**SANDIA REPORT**
SAND2017-11428
Unlimited Release
Printed October 2017

# Next Generation Qualification: Kinemetrics STS-5A Seismometer Evaluation

B. John Merchant
George W. Slad

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

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B. John Merchant
George W. Slad

Ground-Based Monitoring R&E
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0404

**Abstract**

Sandia National Laboratories has tested and evaluated two seismometers, the STS-5A, manufactured by Kinemetrics. These seismometers measure three axes of 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 Kinemetrics STS-5A 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 two Kinematics STS-5A seismometers, serial numbers 130877 and 130880, was performed to determine the performance characteristics of the instruments including sensitivity, self-noise, dynamic range, frequency response, and passband. In addition, a third STS-5A with serial number 139759, was borrowed from PASSCAL to assist in the measurement of self-noise.

**Figure 1 Kinemetrics STS-5A (Kinemetrics STS-5A datasheet)**

The STS-5A seismometer measures 3-axes of ground motion across a customizable passband, in this case 0.00833 Hz (120 seconds) – 50 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

| | |
|---|---|
| **Generator constant:** | 2x750 vs/m ±1% |
| **Response:** | Flat to ground velocity from 8.33mHz (120s) to 50Hz; a 360s version called STS-5A-360 is also available |
| **Clip level:** | ≤20Hz: ±13 mm/s ground velocity<br>>20Hz: linearly derating from ±13 mm/s to ±5.3 mm/s ground velocity |
| **Normalized to frequency:** | 20.50Hz 0.34g / 10Hz 0.17 / 1Hz 0.017g / 0.1Hz 0.0017g / 0.03Hz 0.00055g |
| **Case tilt range limit:** | +/-5º in any direction where a centering is successful |
| **Operating temperature:** | -20°C to 70°C (guaranteed), -40°C to 70°C (functional) |
| **Humidity:** | 0-100% RH |
| **Power supply voltage:** | 10...30VDC, galvanically isolated |
| **Power consumption:** | Average: 0.45W |
| **Seismic signals output:** | max. ±20V differential, 220Ω serial resistance per line |
| **Boom position output:** | max. ±10V single-ended, 1kΩ serial resistance |
| **Humidity:** | 0-100% RH |
| **Calibration input:** | max. ±10VDC |
| **Control inputs:** | 3...30VDC, 0.5mA, galvanically isolated |
| **Communication:** | RS485, galvanically isolated |
| **Enclosure rating:** | Exceeds IP69 |
| **Various:** | RoHS and CE Compliant |
| **Size:** | Diameter 5.75" (146 mm) . Length 18.5" (470 mm) |
| **Weight:** | 20kg |

**Table 1 Seismometer Specifications (Kinemetrics STS-5A 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**

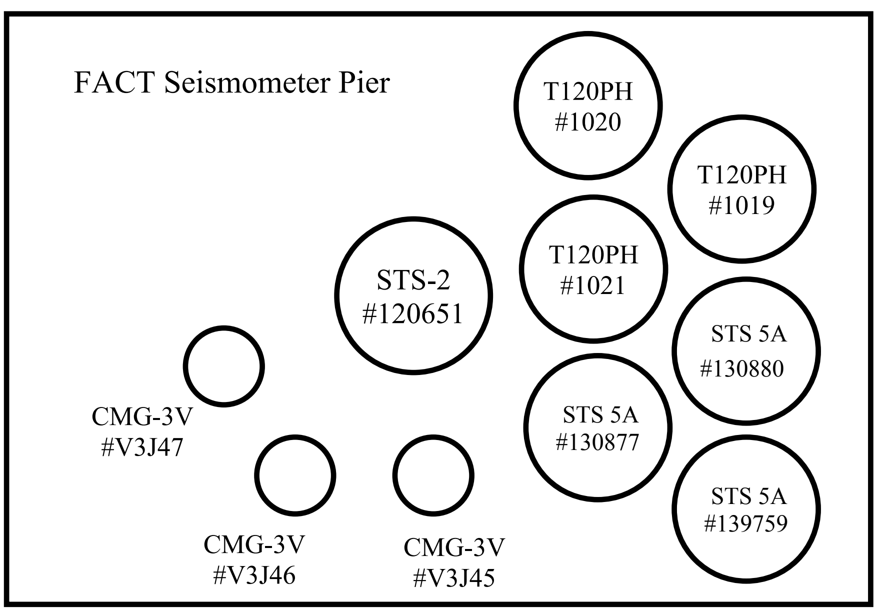



**Figure 6 Diagram of installed Seismometers**

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 Kinemetrics STS-5A seismometers were connected to a Quanterra Q330HR digitizer for recording of the time series data. The seismometer and digitizer channel assignments are contained in the table below.


**Figure 9 Quanterra Q330HR Digitizer**

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.

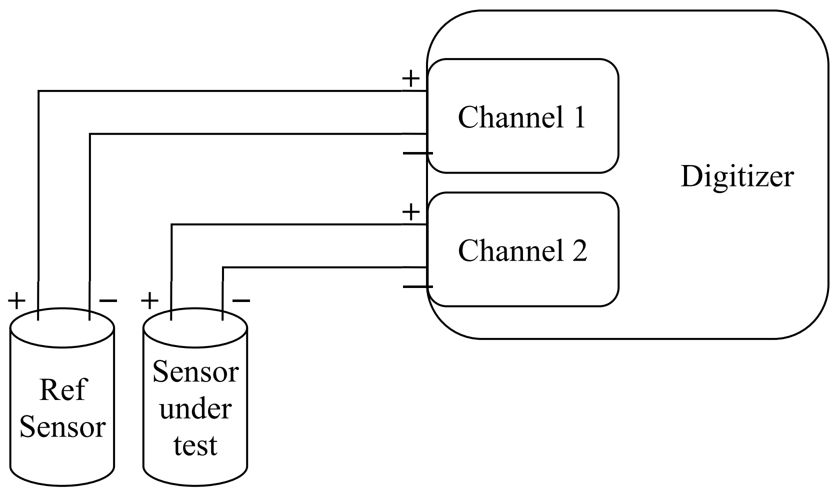



**Figure 10 Sensitivity Configuration Diagram**

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 | Kinemetrics STS-5A | # 130877, 130880, 139759 | 1500 V/(m/s) |
| Sensor Digitizers | Kinemetrics Q330 | # 6162, #6164 | 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).

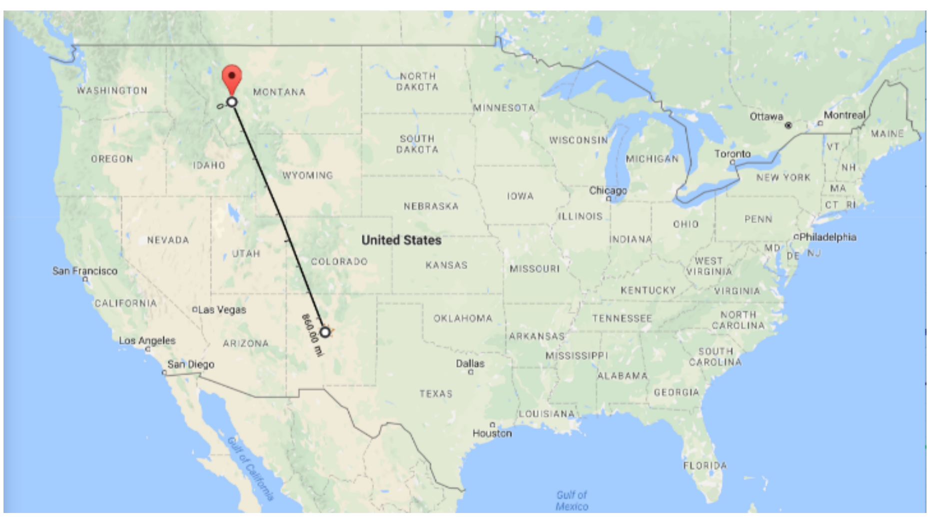



**Figure 11 Sensitivity Earthquake Location**

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.

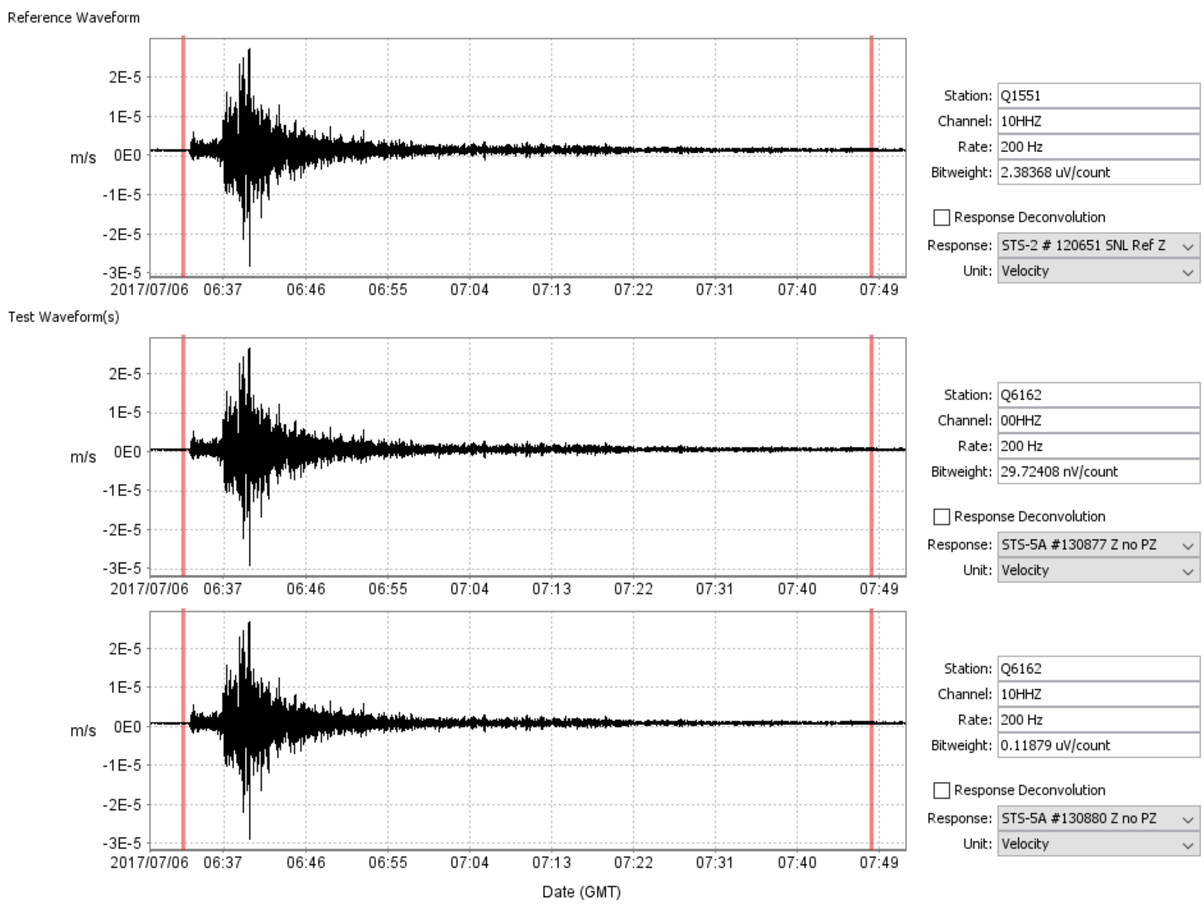



**Figure 12 Sensitivity Time Series**

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.

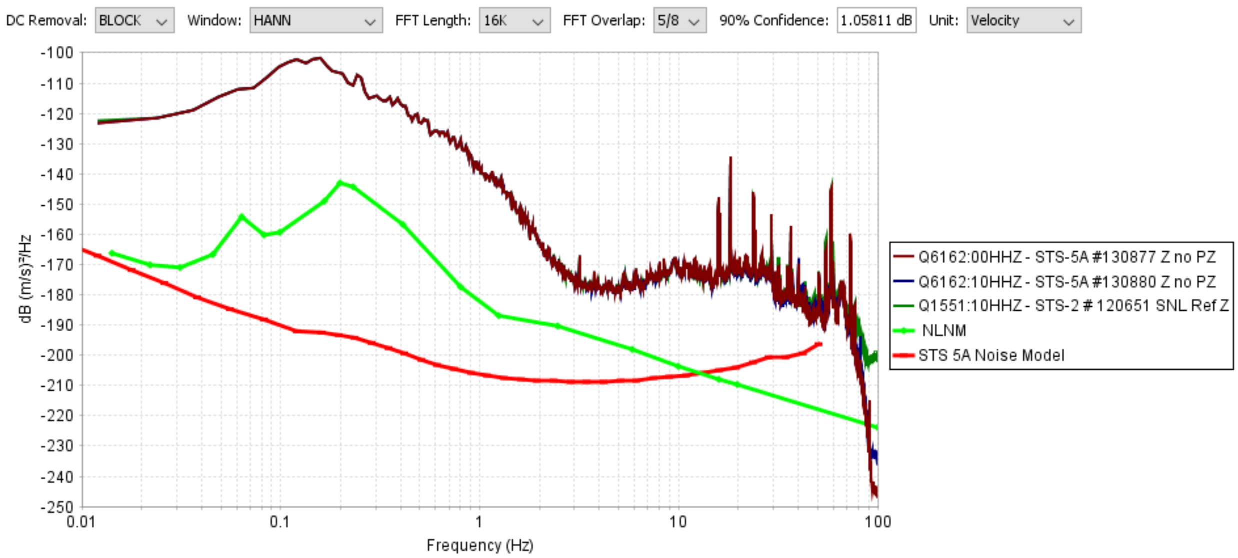



**Figure 13 Sensitivity Power Spectra**

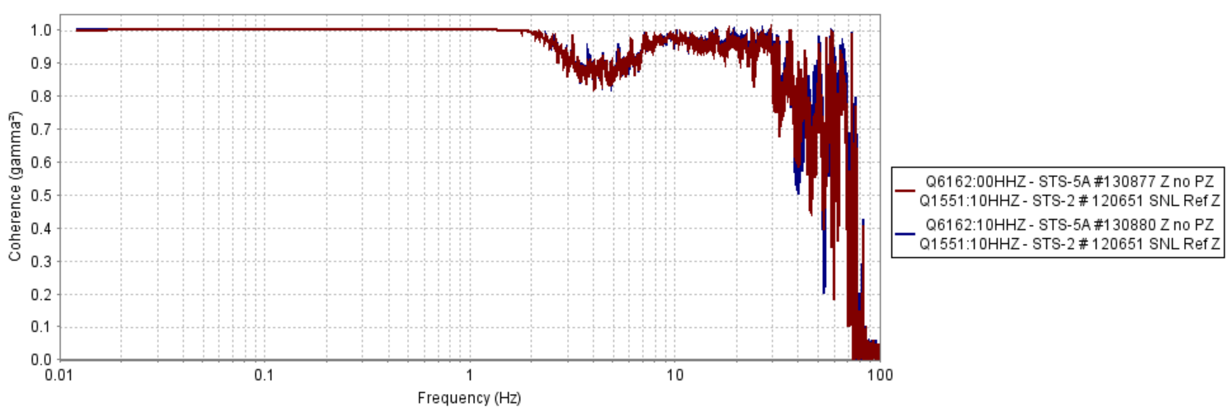



**Figure 14 Sensitivity Coherence**

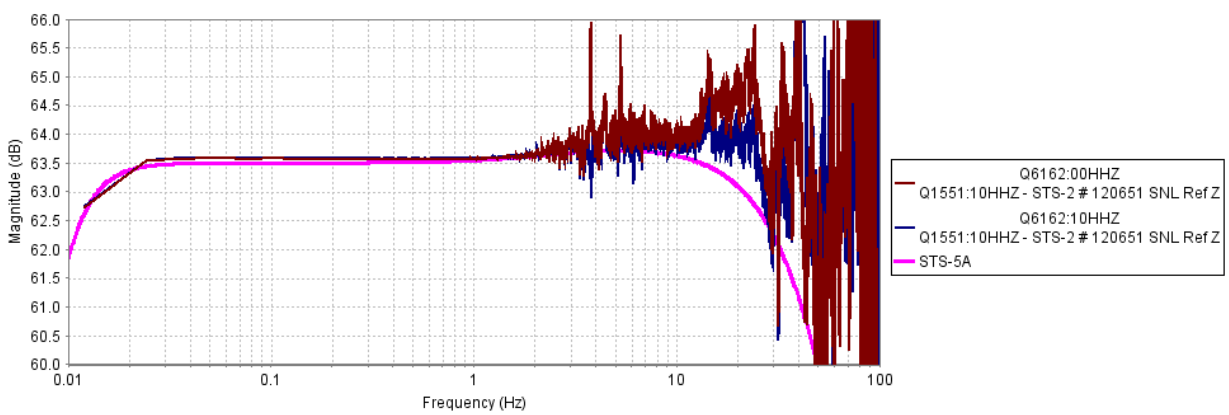



**Figure 15 Sensitivity Amplitude Response**

Note that the amplitude response curves shown above are consistent with the nominal amplitude response model for a Kinematics STS-5A, shown in purple, 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 | % |
| STS5A #130877 | 1500 V/(m/s) | 1508 V/(m/s) | 0.53% | 1505 V/(m/s) | 0.33% | 1506 V/(m/s) | 0.40% |
| STS5A #130880 | 1500 V/(m/s) | 1510 V/(m/s) | 0.67% | 1507 V/(m/s) | 0.47% | 1508 V/(m/s) | 0.53% |

The measured sensitivities were between 1505 and 1510 V/(m/s). These values differ from the nominal 1500 V/(m/s) by between 0.33 and 0.67 %. The specification from Kinemetrics state that they trim the seismometers to match the sensitivity to within +/- 1% of nominal. These measured sensitivities are consistent with that specification.

