100 mA ranges



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

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

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



PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Calibration Data Report

Primary Electrical Lab

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

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

COMMENTS:

Standards Used

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

Test Results

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MMS: 9300

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

Agilent 3458A Asset # 6652541
Calibration Date: 9/30/2016 10:32:19

Primary Electrical Lab TUR Report version 03/30/16

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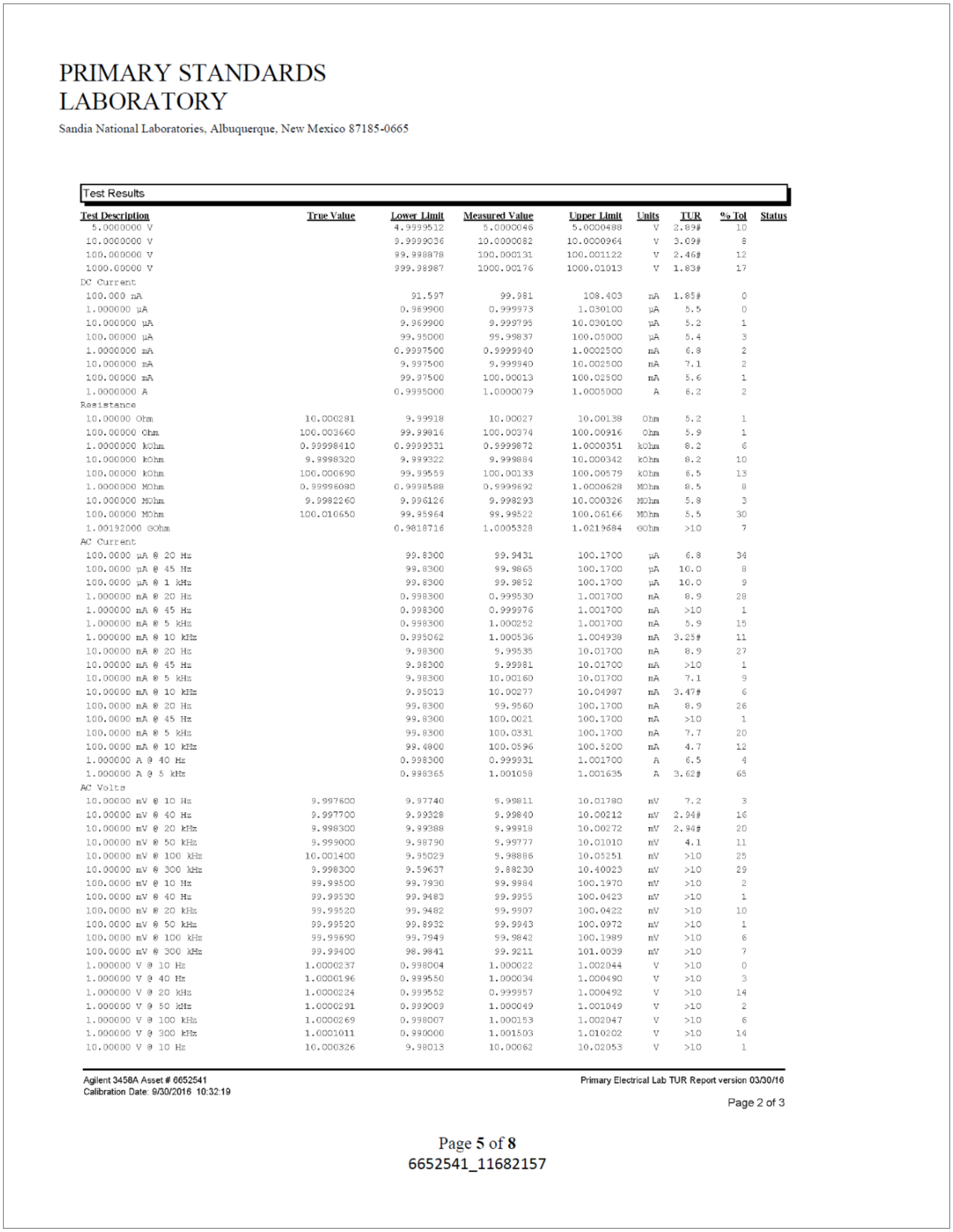
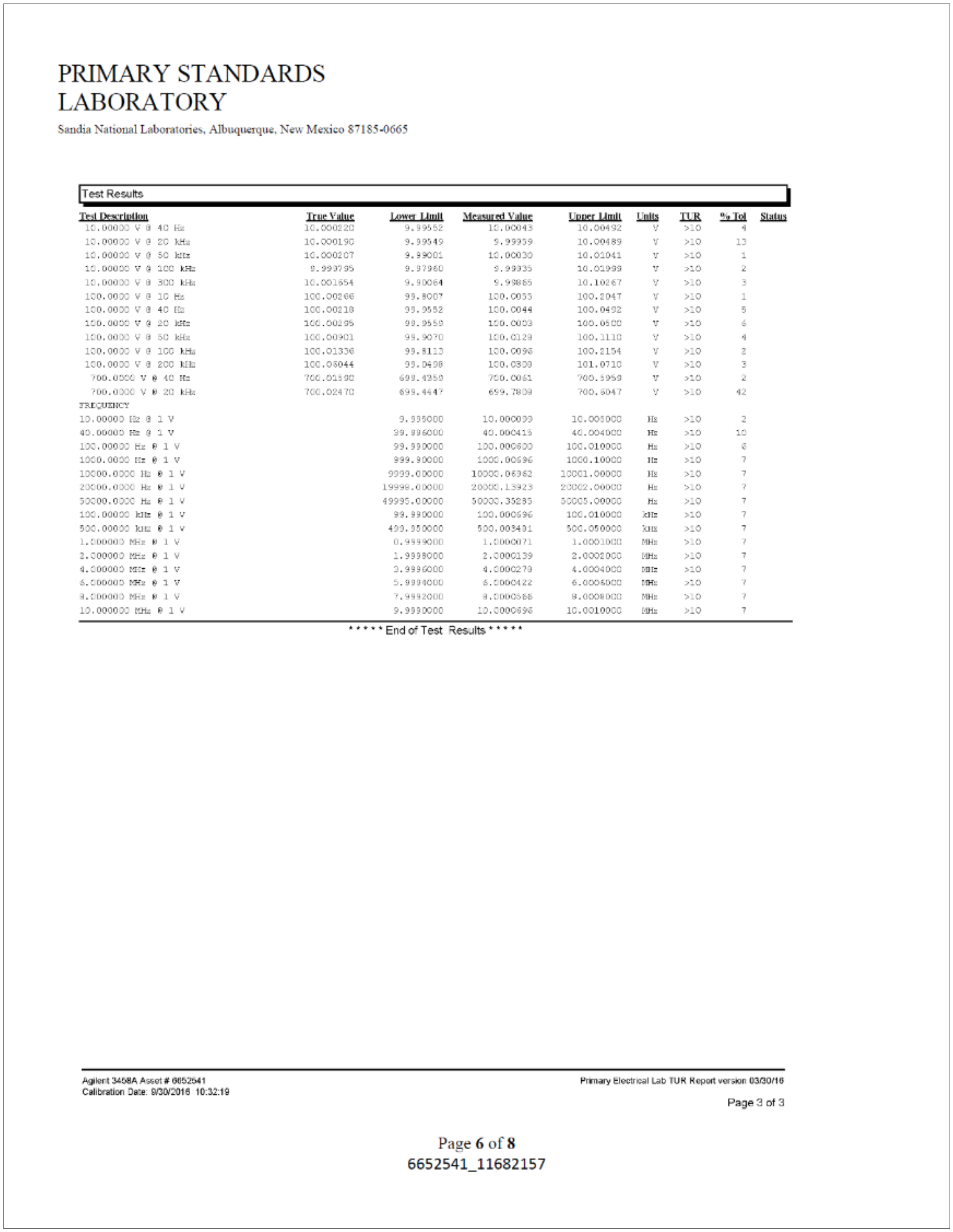


PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

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



PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

Test Results

Test Description	True Value	Lower Limit	Measured Value	Upper Limit	Units	TUR	% Tol	Status
10.00000 V @ 40 Hz	10.000220	9.99552	10.00043	10.00492	V	>10	4	
10.00000 V @ 20 kHz	10.000190	9.99549	9.99959	10.00489	V	>10	13	
10.00000 V @ 50 kHz	10.000207	9.99001	10.00030	10.01041	V	>10	1	
10.00000 V @ 100 kHz	9.999795	9.97960	9.99935	10.01999	V	>10	2	
10.00000 V @ 300 kHz	10.001654	9.90064	9.99865	10.10267	V	>10	3	
100.0000 V @ 10 Hz	100.00266	99.8007	100.0055	100.2047	V	>10	1	
100.0000 V @ 40 Hz	100.00218	99.9552	100.0044	100.0492	V	>10	5	
100.0000 V @ 20 kHz	100.00295	99.9559	100.0003	100.0500	V	>10	6	
100.0000 V @ 50 kHz	100.00901	99.9070	100.0129	100.1110	V	>10	4	
100.0000 V @ 100 kHz	100.01336	99.8113	100.0096	100.2154	V	>10	2	
100.0000 V @ 200 kHz	100.06044	99.0498	100.0300	101.0710	V	>10	3	
700.0000 V @ 40 Hz	700.01590	699.4359	700.0061	700.5959	V	>10	2	
700.0000 V @ 20 kHz	700.02470	699.4447	699.7808	700.6047	V	>10	42	
FREQUENCY								
10.00000 Hz @ 1 V		9.995000	10.000099	10.005000	Hz	>10	2	
40.00000 Hz @ 1 V		39.996000	40.000415	40.004000	Hz	>10	10	
100.00000 Hz @ 1 V		99.990000	100.000600	100.010000	Hz	>10	6	
1000.0000 Hz @ 1 V		999.90000	1000.00696	1000.10000	Hz	>10	7	
10000.0000 Hz @ 1 V		9999.00000	10000.06962	10001.00000	Hz	>10	7	
20000.0000 Hz @ 1 V		19998.00000	20000.13923	20002.00000	Hz	>10	7	
50000.0000 Hz @ 1 V		49995.00000	50000.35285	50005.00000	Hz	>10	7	
100.00000 kHz @ 1 V		99.990000	100.000696	100.010000	kHz	>10	7	
500.00000 kHz @ 1 V		499.950000	500.003481	500.050000	kHz	>10	7	
1.000000 MHz @ 1 V		0.9999000	1.0000071	1.0001000	MHz	>10	7	
2.000000 MHz @ 1 V		1.9998000	2.0000139	2.0002000	MHz	>10	7	
4.000000 MHz @ 1 V		3.9996000	4.0000278	4.0004000	MHz	>10	7	
6.000000 MHz @ 1 V		5.9994000	6.0000422	6.0006000	MHz	>10	7	
8.000000 MHz @ 1 V		7.9992000	8.0000566	8.0008000	MHz	>10	7	
10.000000 MHz @ 1 V		9.9990000	10.0000696	10.0010000	MHz	>10	7	