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

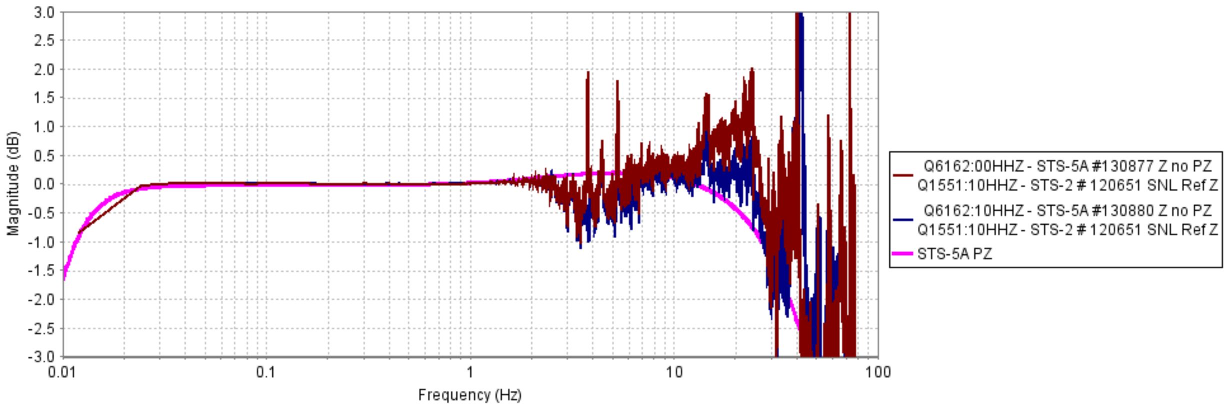



**Figure 16 Sensitivity Corrected Amplitude Response**

The amplitude response curves are now corrected for the measured sensitivities and show greater agreement with the nominal Kinemetrics STS-5A 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.

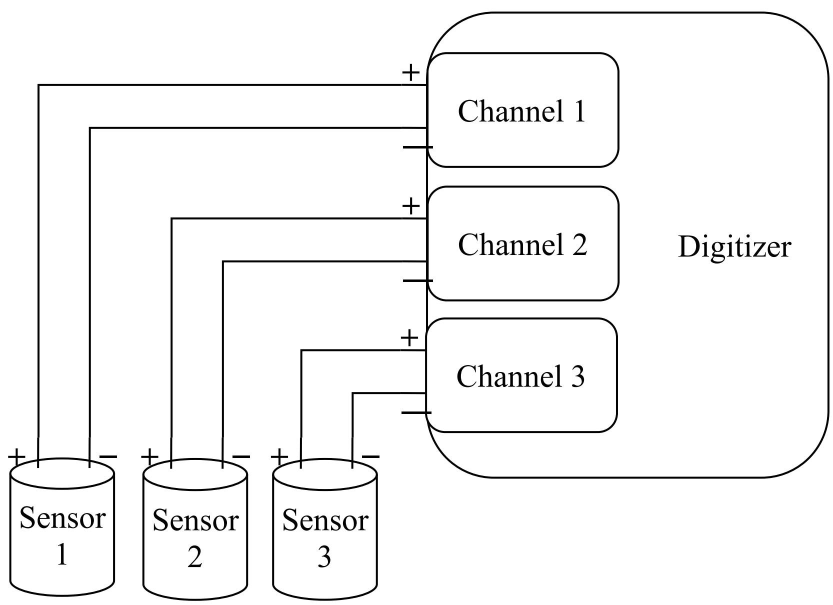



**Figure 17 Self-Noise Configuration Diagram**

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-NoiseTestbed Equipment**

| | Manufacturer / Model | Serial Number | Nominal Configuration |
|---|---|---|---|
| Sensor under test | Kinemetrics STS-5A | # 130877, 130880, 139759 | 1500 V/(m/s) |
| Sensor Digitizers | Kinemetrics Q330 | # 6162, #6164 | 200 Hz, 40 Vpp |

The digitizer records the output of the reference sensors.

### 3.2.3 Analysis

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

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 32k-sample Hann window. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation pass-band of 0.01 Hz and the 90% confidence interval of approximately 0.5 dB. The resulting 90% confidence interval was determined to be 0.56 dB.

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

Over frequencies (in Hertz):

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

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

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

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

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

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

### 3.2.4 Result

A review of the data recorded collected determined that the quietest time period while all three sensors were operating occurred on April 13, 2017 between approximately 04:00 and 12:00 UTC. In local time, this corresponds to an overnight during a weekend between Wednesday, April 12 20:00 and Thursday, April 13, 04:00.

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.

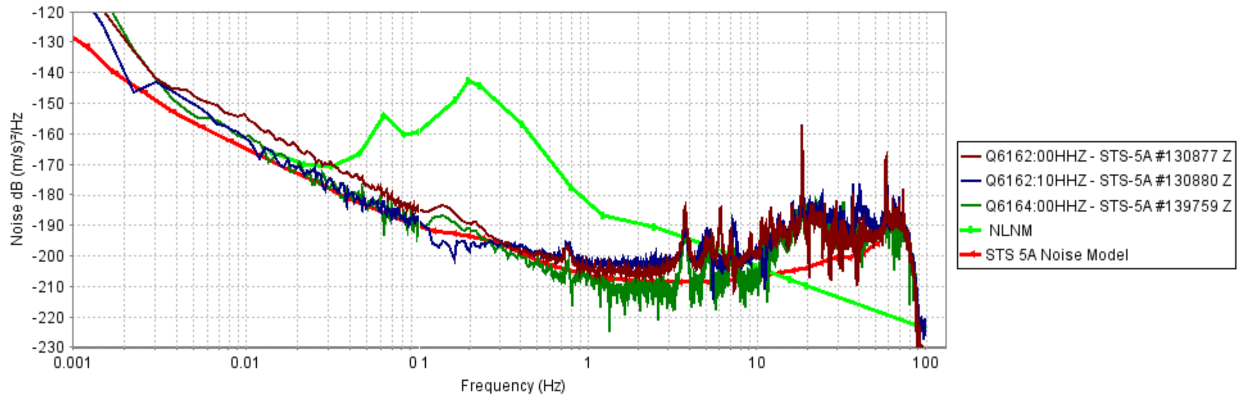



**Figure 18 Z Axis Self Noise**

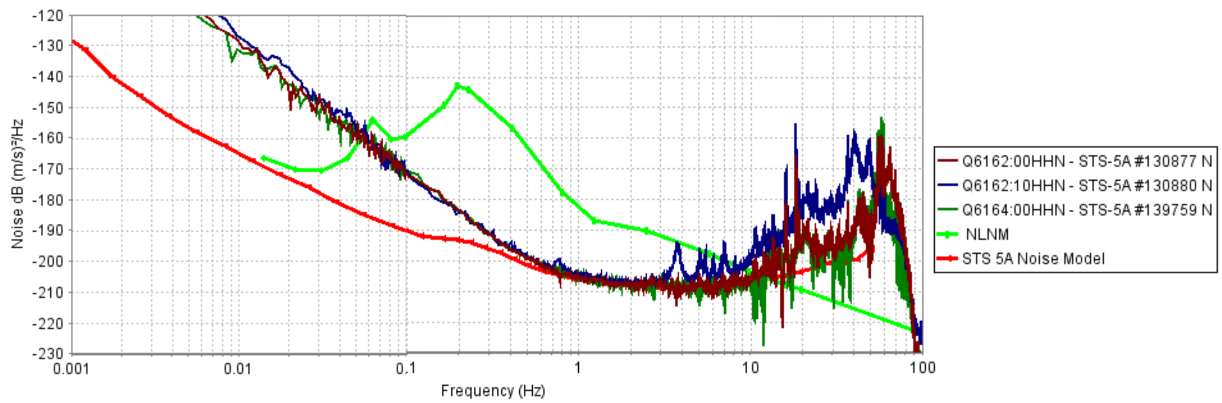



**Figure 19 N Axis Self Noise**

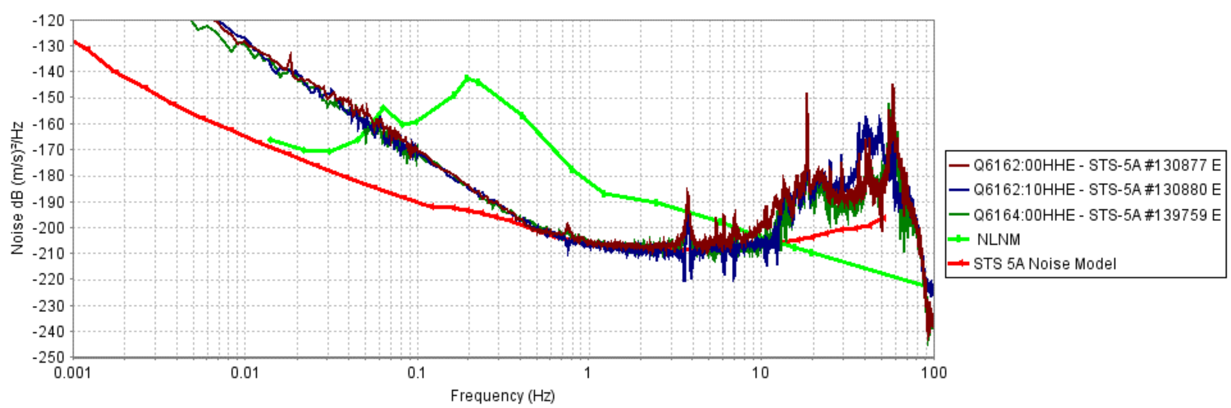



**Figure 20 E Axis Self Noise**

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). It is unknown what the cause of this is, however it could be 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 - 50 Hz | 20 mHz - 1 Hz | 20 mHz - 16 Hz | 0.5 Hz - 16 Hz |
|---|---|---|---|---|
| STS5A #130877 | 3.666 nm/s rms | 0.589 nm/s rms | 0.842 nm/s rms | 0.604 nm/s rms |
| STS5A #130880 | 3.719 nm/s rms | 0.315 nm/s rms | 0.654 nm/s rms | 0.577 nm/s rms |
| STS5A #139759 | 3.035 nm/s rms | 0.323 nm/s rms | 0.504 nm/s rms | 0.389 nm/s rms |

**Table 9 Self Noise RMS - N**

| | 8.3 mHz - 50 Hz | 20 mHz - 1 Hz | 20 mHz - 16 Hz | 0.5 Hz - 16 Hz |
|---|---|---|---|---|
| STS5A #130877 | 28.221 nm/s rms | 6.484 nm/s rms | 6.488 nm/s rms | 0.247 nm/s rms |
| STS5A #130880 | 43.147 nm/s rms | 8.777 nm/s rms | 8.793 nm/s rms | 0.536 nm/s rms |
| STS5A #139759 | 23.874 nm/s rms | 6.360 nm/s rms | 6.368 nm/s rms | 0.307 nm/s rms |

**Table 10 Self Noise RMS - E**

| | 8.3 mHz - 50 Hz | 20 mHz - 1 Hz | 20 mHz - 16 Hz | 0.5 Hz - 16 Hz |
|---|---|---|---|---|
| STS5A #130877 | 28.569 nm/s rms | 6.814 nm/s rms | 6.856 nm/s rms | 0.751 nm/s rms |
| STS5A #130880 | 35.561 nm/s rms | 6.313 nm/s rms | 6.336 nm/s rms | 0.544 nm/s rms |
| STS5A #139759 | 22.002 nm/s rms | 6.013 nm/s rms | 6.027 nm/s rms | 0.413 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 | #130877 | #130880 | #139759 | #130877 | #130880 | #139759 | #130877 | #130880 | #139759 |
| 0.001 Hz | -109.9 dB | -114.3 dB | -105.3 dB | -90.2 dB | -84.7 dB | -89.6 dB | -92.0 dB | -91.1 dB | -92.6 dB |
| 0.00125 Hz | -120.2 dB | -125.7 dB | -116.5 dB | -90.2 dB | -84.7 dB | -89.6 dB | -92.0 dB | -91.1 dB | -92.6 dB |
| 0.0016 Hz | -127.6 dB | -134.0 dB | -127.5 dB | -97.4 dB | -91.6 dB | -94.2 dB | -96.6 dB | -95.3 dB | -99.0 dB |
| 0.002 Hz | -134.3 dB | -136.2 dB | -134.6 dB | -99.3 dB | -94.4 dB | -96.5 dB | -96.4 dB | -95.3 dB | -99.0 dB |
| 0.0025 Hz | -137.4 dB | -140.7 dB | -139.1 dB | -106.8 dB | -102.7 dB | -106.7 dB | -105.9 dB | -107.4 dB | -106.7 dB |
| 0.00315 Hz | -142.6 dB | -145.2 dB | -145.3 dB | -109.3 dB | -104.8 dB | -109.5 dB | -109.2 dB | -108.0 dB | -108.1 dB |
| 0.004 Hz | -146.3 dB | -147.6 dB | -150.1 dB | -112.4 dB | -106.8 dB | -111.9 dB | -112.8 dB | -112.4 dB | -115.3 dB |
| 0.005 Hz | -146.2 dB | -150.3 dB | -146.5 dB | -119.0 dB | -115.1 dB | -122.4 dB | -117.6 dB | -118.1 dB | -120.3 dB |
| 0.0063 Hz | -150.2 dB | -154.3 dB | -156.1 dB | -121.5 dB | -117.6 dB | -123.1 dB | -119.8 dB | -119.4 dB | -125.0 dB |
| 0.008 Hz | -153.1 dB | -158.0 dB | -157.4 dB | -125.2 dB | -121.1 dB | -125.8 dB | -124.9 dB | -123.3 dB | -128.2 dB |
| 0.010 Hz | -153.1 dB | -160.4 dB | -160.7 dB | -129.3 dB | -126.9 dB | -131.4 dB | -128.3 dB | -127.9 dB | -129.8 dB |
| 0.0125 Hz | -159.9 dB | -166.6 dB | -163.4 dB | -133.8 dB | -131.7 dB | -134.9 dB | -132.9 dB | -133.9 dB | -133.9 dB |
| 0.016 Hz | -161.7 dB | -169.4 dB | -166.5 dB | -137.4 dB | -134.8 dB | -137.2 dB | -138.1 dB | -139.8 dB | -139.1 dB |
| 0.020 Hz | -164.6 dB | -171.4 dB | -171.6 dB | -142.0 dB | -137.4 dB | -142.0 dB | -143.4 dB | -141.3 dB | -141.2 dB |
| 0.025 Hz | -167.7 dB | -170.6 dB | -177.4 dB | -147.7 dB | -144.6 dB | -147.4 dB | -145.4 dB | -147.8 dB | -145.0 dB |
| 0.0315 Hz | -169.7 dB | -174.2 dB | -178.3 dB | -149.0 dB | -148.3 dB | -150.6 dB | -149.6 dB | -148.7 dB | -151.4 dB |
| 0.040 Hz | -173.3 dB | -179.8 dB | -179.4 dB | -155.4 dB | -152.4 dB | -155.1 dB | -152.6 dB | -156.7 dB | -155.1 dB |
| 0.050 Hz | -175.9 dB | -183.7 dB | -182.2 dB | -158.4 dB | -156.0 dB | -158.1 dB | -156.7 dB | -159.9 dB | -159.7 dB |
| 0.063 Hz | -180.3 dB | -182.1 dB | -185.2 dB | -163.5 dB | -161.5 dB | -161.8 dB | -160.8 dB | -163.2 dB | -164.2 dB |
| 0.080 Hz | -184.4 dB | -187.9 dB | -187.4 dB | -166.9 dB | -167.9 dB | -166.7 dB | -166.2 dB | -168.1 dB | -168.2 dB |
| 0.100 Hz | -184.7 dB | -188.3 dB | -191.1 dB | -171.4 dB | -171.4 dB | -170.8 dB | -170.1 dB | -171.2 dB | -171.7 dB |
| 0.125 Hz | -183.7 dB | -190.8 dB | -186.6 dB | -175.9 dB | -176.5 dB | -174.9 dB | -175.0 dB | -175.9 dB | -175.2 dB |
| 0.160 Hz | -186.8 dB | -193.0 dB | -189.8 dB | -179.9 dB | -180.8 dB | -179.5 dB | -180.1 dB | -181.1 dB | -179.9 dB |
| 0.200 Hz | -190.4 dB | -196.8 dB | -192.5 dB | -184.3 dB | -184.2 dB | -183.9 dB | -184.5 dB | -184.3 dB | -184.9 dB |
| 0.250 Hz | -192.7 dB | -198.2 dB | -195.4 dB | -189.1 dB | -187.9 dB | -188.4 dB | -188.4 dB | -188.4 dB | -189.7 dB |
| 0.315 Hz | -197.5 dB | -198.0 dB | -198.4 dB | -192.9 dB | -192.1 dB | -192.6 dB | -192.2 dB | -192.4 dB | -193.5 dB |
| 0.400 Hz | -198.6 dB | -196.4 dB | -202.8 dB | -197.0 dB | -195.7 dB | -196.3 dB | -197.1 dB | -197.3 dB | -197.0 dB |
| 0.500 Hz | -200.5 dB | -202.1 dB | -206.4 dB | -199.6 dB | -198.9 dB | -199.1 dB | -201.1 dB | -200.7 dB | -200.0 dB |
| 0.630 Hz | -202.9 dB | -201.5 dB | -206.7 dB | -202.4 dB | -201.8 dB | -201.9 dB | -202.7 dB | -203.0 dB | -202.9 dB |
| 0.800 Hz | -200.7 dB | -200.4 dB | -208.4 dB | -204.9 dB | -202.3 dB | -204.0 dB | -203.8 dB | -205.3 dB | -204.3 dB |
| 1.000 Hz | -204.5 dB | -202.8 dB | -206.9 dB | -205.7 dB | -204.6 dB | -205.2 dB | -205.9 dB | -206.8 dB | -205.8 dB |
| 1.250 Hz | -205.0 dB | -202.8 dB | -209.5 dB | -206.5 dB | -205.7 dB | -206.9 dB | -206.6 dB | -207.8 dB | -206.7 dB |
| 1.600 Hz | -205.1 dB | -202.7 dB | -211.3 dB | -207.9 dB | -206.6 dB | -207.6 dB | -207.2 dB | -208.8 dB | -207.4 dB |
| 2.000 Hz | -206.0 dB | -202.7 dB | -210.0 dB | -208.2 dB | -207.2 dB | -208.3 dB | -207.6 dB | -209.2 dB | -207.7 dB |
| 2.500 Hz | -205.6 dB | -202.4 dB | -210.7 dB | -207.8 dB | -207.0 dB | -209.0 dB | -207.4 dB | -209.4 dB | -207.7 dB |
| 3.150 Hz | -203.3 dB | -202.1 dB | -211.1 dB | -208.5 dB | -206.4 dB | -208.0 dB | -206.7 dB | -209.9 dB | -207.2 dB |
| 4.000 Hz | -196.6 dB | -198.4 dB | -202.4 dB | -209.3 dB | -201.4 dB | -208.7 dB | -205.8 dB | -209.6 dB | -207.7 dB |
| 5.000 Hz | -199.2 dB | -196.8 dB | -203.3 dB | -208.4 dB | -204.2 dB | -209.4 dB | -206.5 dB | -208.6 dB | -208.7 dB |
| 6.300 Hz | -198.9 dB | -202.4 dB | -206.9 dB | -208.7 dB | -204.5 dB | -208.6 dB | -205.2 dB | -208.2 dB | -208.3 dB |
| 8.000 Hz | -202.2 dB | -201.0 dB | -206.8 dB | -207.5 dB | -203.4 dB | -208.4 dB | -203.6 dB | -207.3 dB | -207.8 dB |
| 10.000 Hz | -198.6 dB | -200.0 dB | -206.0 dB | -206.2 dB | -199.5 dB | -207.8 dB | -200.2 dB | -206.6 dB | -206.6 dB |
| 12.500 Hz | -193.1 dB | -194.7 dB | -199.0 dB | -202.7 dB | -194.8 dB | -203.1 dB | -191.9 dB | -201.7 dB | -199.6 dB |
| 16.000 Hz | -192.2 dB | -191.1 dB | -193.8 dB | -201.5 dB | -190.6 dB | -200.0 dB | -186.1 dB | -188.3 dB | -190.9 dB |
| 20.000 Hz | -187.0 dB | -185.7 dB | -187.3 dB | -192.3 dB | -181.2 dB | -193.0 dB | -182.0 dB | -183.2 dB | -186.5 dB |
| 25.000 Hz | -190.7 dB | -187.2 dB | -189.2 dB | -196.5 dB | -184.5 dB | -198.7 dB | -185.7 dB | -184.6 dB | -189.7 dB |
| 31.500 Hz | -194.3 dB | -191.1 dB | -192.3 dB | -195.2 dB | -182.5 dB | -198.2 dB | -188.1 dB | -183.7 dB | -191.2 dB |
| 40.000 Hz | -194.7 dB | -187.1 dB | -193.3 dB | -190.3 dB | -166.6 dB | -191.5 dB | -185.9 dB | -169.5 dB | -185.4 dB |
| 50.000 Hz | -193.4 dB | -190.5 dB | -192.5 dB | -188.3 dB | -172.1 dB | -184.2 dB | -182.1 dB | -169.7 dB | -180.2 dB |
| 63.000 Hz | -188.7 dB | -188.6 dB | -190.2 dB | -173.3 dB | -188.8 dB | -181.9 dB | -180.2 dB | -187.3 dB | -181.3 dB |
| 80.000 Hz | -196.8 dB | -195.3 dB | -196.8 dB | -195.2 dB | -197.8 dB | -202.5 dB | -198.8 dB | -198.7 dB | -200.2 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 8 hour segment of data used for analysis.

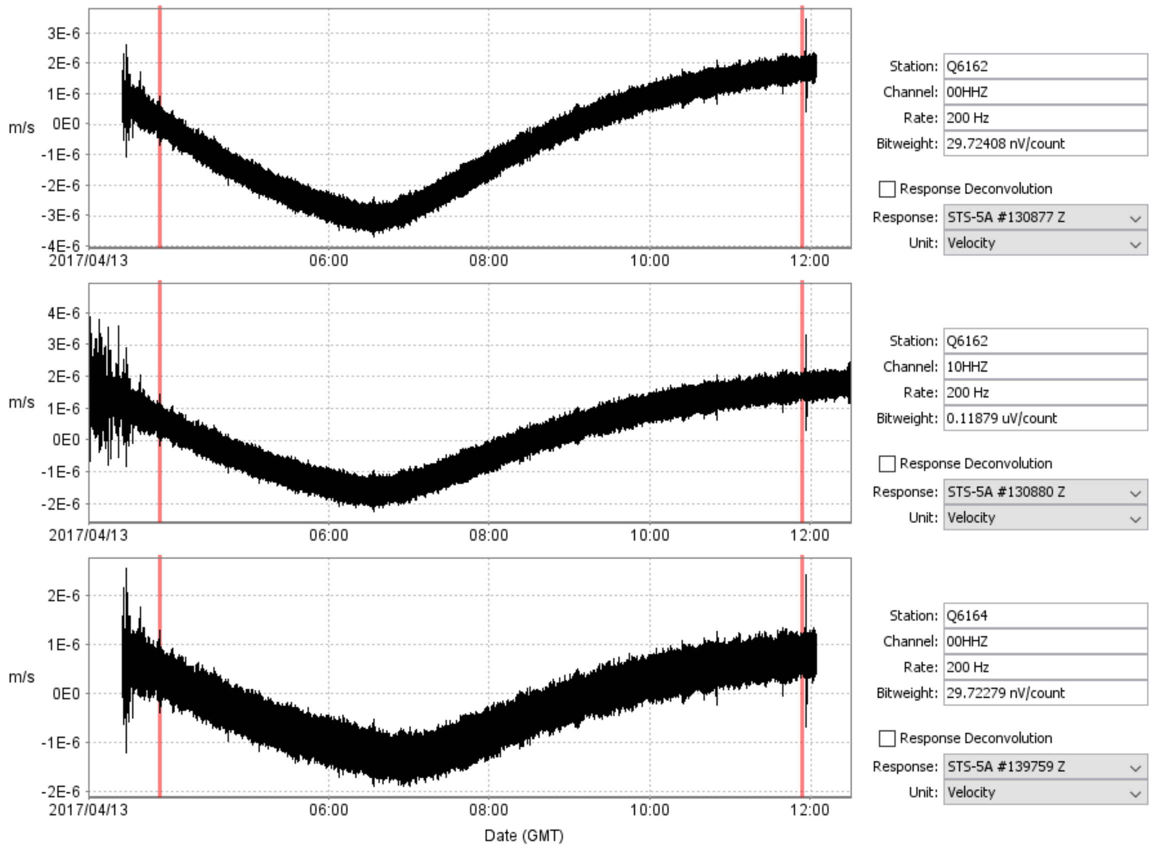



**Figure 21 Self Noise Time Series**

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

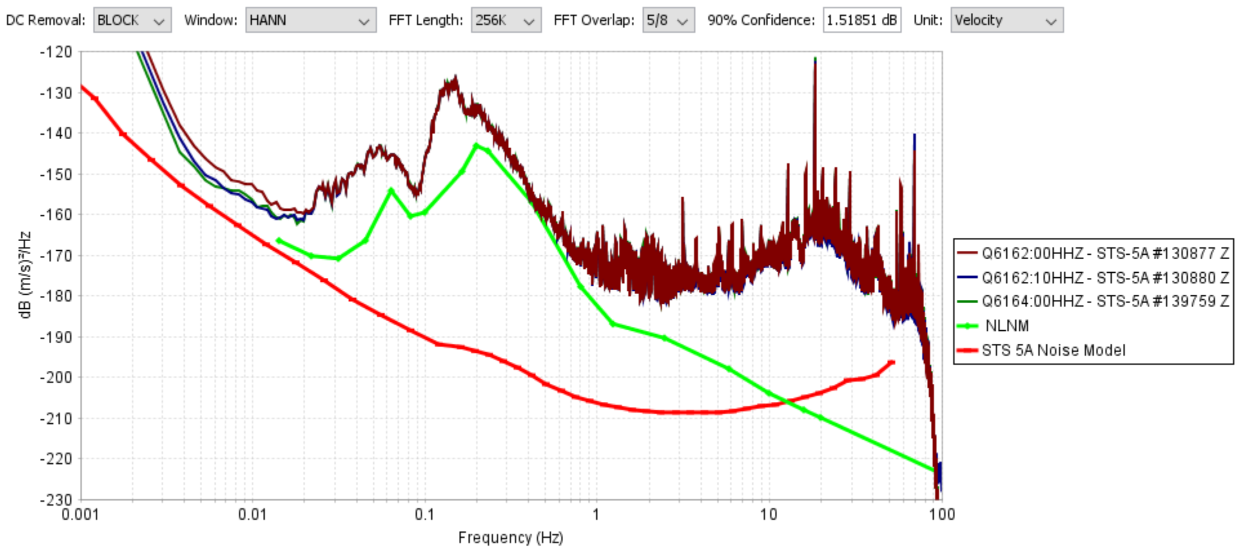



**Figure 22 Self Noise Raw Power Spectra**

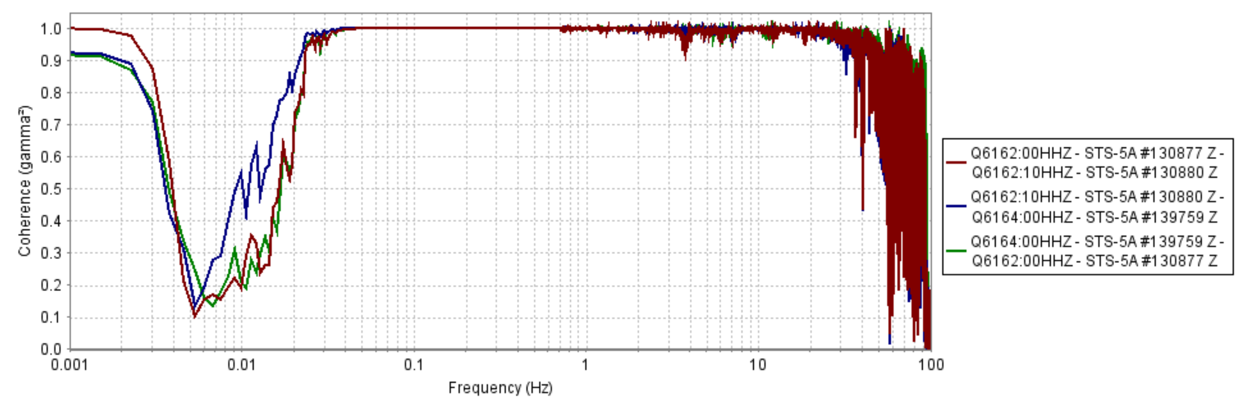



**Figure 23 Self Noise Coherence**

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 STS-5A noise model are overlaid for comparison.

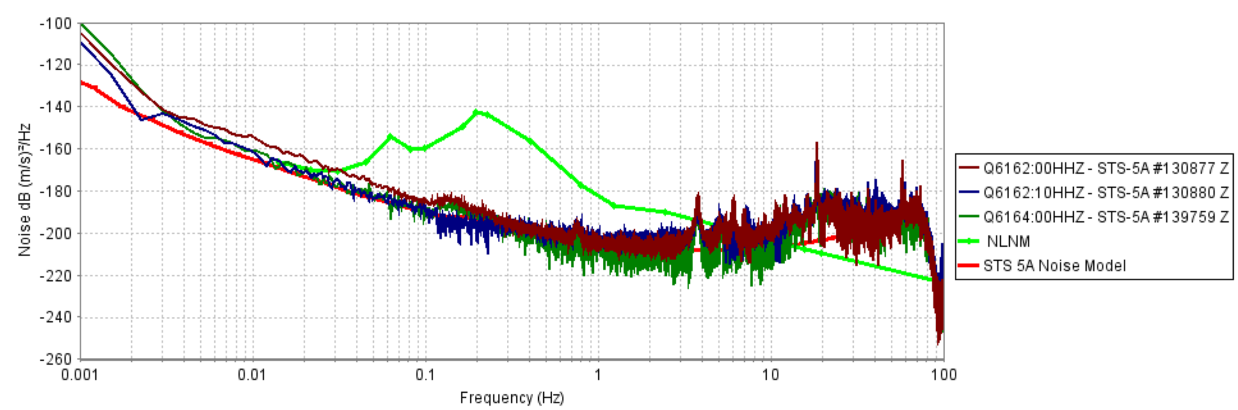



**Figure 24 Self Noise**

We observe that there is good signal coherence, even when recording just quiet background, between 0.04 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 8 hour segment of data used for analysis.