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

Agilent 3458A Asset # 6652541
Calibration Date: 9/30/2016 10:32:19

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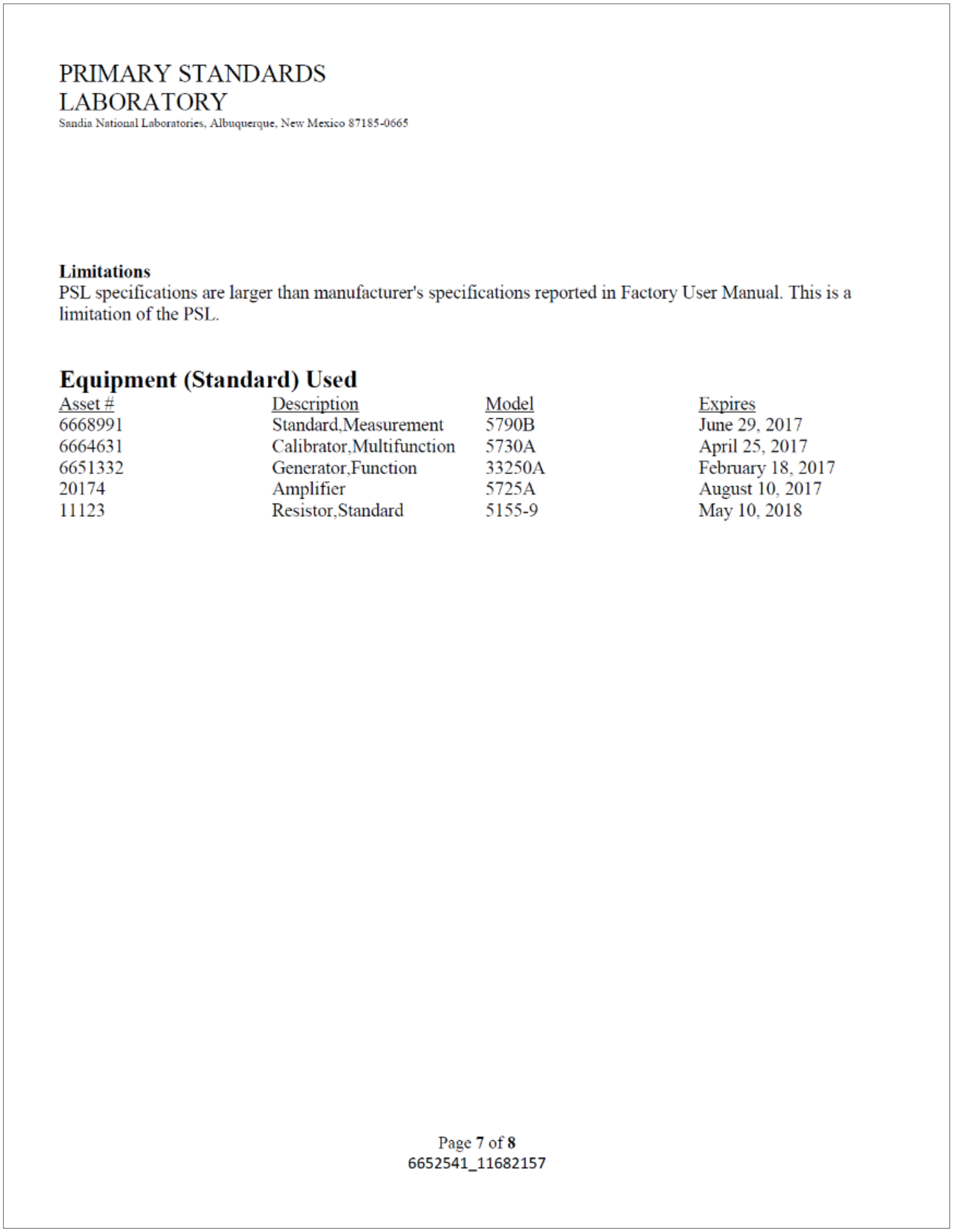