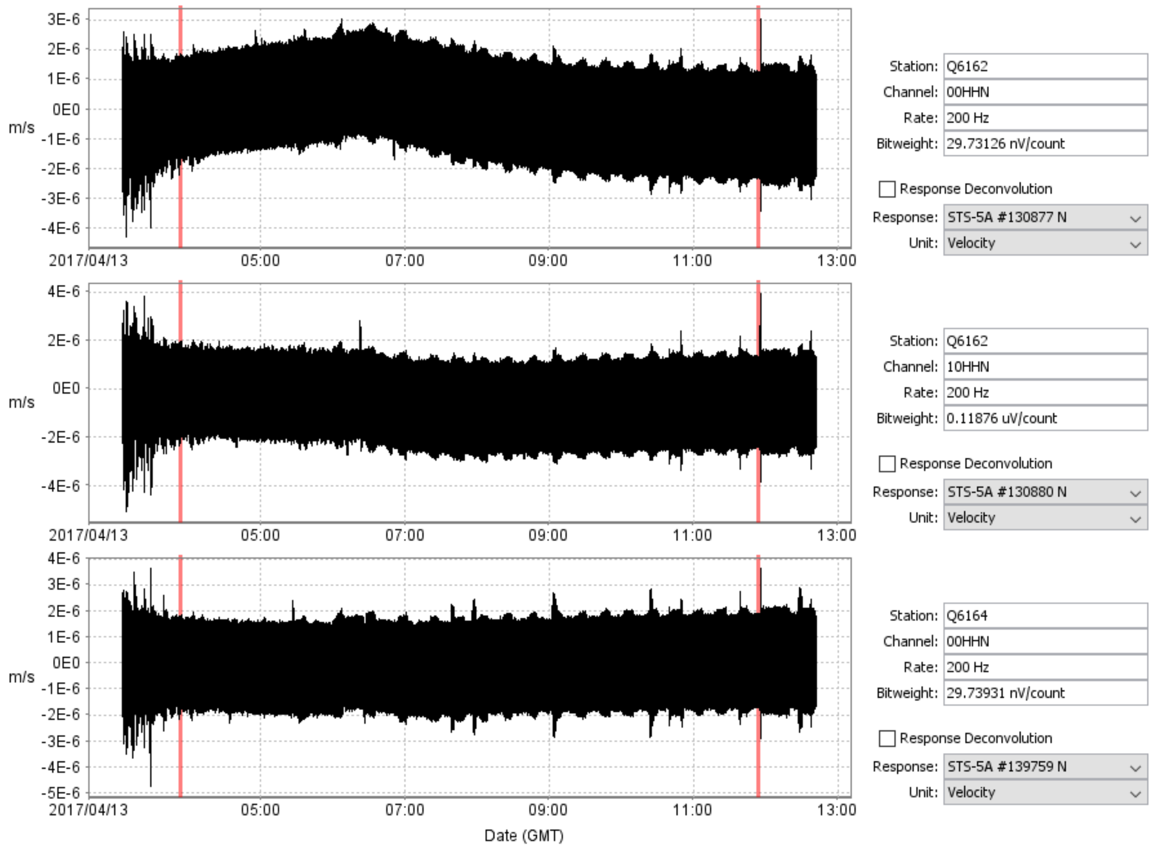



**Figure 25 Self Noise Time Series**

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

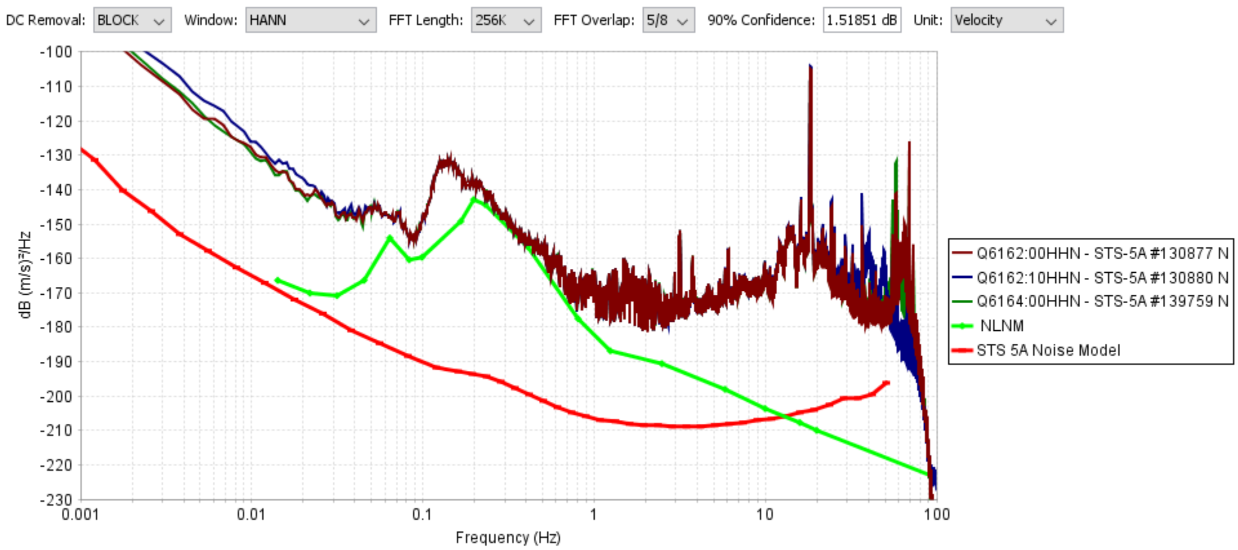



**Figure 26 Self Noise Raw Power Spectra**

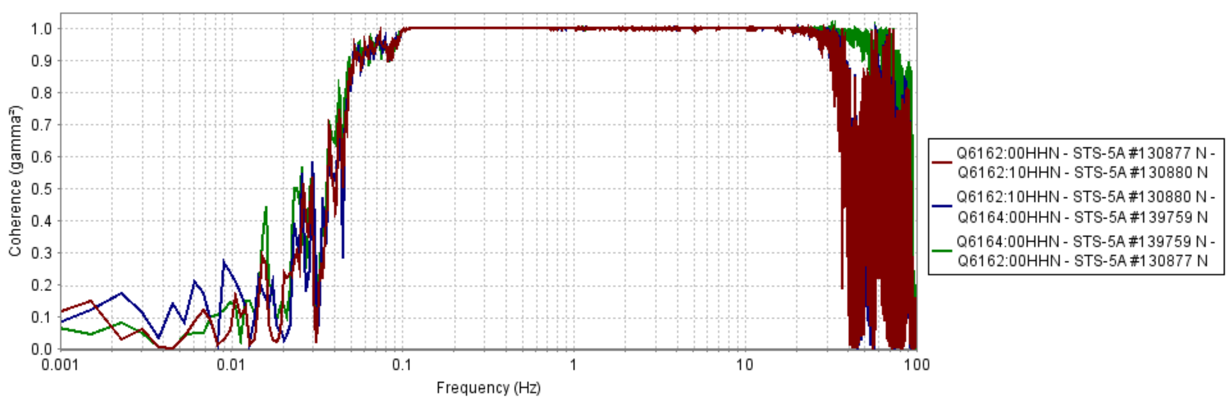



**Figure 27 Self Noise Coherence**

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 STS-5A noise model are overlaid for comparison.

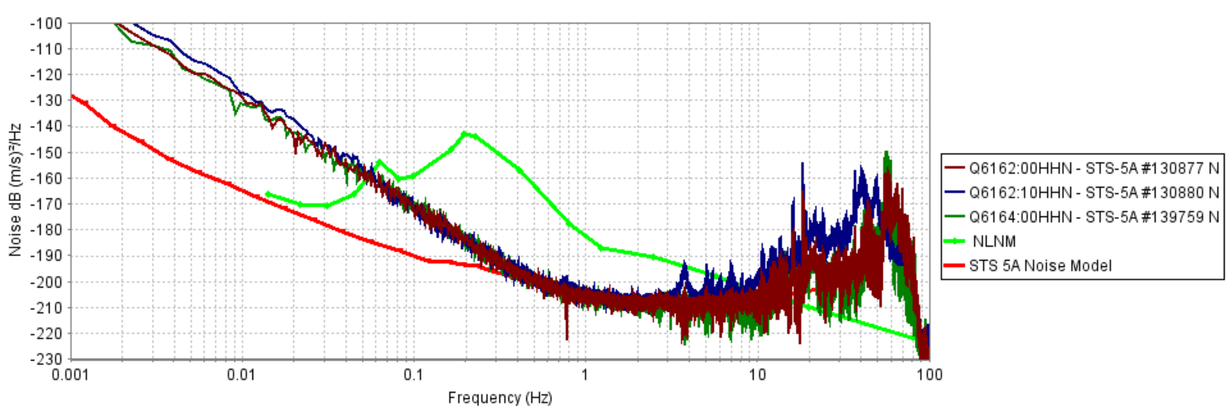



**Figure 28 Self Noise**

We observe that there is good signal coherence, even when recording just quiet background, between 0.1 and 25 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 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 8 hour segment of data used for analysis.

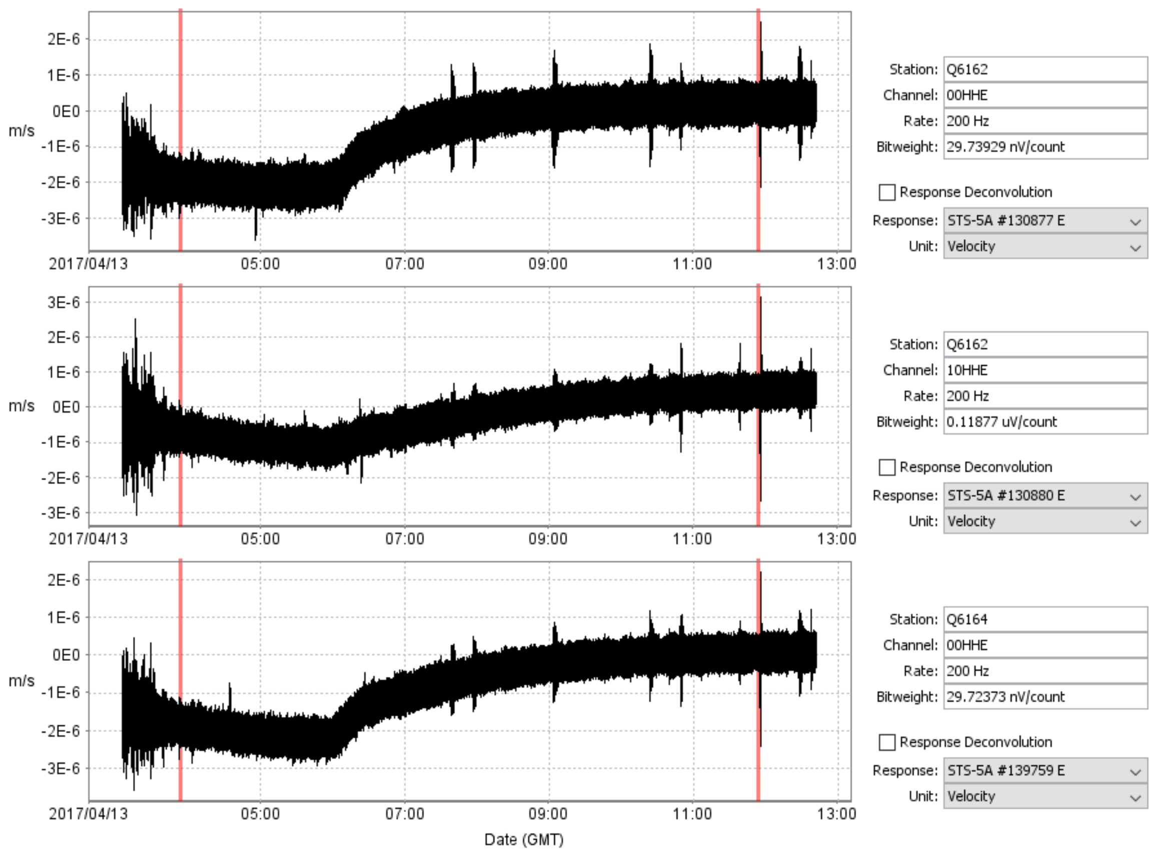



**Figure 29 Self Noise Time Series**

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

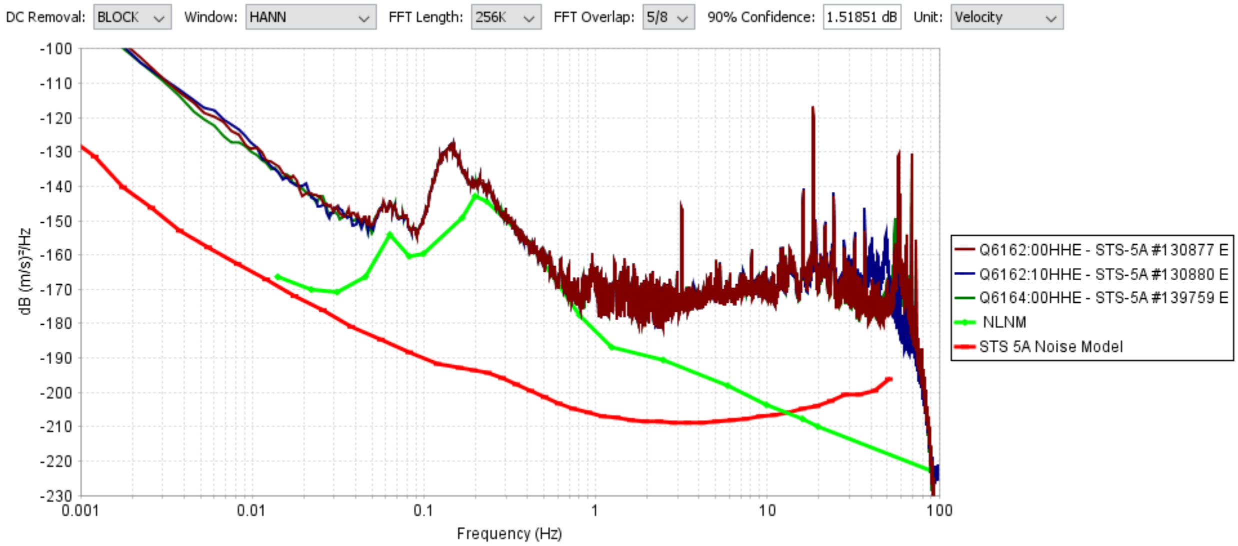



**Figure 30 Self Noise Raw Power Spectra**

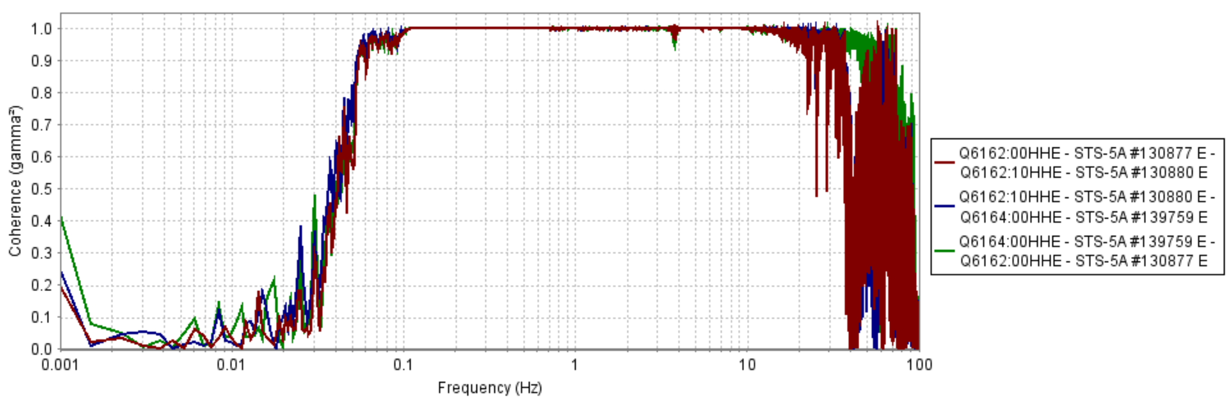



**Figure 31 Self Noise Coherence**

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 STS-5A noise model are overlaid for comparison.

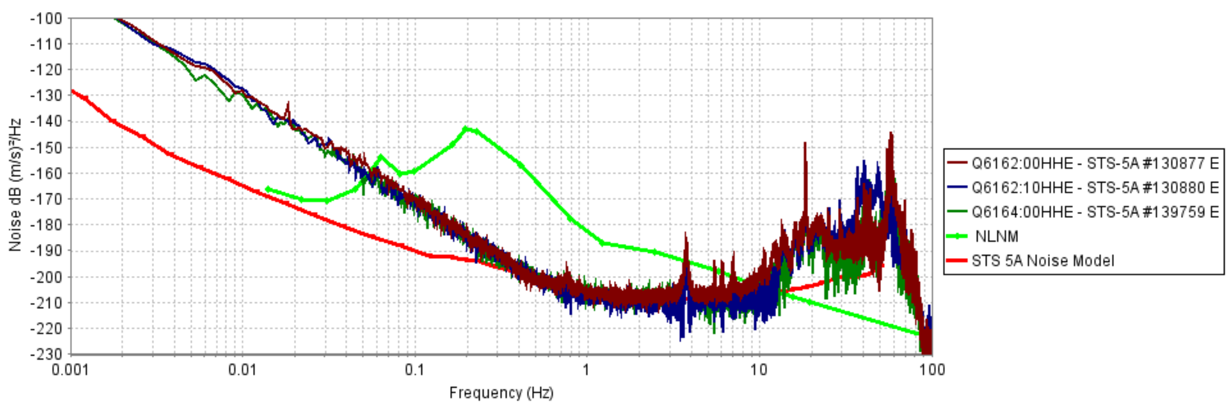



**Figure 32 Self Noise**

We observe that there is good signal coherence, even when recording just quiet background, between 0.1 and 20 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 20 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 - 50 Hz | 20 mHz - 1 Hz | 20 mHz - 16 Hz | 0.5 Hz - 16 Hz |
|---|---|---|---|---|
| STS5A #130877 | 128.15819 dB | 144.03839 dB | 140.93607 dB | 143.82027 dB |
| STS5A #130880 | 128.02158 dB | 149.47748 dB | 143.1165 dB | 144.2116 dB |
| STS5A #139759 | 129.84408 dB | 149.31338 dB | 145.43907 dB | 147.68641 dB |

**Table 13 Dynamic Range - N**

| | 8.3 mHz - 50 Hz | 20 mHz - 1 Hz | 20 mHz - 16 Hz | 0.5 Hz - 16 Hz |
|---|---|---|---|---|
| STS5A #130877 | 110.44798 dB | 123.22286 dB | 123.21681 dB | 151.59184 dB |
| STS5A #130880 | 106.74898 dB | 120.58146 dB | 120.56545 dB | 144.85784 dB |
| STS5A #139759 | 111.92984 dB | 123.41867 dB | 123.40887 dB | 149.74505 dB |

**Table 14 Dynamic Range - E**

| | 8.3 mHz - 50 Hz | 20 mHz - 1 Hz | 20 mHz - 16 Hz | 0.5 Hz - 16 Hz |
|---|---|---|---|---|
| STS5A #130877 | 110.33589 dB | 122.78521 dB | 122.73301 dB | 141.94145 dB |
| STS5A #130880 | 108.42273 dB | 123.43786 dB | 123.40599 dB | 144.73587 dB |
| STS5A #139759 | 112.63939 dB | 123.90683 dB | 123.88667 dB | 147.17048 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 120.5 and 145.4 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.

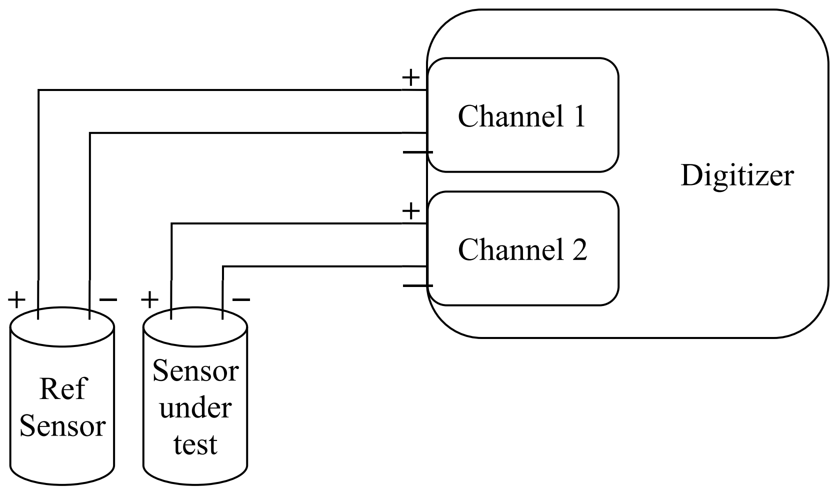



**Figure 33 Frequency Response Configuration Diagram**

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 | Kinemetrics STS-5A | # 130877, 130880 | 1500 V/(m/s) |
| Sensor Digitizers | Kinemetrics Q330 | # 6162 | 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 |
|---|---|---|---|
| < 0.1 Hz | July 17, 2017, 23:44 | 7.7 | Eastern Russia |
| 0.1 – 1 Hz | June 6, 2017, 06:30 | 5.8 | Montana |
| > 1 Hz | July 14, 2017, 13:46 | 4.2 | Oklahoma |

The following table contains the composite seismometer response values, smoothed with a filter, expressed as dB of amplitude relative to each seismometers sensitivity at 1 Hz and degrees of phase.

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

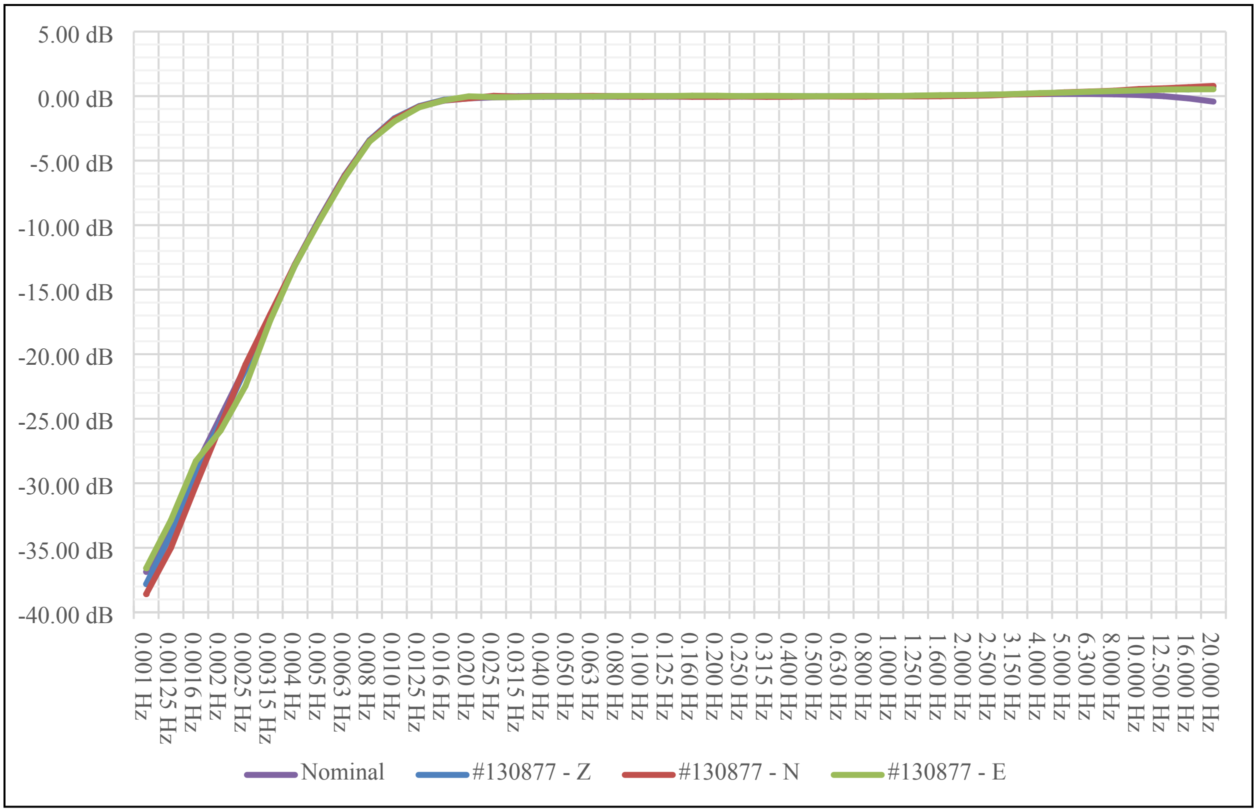



**Figure 34 Amplitude Response - #130877**

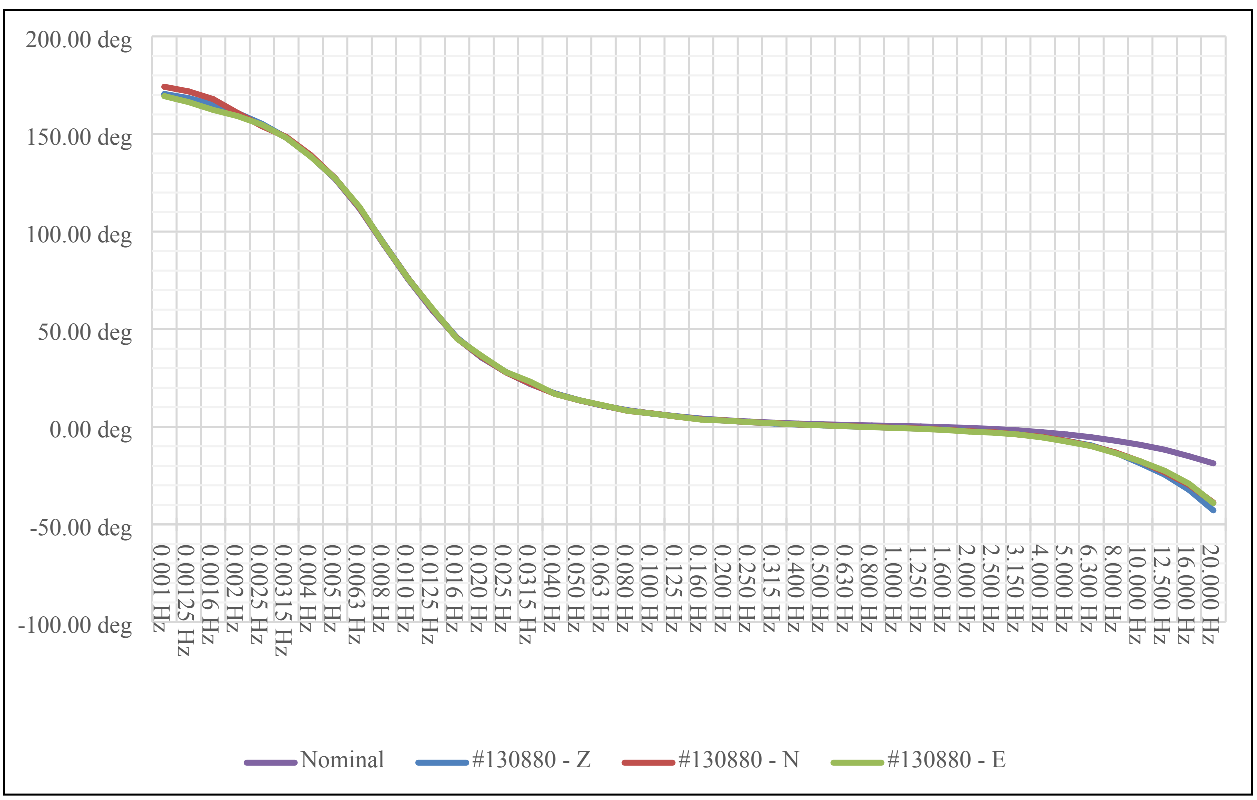



**Figure 35 Phase Response - #130877**

## Table 17 Frequency Response - #130877

| | Nominal | | Z | | N | | E | |
|---|---|---|---|---|---|---|---|---|
| Frequency | Amplitude | Phase | Amplitude | Phase | Amplitude | Phase | Amplitude | Phase |
| 0.00100 Hz | -36.87 dB | 170.22 deg | -37.81 dB | 170.55 deg | -38.59 dB | 164.67 deg | -36.59 dB | 172.65 deg |
| 0.00125 Hz | -32.99 dB | 167.75 deg | -33.96 dB | 168.42 deg | -35.00 dB | 160.70 deg | -32.85 dB | 173.54 deg |
| 0.00160 Hz | -28.71 dB | 164.25 deg | -29.01 dB | 165.24 deg | -30.18 dB | 155.76 deg | -28.29 dB | 172.79 deg |
| 0.00200 Hz | -24.84 dB | 160.18 deg | -25.27 dB | 160.81 deg | -25.50 dB | 152.77 deg | -25.92 dB | 163.50 deg |
| 0.00250 Hz | -20.98 dB | 154.99 deg | -21.19 dB | 155.31 deg | -20.81 dB | 149.64 deg | -22.46 dB | 154.18 deg |
| 0.00315 Hz | -17.02 dB | 148.03 deg | -17.11 dB | 148.21 deg | -16.90 dB | 146.28 deg | -17.38 dB | 146.21 deg |
| 0.00400 Hz | -13.01 dB | 138.56 deg | -13.09 dB | 138.77 deg | -13.04 dB | 138.69 deg | -13.09 dB | 136.73 deg |
| 0.00500 Hz | -9.44 dB | 126.99 deg | -9.51 dB | 127.38 deg | -9.55 dB | 126.98 deg | -9.60 dB | 127.05 deg |
| 0.00630 Hz | -6.12 dB | 111.79 deg | -6.17 dB | 112.28 deg | -6.19 dB | 111.73 deg | -6.30 dB | 113.14 deg |
| 0.00800 Hz | -3.42 dB | 93.25 deg | -3.42 dB | 93.79 deg | -3.47 dB | 93.62 deg | -3.52 dB | 93.46 deg |
| 0.01000 Hz | -1.75 dB | 75.41 deg | -1.72 dB | 75.90 deg | -1.78 dB | 75.67 deg | -1.96 dB | 76.40 deg |
| 0.01250 Hz | -0.82 dB | 59.45 deg | -0.78 dB | 59.98 deg | -0.82 dB | 60.10 deg | -0.87 dB | 60.58 deg |
| 0.01600 Hz | -0.35 dB | 45.27 deg | -0.28 dB | 45.41 deg | -0.32 dB | 45.19 deg | -0.33 dB | 45.03 deg |
| 0.02000 Hz | -0.17 dB | 35.46 deg | -0.12 dB | 35.62 deg | -0.18 dB | 35.82 deg | -0.02 dB | 36.49 deg |
| 0.02500 Hz | -0.10 dB | 27.92 deg | -0.02 dB | 28.03 deg | 0.02 dB | 27.93 deg | -0.08 dB | 28.11 deg |
| 0.03150 Hz | -0.06 dB | 21.90 deg | -0.01 dB | 21.92 deg | -0.03 dB | 22.15 deg | -0.07 dB | 23.41 deg |
| 0.04000 Hz | -0.05 dB | 17.10 deg | 0.01 dB | 17.02 deg | 0.00 dB | 16.86 deg | -0.02 dB | 16.84 deg |
| 0.05000 Hz | -0.05 dB | 13.61 deg | 0.01 dB | 13.50 deg | 0.00 dB | 13.57 deg | 0.00 dB | 13.64 deg |
| 0.06300 Hz | -0.04 dB | 10.76 deg | 0.01 dB | 10.66 deg | 0.02 dB | 10.92 deg | -0.03 dB | 10.99 deg |
| 0.08000 Hz | -0.04 dB | 8.45 deg | 0.01 dB | 8.29 deg | -0.01 dB | 8.12 deg | 0.01 dB | 8.13 deg |
| 0.1000 Hz | -0.04 dB | 6.75 deg | 0.01 dB | 6.72 deg | -0.04 dB | 6.87 deg | 0.02 dB | 6.78 deg |
| 0.1250 Hz | -0.04 dB | 5.39 deg | 0.00 dB | 5.34 deg | -0.01 dB | 5.23 deg | 0.00 dB | 5.25 deg |
| 0.1600 Hz | -0.04 dB | 4.20 deg | 0.00 dB | 3.95 deg | -0.05 dB | 3.79 deg | 0.03 dB | 3.63 deg |
| 0.2000 Hz | -0.04 dB | 3.35 deg | 0.00 dB | 3.12 deg | -0.05 dB | 3.26 deg | 0.03 dB | 3.17 deg |
| 0.2500 Hz | -0.04 dB | 2.67 deg | -0.01 dB | 2.39 deg | -0.03 dB | 2.37 deg | 0.00 dB | 2.37 deg |
| 0.3150 Hz | -0.04 dB | 2.10 deg | 0.00 dB | 1.66 deg | -0.05 dB | 1.90 deg | 0.02 dB | 1.84 deg |
| 0.4000 Hz | -0.04 dB | 1.63 deg | -0.01 dB | 1.13 deg | -0.04 dB | 1.22 deg | 0.01 dB | 1.21 deg |
| 0.5000 Hz | -0.03 dB | 1.27 deg | -0.01 dB | 0.71 deg | -0.02 dB | 0.79 deg | -0.01 dB | 0.73 deg |
| 0.6300 Hz | -0.02 dB | 0.96 deg | -0.01 dB | 0.30 deg | -0.03 dB | 0.35 deg | 0.01 dB | 0.22 deg |
| 0.8000 Hz | -0.01 dB | 0.68 deg | -0.01 dB | -0.11 deg | -0.04 dB | -0.09 deg | 0.02 dB | -0.20 deg |
| 1.0000 Hz | 0.00 dB | 0.43 deg | 0.00 dB | -0.47 deg | -0.01 dB | -0.50 deg | 0.00 dB | -0.62 deg |
| 1.2500 Hz | 0.02 dB | 0.16 deg | 0.02 dB | -0.90 deg | -0.02 dB | -0.90 deg | 0.04 dB | -1.05 deg |
| 1.6000 Hz | 0.05 dB | -0.18 deg | 0.03 dB | -1.39 deg | -0.01 dB | -1.51 deg | 0.07 dB | -1.66 deg |
| 2.0000 Hz | 0.08 dB | -0.59 deg | 0.07 dB | -2.06 deg | 0.02 dB | -2.26 deg | 0.09 dB | -2.51 deg |
| 2.5000 Hz | 0.11 dB | -1.12 deg | 0.10 dB | -2.75 deg | 0.05 dB | -2.75 deg | 0.11 dB | -3.10 deg |
| 3.1500 Hz | 0.14 dB | -1.85 deg | 0.15 dB | -3.83 deg | 0.14 dB | -3.80 deg | 0.16 dB | -4.01 deg |
| 4.0000 Hz | 0.16 dB | -2.81 deg | 0.21 dB | -5.38 deg | 0.18 dB | -5.09 deg | 0.24 dB | -5.57 deg |
| 5.0000 Hz | 0.17 dB | -3.94 deg | 0.27 dB | -7.01 deg | 0.30 dB | -7.30 deg | 0.27 dB | -7.68 deg |
| 6.3000 Hz | 0.17 dB | -5.37 deg | 0.32 dB | -10.10 deg | 0.35 dB | -9.92 deg | 0.34 dB | -10.17 deg |
| 8.0000 Hz | 0.14 dB | -7.18 deg | 0.39 dB | -13.56 deg | 0.42 dB | -13.59 deg | 0.39 dB | -13.71 deg |
| 10.0000 Hz | 0.09 dB | -9.24 deg | 0.42 dB | -19.74 deg | 0.55 dB | -18.68 deg | 0.44 dB | -17.63 deg |
| 12.5000 Hz | -0.01 dB | -11.73 deg | 0.55 dB | -26.76 deg | 0.61 dB | -24.95 deg | 0.50 dB | -22.79 deg |
| 16.0000 Hz | -0.18 dB | -15.09 deg | 0.51 dB | -35.66 deg | 0.69 dB | -30.32 deg | 0.53 dB | -30.03 deg |
| 20.0000 Hz | -0.42 dB | -18.74 deg | 0.73 dB | -46.44 deg | 0.79 dB | -41.33 deg | 0.53 dB | -38.40 deg |