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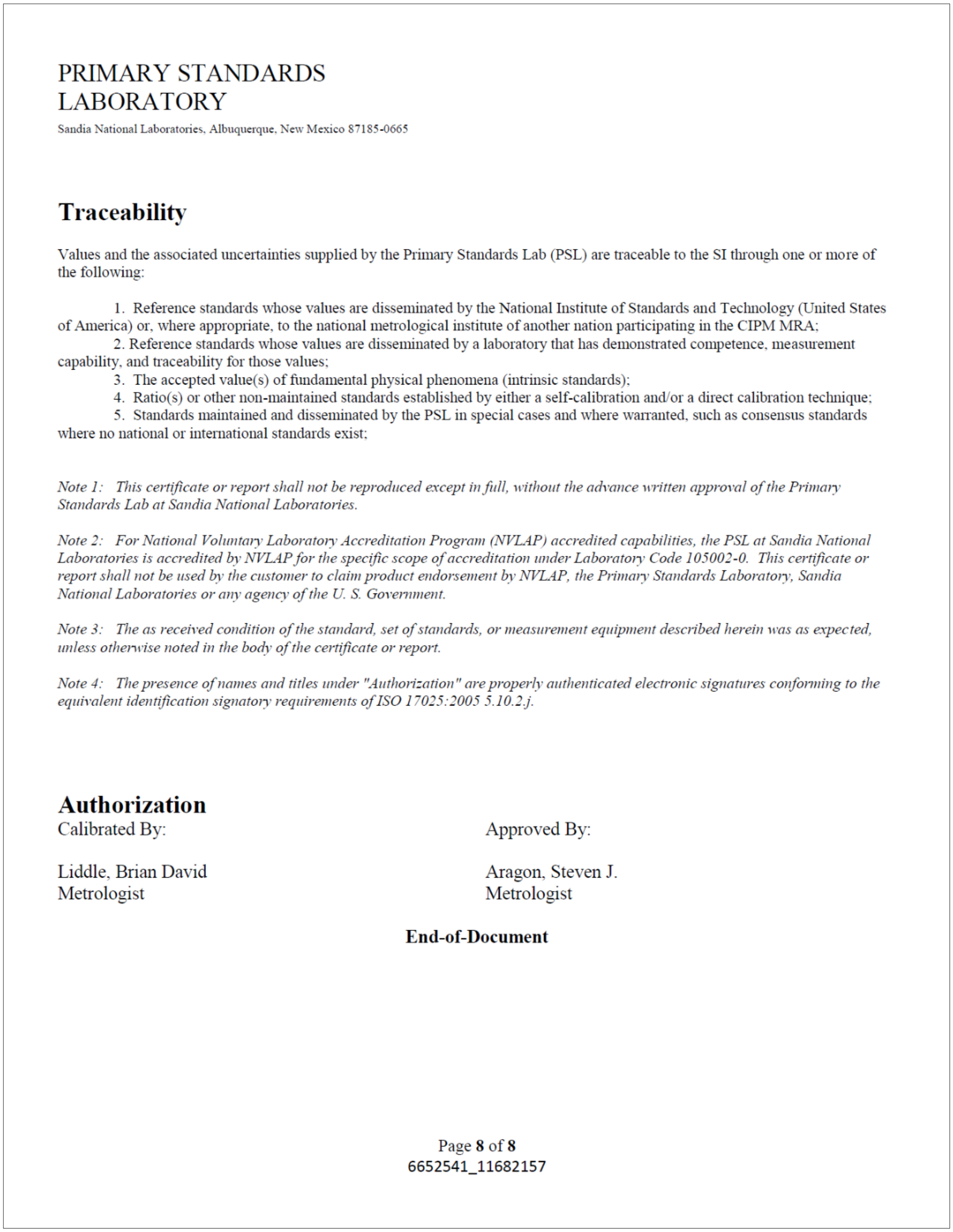
Limitations
PSL specifications are larger than manufacturer's specifications reported in Factory User Manual. This is a limitation of the PSL.

Equipment (Standard) Used

Asset #	Description	Model	Expires
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



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Traceability

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

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

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

Authorization

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

End-of-Document

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