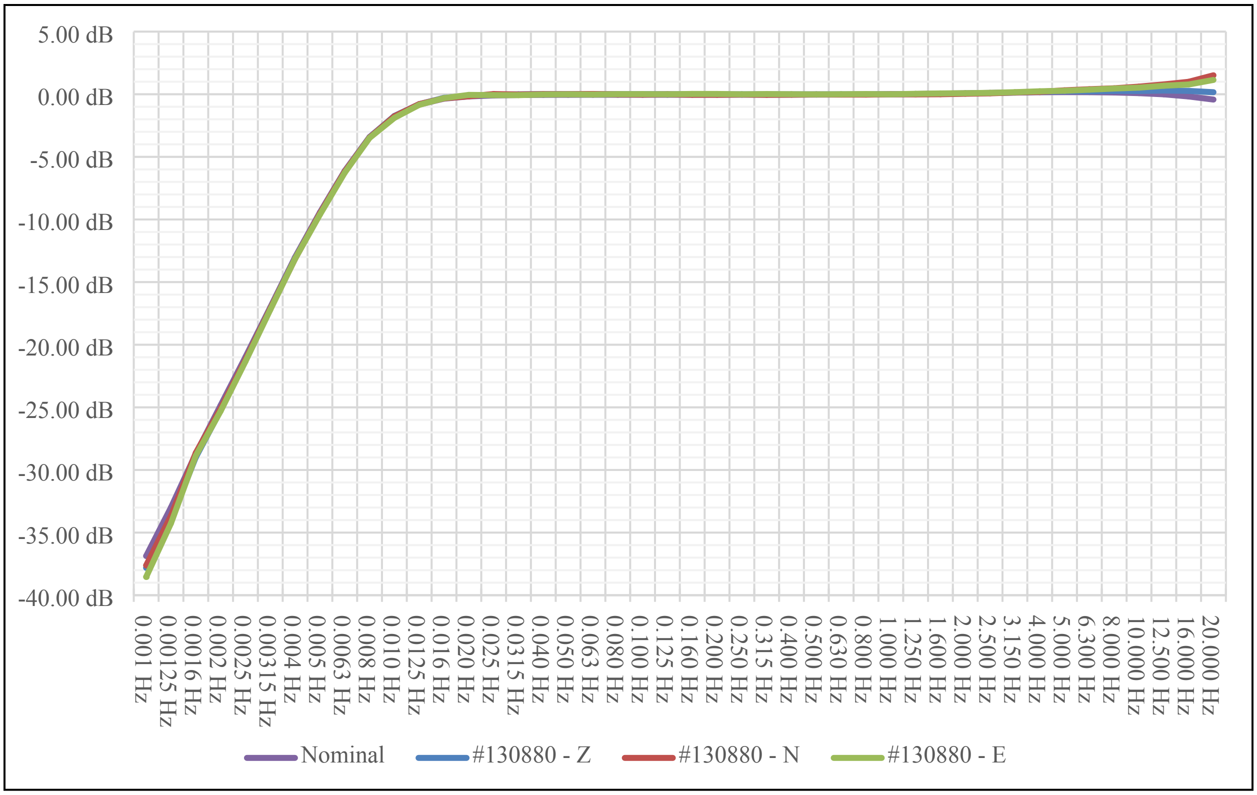



**Figure 36 Amplitude Response - #130880**

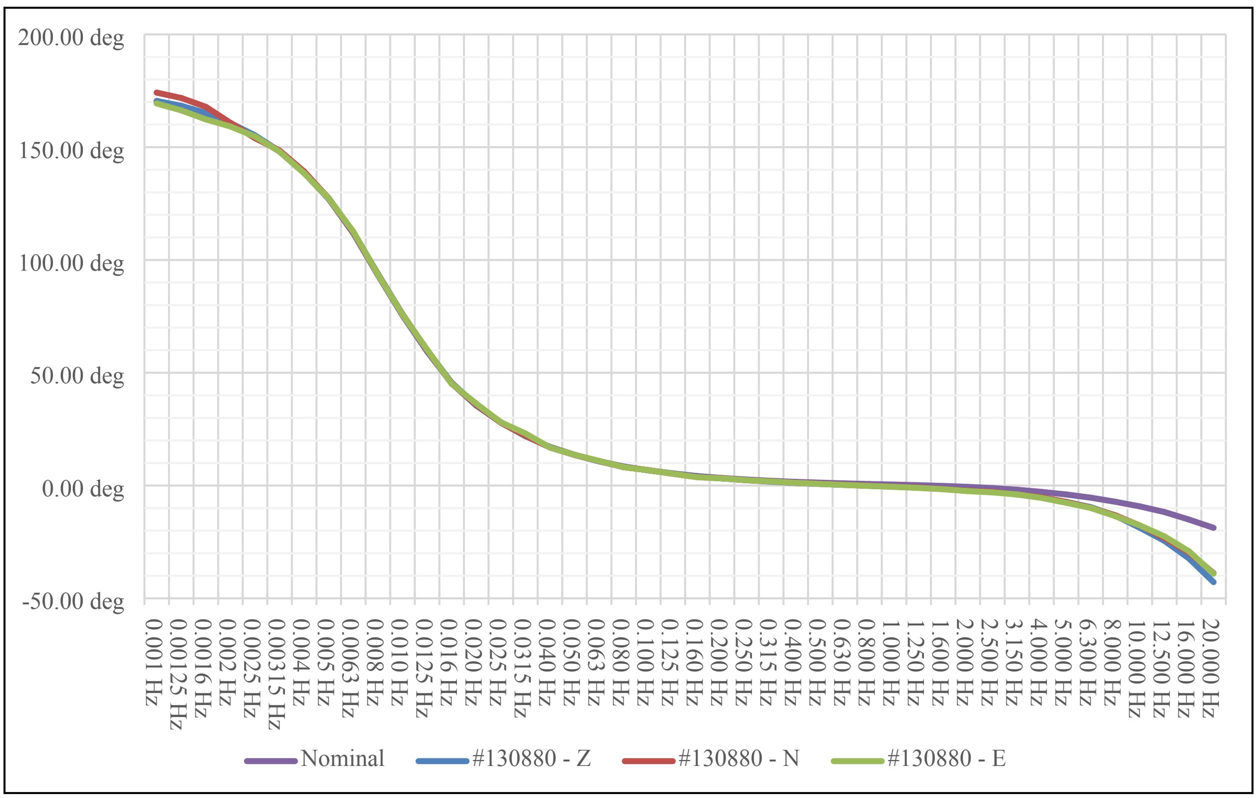



**Figure 37 Phase Response - #130880**

## Table 18 Frequency Response - #130880

| | Nominal | | Z | | N | | E | |
|---|---|---|---|---|---|---|---|---|
| Frequency | Amplitude | Phase | Amplitude | Phase | Amplitude | Phase | Amplitude | Phase |
| 0.00100 Hz | -37.81 dB | 170.50 deg | -37.62 dB | 174.19 deg | -38.54 dB | 169.39 deg | -37.81 dB | 170.50 deg |
| 0.00125 Hz | -33.94 dB | 168.35 deg | -33.66 dB | 171.81 deg | -34.25 dB | 166.32 deg | -33.94 dB | 168.35 deg |
| 0.00160 Hz | -28.98 dB | 165.15 deg | -28.63 dB | 167.88 deg | -28.86 dB | 162.34 deg | -28.98 dB | 165.15 deg |
| 0.00200 Hz | -25.24 dB | 160.70 deg | -25.11 dB | 160.80 deg | -25.30 dB | 159.17 deg | -25.24 dB | 160.70 deg |
| 0.00250 Hz | -21.17 dB | 155.22 deg | -21.20 dB | 153.99 deg | -21.33 dB | 154.74 deg | -21.17 dB | 155.22 deg |
| 0.00315 Hz | -17.11 dB | 148.21 deg | -17.12 dB | 148.49 deg | -17.20 dB | 148.01 deg | -17.11 dB | 148.21 deg |
| 0.00400 Hz | -13.10 dB | 138.77 deg | -13.13 dB | 139.19 deg | -13.13 dB | 138.43 deg | -13.10 dB | 138.77 deg |
| 0.00500 Hz | -9.53 dB | 127.34 deg | -9.53 dB | 127.35 deg | -9.61 dB | 127.28 deg | -9.53 dB | 127.34 deg |
| 0.00630 Hz | -6.18 dB | 112.28 deg | -6.18 dB | 112.23 deg | -6.26 dB | 112.57 deg | -6.18 dB | 112.28 deg |
| 0.00800 Hz | -3.45 dB | 93.88 deg | -3.46 dB | 93.64 deg | -3.49 dB | 93.60 deg | -3.45 dB | 93.88 deg |
| 0.01000 Hz | -1.73 dB | 75.99 deg | -1.76 dB | 75.89 deg | -1.89 dB | 75.80 deg | -1.73 dB | 75.99 deg |
| 0.01250 Hz | -0.79 dB | 60.01 deg | -0.79 dB | 60.07 deg | -0.85 dB | 60.27 deg | -0.79 dB | 60.01 deg |
| 0.01600 Hz | -0.29 dB | 45.61 deg | -0.32 dB | 45.26 deg | -0.31 dB | 45.13 deg | -0.29 dB | 45.61 deg |
| 0.02000 Hz | -0.12 dB | 35.72 deg | -0.16 dB | 35.87 deg | -0.05 dB | 36.34 deg | -0.12 dB | 35.72 deg |
| 0.02500 Hz | -0.03 dB | 28.13 deg | 0.02 dB | 27.89 deg | -0.07 dB | 28.06 deg | -0.03 dB | 28.13 deg |
| 0.03150 Hz | -0.01 dB | 22.00 deg | -0.02 dB | 22.12 deg | -0.07 dB | 23.10 deg | -0.01 dB | 22.00 deg |
| 0.04000 Hz | 0.01 dB | 17.14 deg | 0.01 dB | 16.89 deg | -0.02 dB | 16.87 deg | 0.01 dB | 17.14 deg |
| 0.05000 Hz | 0.01 dB | 13.62 deg | 0.01 dB | 13.57 deg | -0.01 dB | 13.62 deg | 0.01 dB | 13.62 deg |
| 0.06300 Hz | 0.01 dB | 10.73 deg | 0.02 dB | 10.87 deg | -0.03 dB | 10.93 deg | 0.01 dB | 10.73 deg |
| 0.08000 Hz | 0.01 dB | 8.35 deg | -0.01 dB | 8.13 deg | 0.01 dB | 8.17 deg | 0.01 dB | 8.35 deg |
| 0.1000 Hz | 0.01 dB | 6.74 deg | -0.03 dB | 6.85 deg | 0.01 dB | 6.78 deg | 0.01 dB | 6.74 deg |
| 0.1250 Hz | 0.00 dB | 5.33 deg | 0.00 dB | 5.20 deg | 0.00 dB | 5.23 deg | 0.00 dB | 5.33 deg |
| 0.1600 Hz | 0.00 dB | 4.02 deg | -0.04 dB | 3.79 deg | 0.03 dB | 3.68 deg | 0.00 dB | 4.02 deg |
| 0.2000 Hz | 0.00 dB | 3.16 deg | -0.04 dB | 3.22 deg | 0.02 dB | 3.15 deg | 0.00 dB | 3.16 deg |
| 0.2500 Hz | 0.00 dB | 2.42 deg | -0.02 dB | 2.35 deg | 0.00 dB | 2.37 deg | 0.00 dB | 2.42 deg |
| 0.3150 Hz | -0.01 dB | 1.67 deg | -0.05 dB | 1.87 deg | 0.02 dB | 1.81 deg | -0.01 dB | 1.67 deg |
| 0.4000 Hz | -0.01 dB | 1.14 deg | -0.03 dB | 1.20 deg | 0.00 dB | 1.20 deg | -0.01 dB | 1.14 deg |
| 0.5000 Hz | -0.01 dB | 0.71 deg | -0.01 dB | 0.79 deg | -0.01 dB | 0.72 deg | -0.01 dB | 0.71 deg |
| 0.6300 Hz | 0.00 dB | 0.27 deg | -0.03 dB | 0.35 deg | 0.00 dB | 0.25 deg | 0.00 dB | 0.27 deg |
| 0.8000 Hz | 0.00 dB | -0.13 deg | -0.03 dB | -0.10 deg | 0.02 dB | -0.19 deg | 0.00 dB | -0.13 deg |
| 1.0000 Hz | 0.00 dB | -0.50 deg | 0.00 dB | -0.51 deg | 0.00 dB | -0.59 deg | 0.00 dB | -0.50 deg |
| 1.2500 Hz | 0.02 dB | -0.95 deg | -0.01 dB | -0.91 deg | 0.04 dB | -1.05 deg | 0.02 dB | -0.95 deg |
| 1.6000 Hz | 0.03 dB | -1.45 deg | 0.00 dB | -1.53 deg | 0.07 dB | -1.64 deg | 0.03 dB | -1.45 deg |
| 2.0000 Hz | 0.06 dB | -2.09 deg | 0.04 dB | -2.26 deg | 0.08 dB | -2.46 deg | 0.06 dB | -2.09 deg |
| 2.5000 Hz | 0.10 dB | -2.81 deg | 0.07 dB | -2.76 deg | 0.11 dB | -3.02 deg | 0.10 dB | -2.81 deg |
| 3.1500 Hz | 0.13 dB | -3.81 deg | 0.14 dB | -3.92 deg | 0.16 dB | -3.95 deg | 0.13 dB | -3.81 deg |
| 4.0000 Hz | 0.19 dB | -5.30 deg | 0.19 dB | -5.17 deg | 0.24 dB | -5.48 deg | 0.19 dB | -5.30 deg |
| 5.0000 Hz | 0.24 dB | -7.23 deg | 0.31 dB | -7.26 deg | 0.28 dB | -7.61 deg | 0.24 dB | -7.23 deg |
| 6.3000 Hz | 0.24 dB | -9.58 deg | 0.40 dB | -9.85 deg | 0.36 dB | -9.92 deg | 0.24 dB | -9.58 deg |
| 8.0000 Hz | 0.27 dB | -13.34 deg | 0.47 dB | -13.18 deg | 0.45 dB | -13.58 deg | 0.27 dB | -13.34 deg |
| 10.0000 Hz | 0.26 dB | -18.73 deg | 0.61 dB | -17.72 deg | 0.53 dB | -17.68 deg | 0.26 dB | -18.73 deg |
| 12.5000 Hz | 0.29 dB | -24.51 deg | 0.78 dB | -23.25 deg | 0.68 dB | -22.53 deg | 0.29 dB | -24.51 deg |
| 16.0000 Hz | 0.27 dB | -32.33 deg | 0.99 dB | -29.76 deg | 0.78 dB | -29.16 deg | 0.27 dB | -32.33 deg |
| 20.0000 Hz | 0.16 dB | -42.82 deg | 1.51 dB | -38.80 deg | 1.14 dB | -39.10 deg | 0.16 dB | -42.82 deg |

#### 3.4.4.1 Low Frequency

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

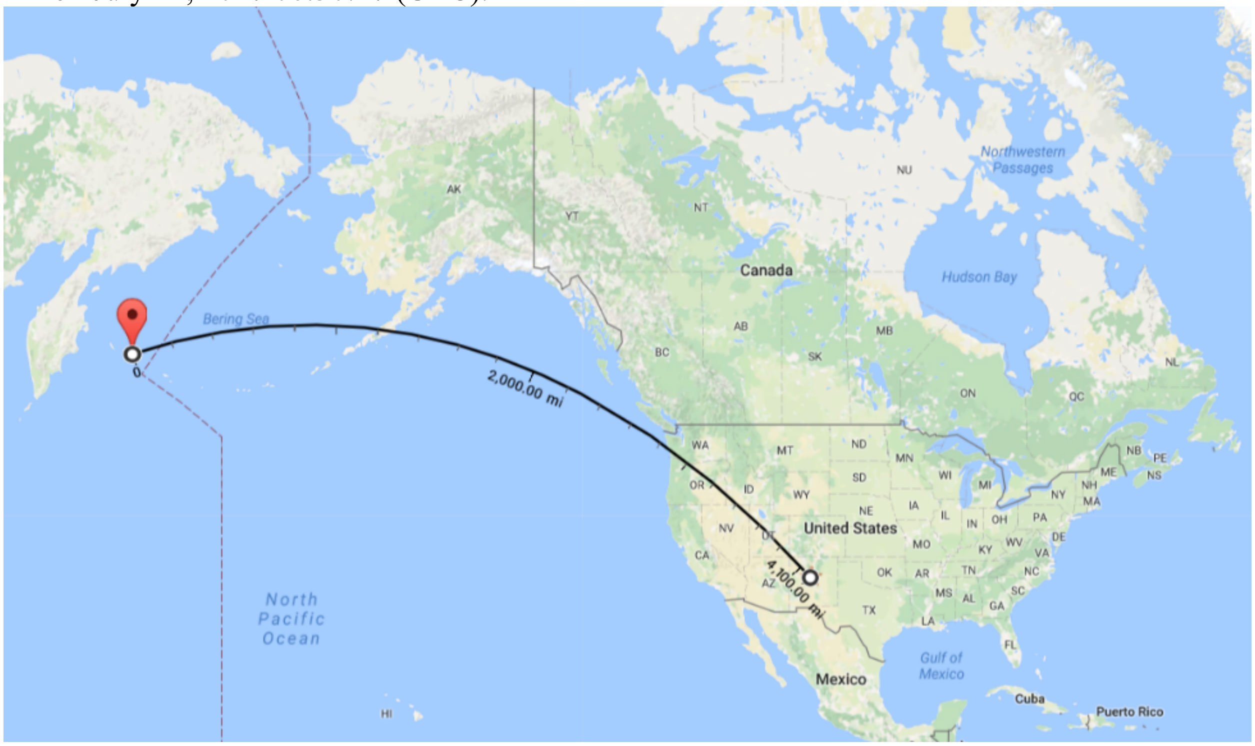



**Figure 38 Sensitivity Earthquake Location**

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.

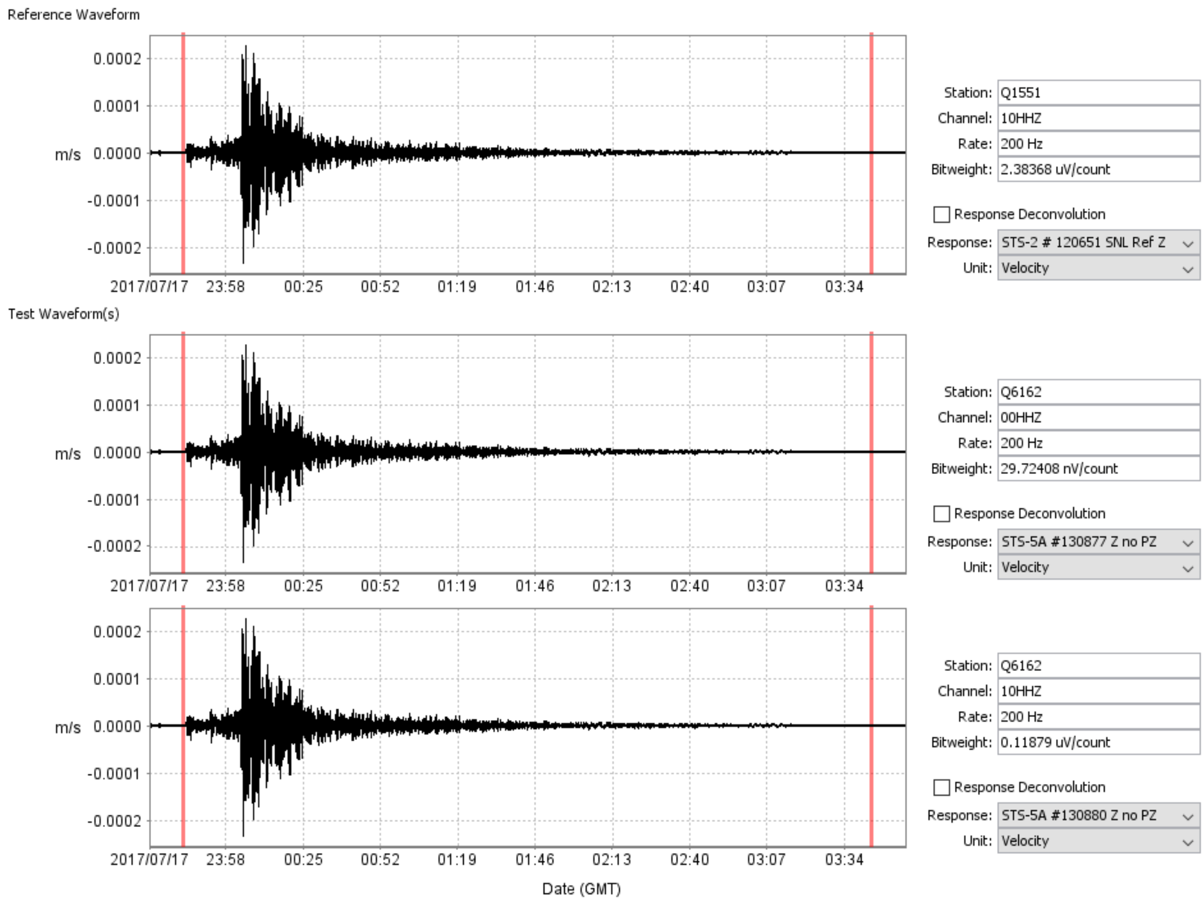



**Figure 39 Low Frequency Response Time Series**

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

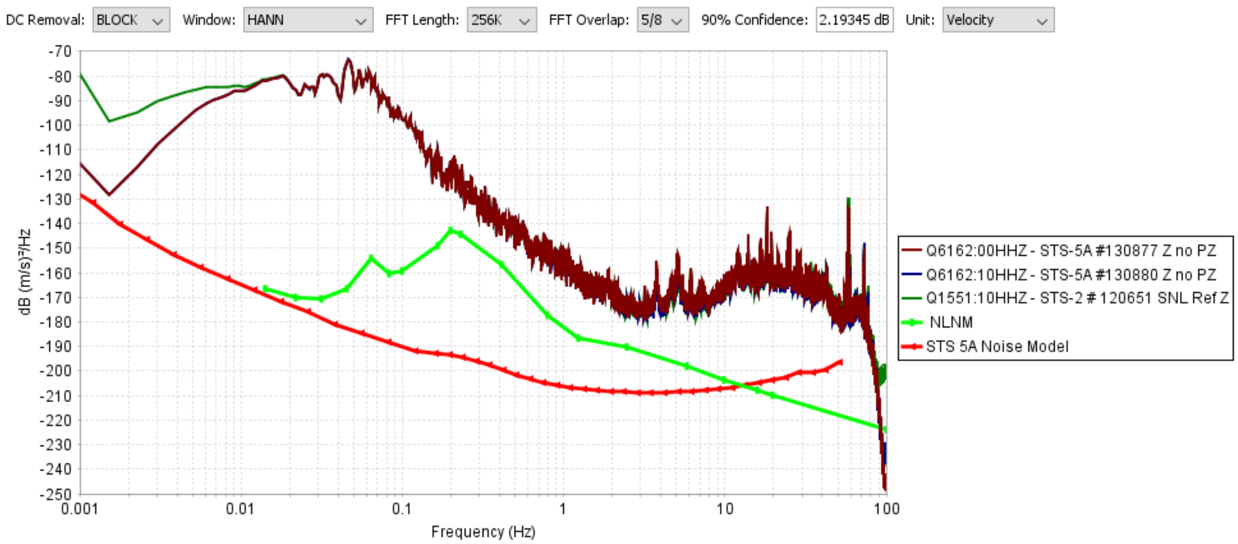



**Figure 40 Low Frequency Response Power Spectra**

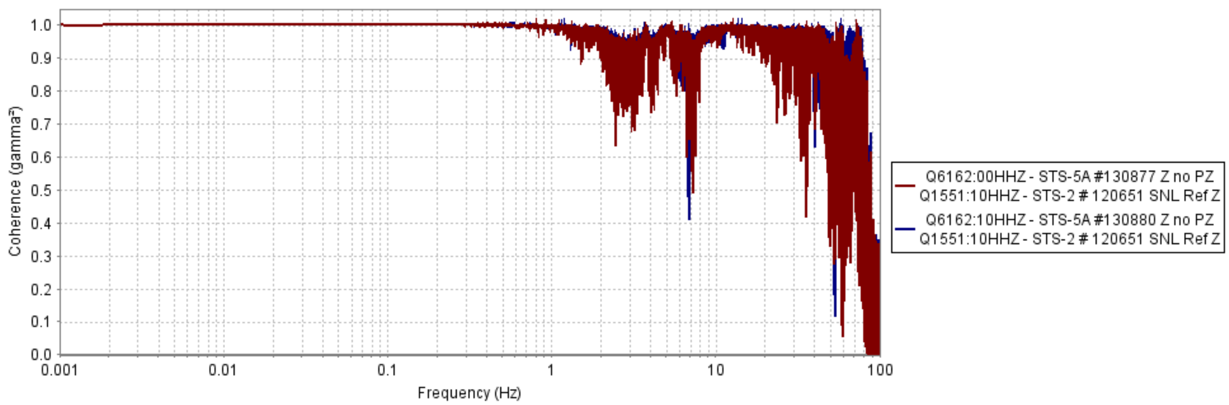



**Figure 41 Low Frequency Response Coherence**

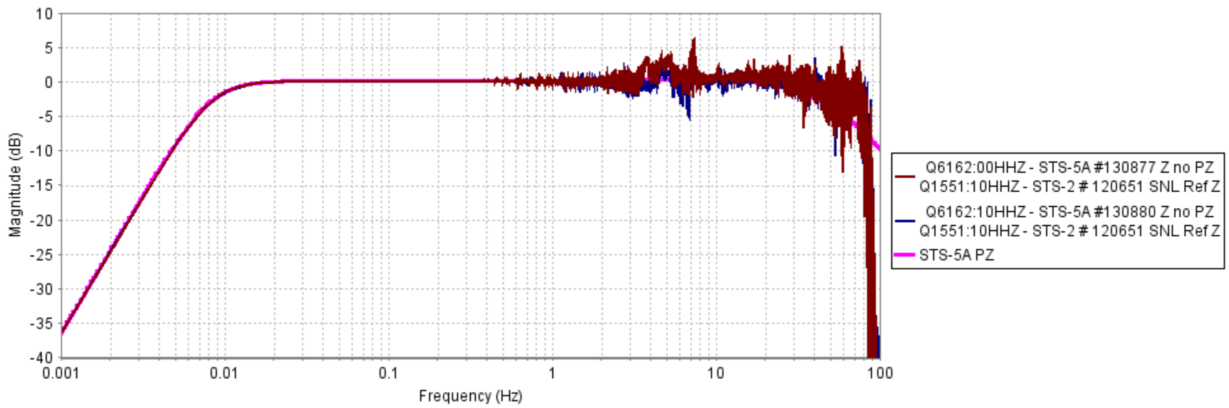



**Figure 42 Low Frequency Amplitude Response**

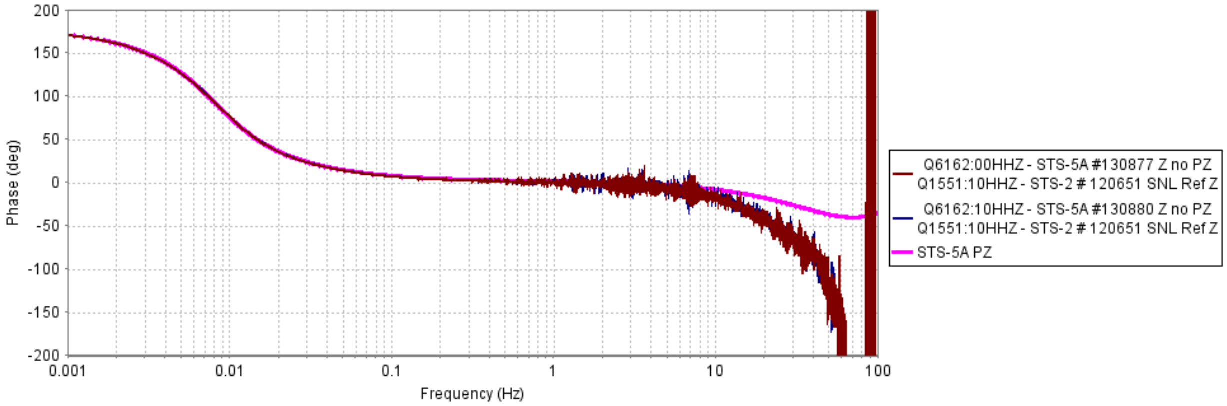



**Figure 43 Low Frequency Phase Response**

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 STS 5A 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).

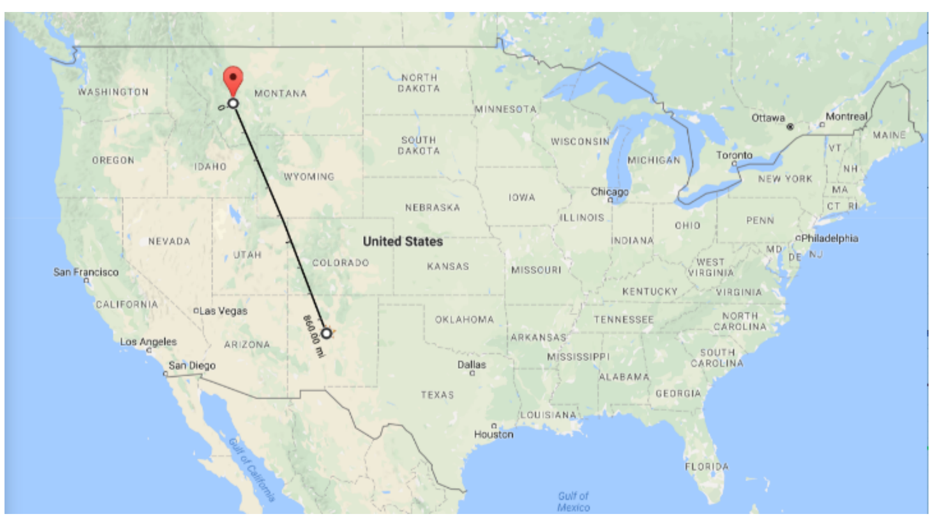



**Figure 44 Sensitivity Earthquake Location**

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.

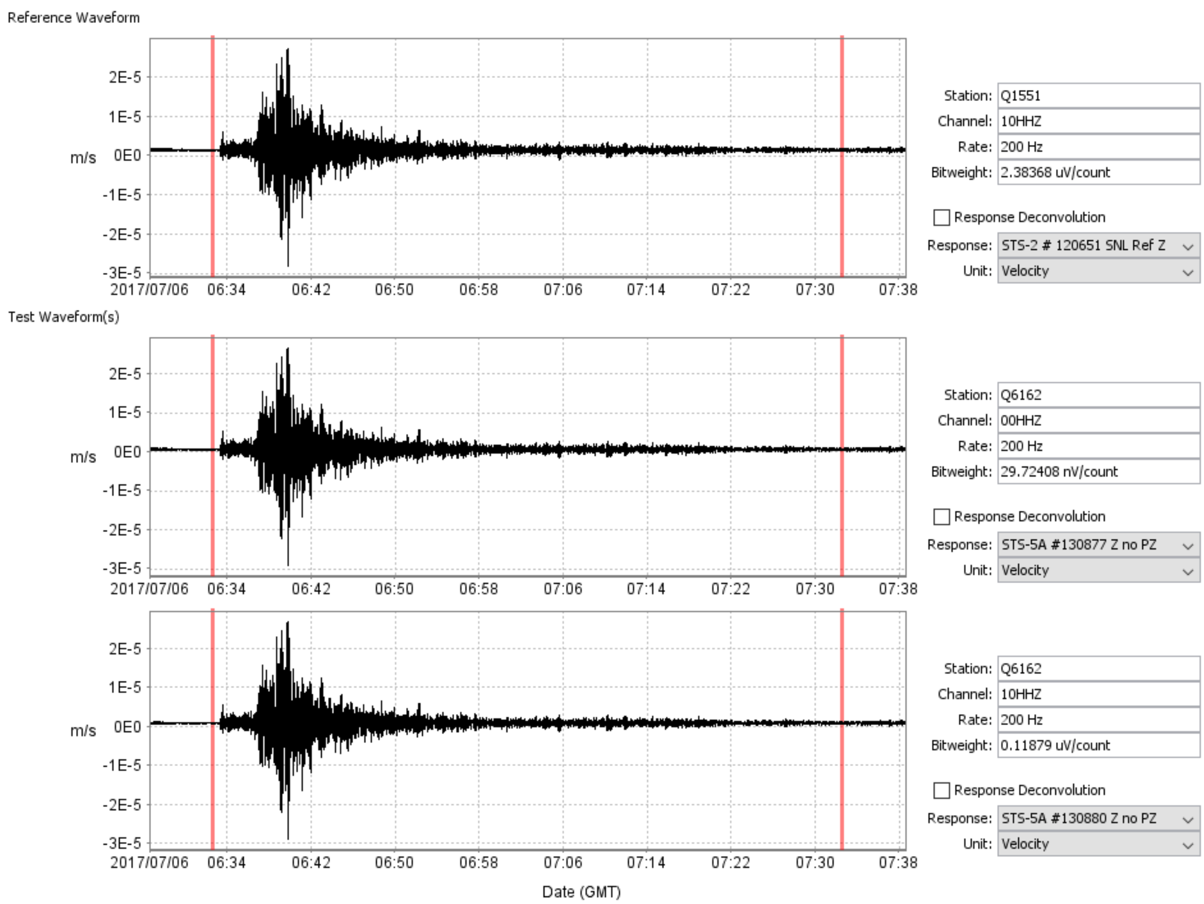



**Figure 45 Mid Frequency Response Time Series**

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

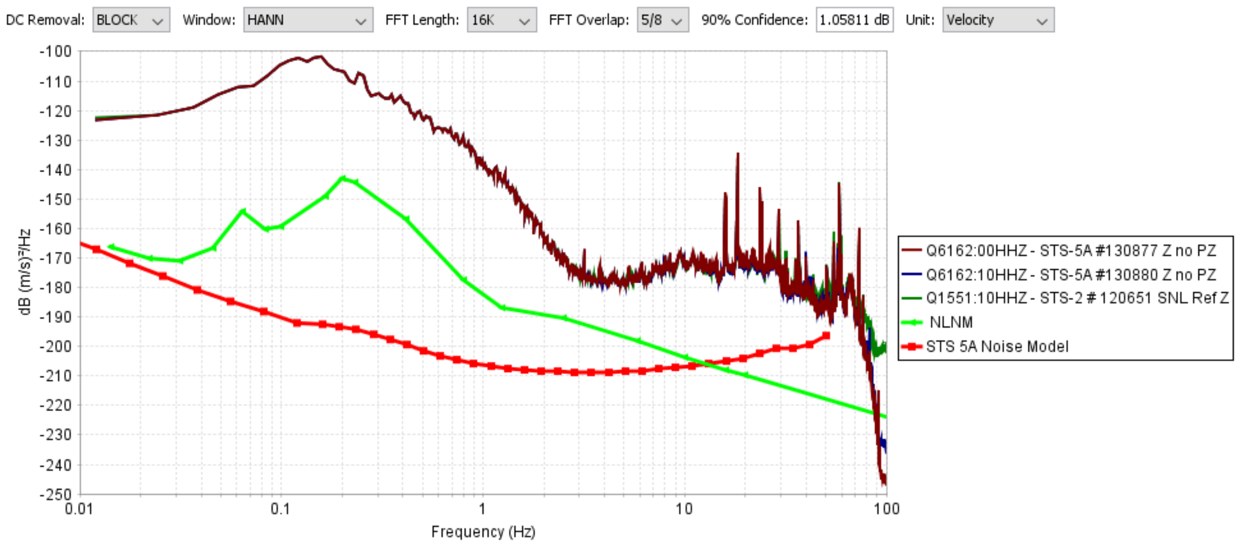



**Figure 46 Mid Frequency Response Power Spectra**

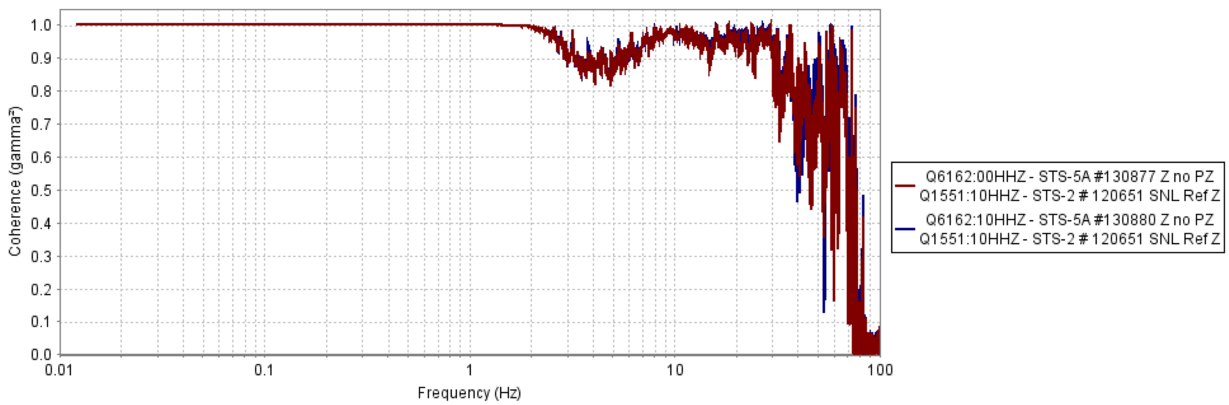



**Figure 47 Mid Frequency Response Coherence**

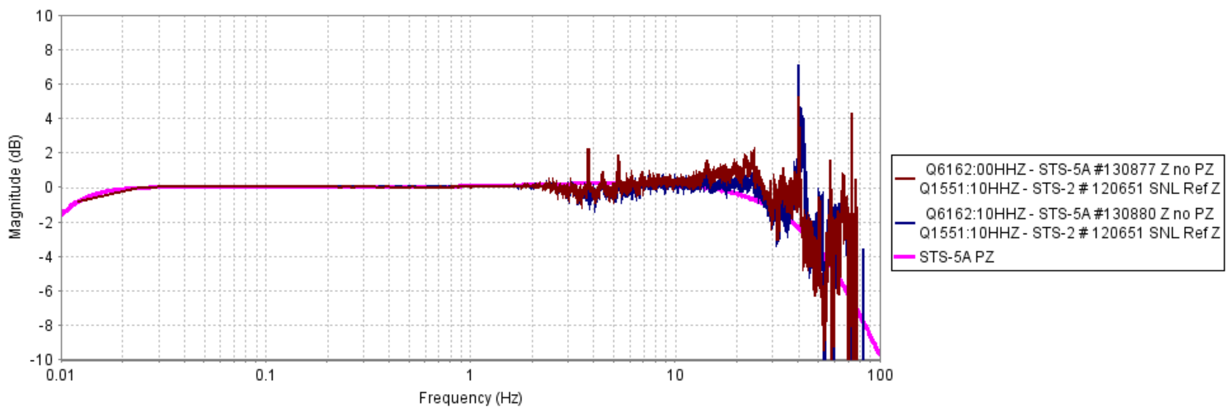



**Figure 48 Mid Frequency Amplitude Response**

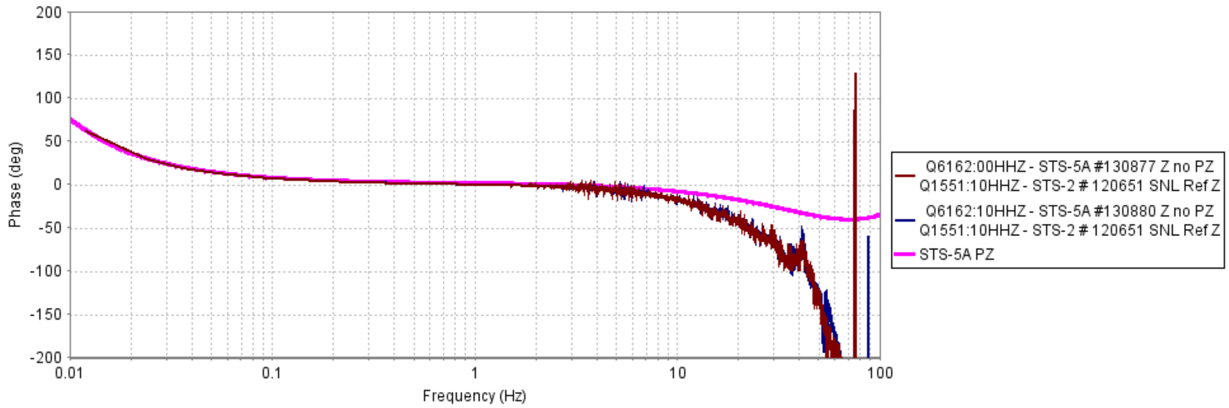



**Figure 49 Mid Frequency Phase Response**

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 0.01 and 2 Hz. Across this pass-band the amplitude and phase response match very closely with the nominal CMG 3V response model, shown with a 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).

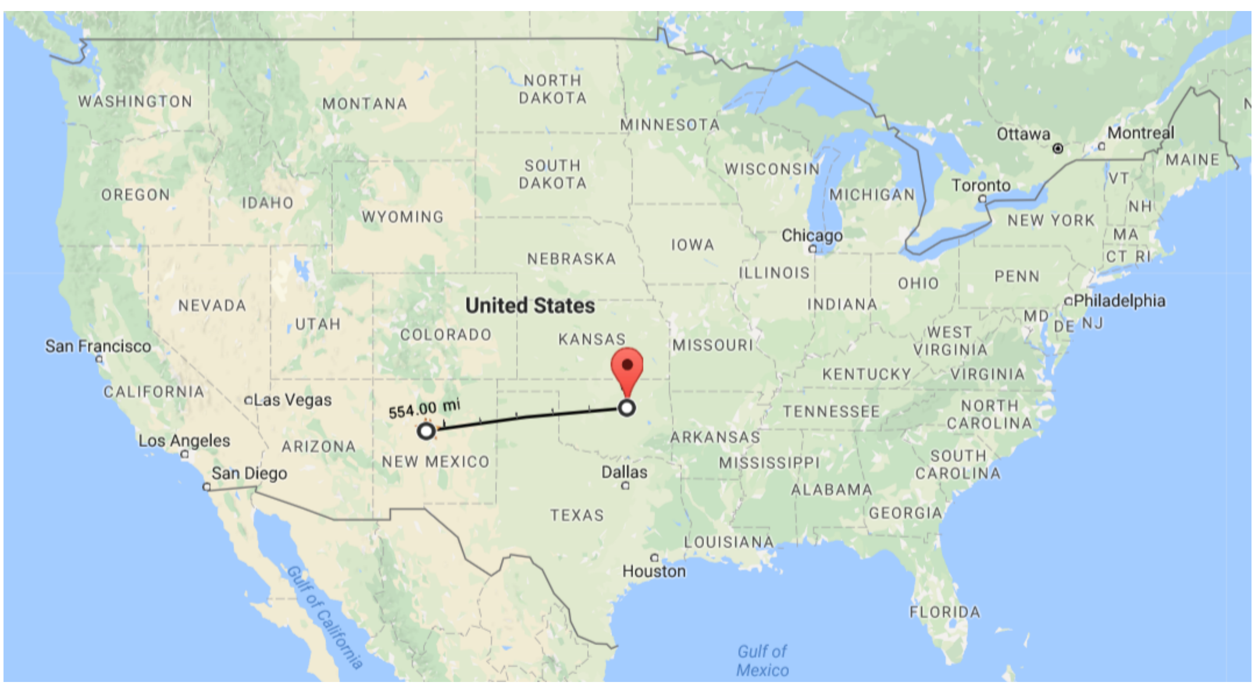



**Figure 50 High Frequency Earthquake Location**

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.

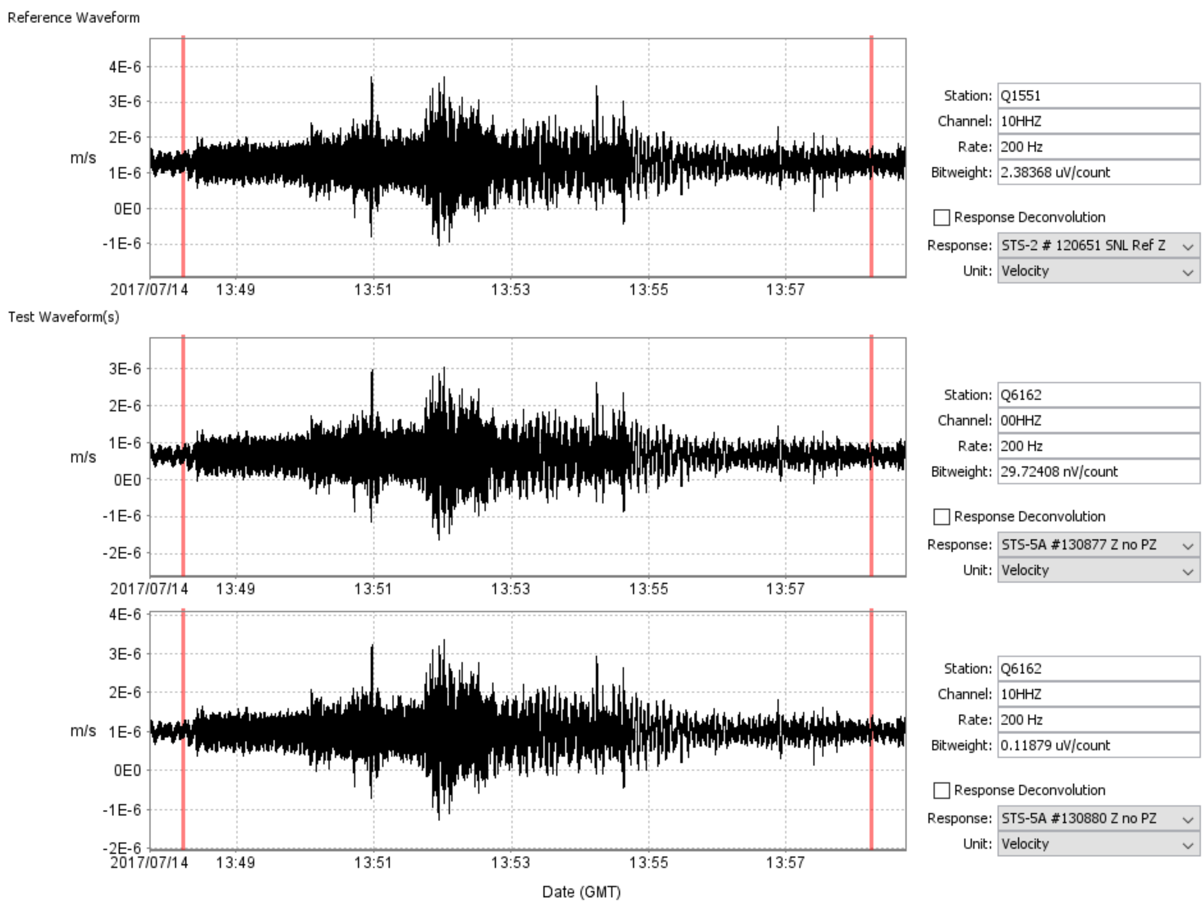



**Figure 51 High Frequency Response Time Series**

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

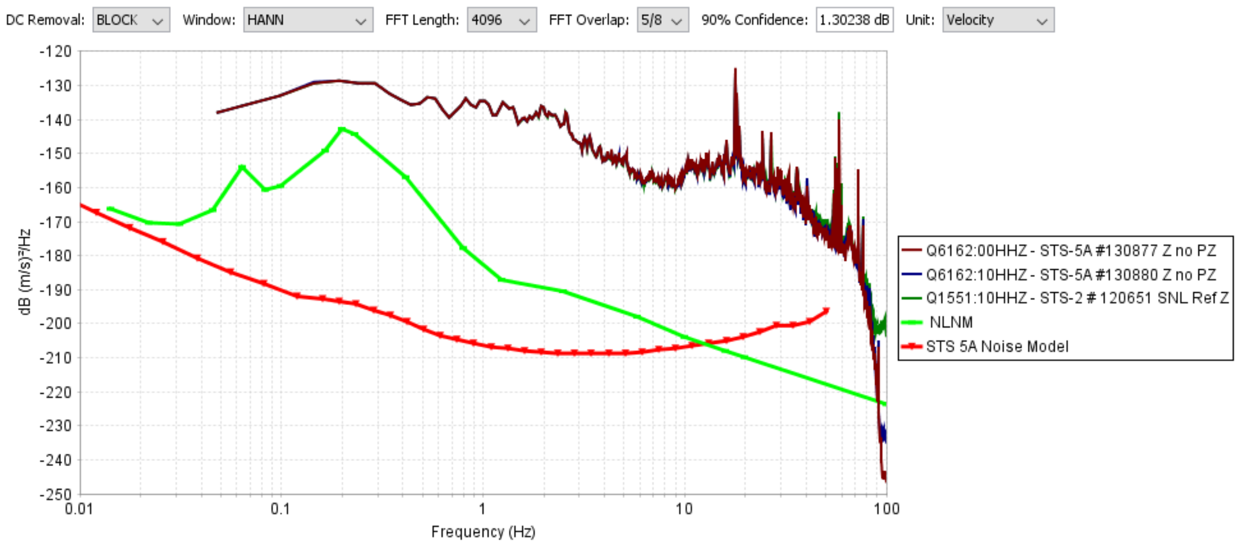



**Figure 52 High Frequency Response Power Spectra**

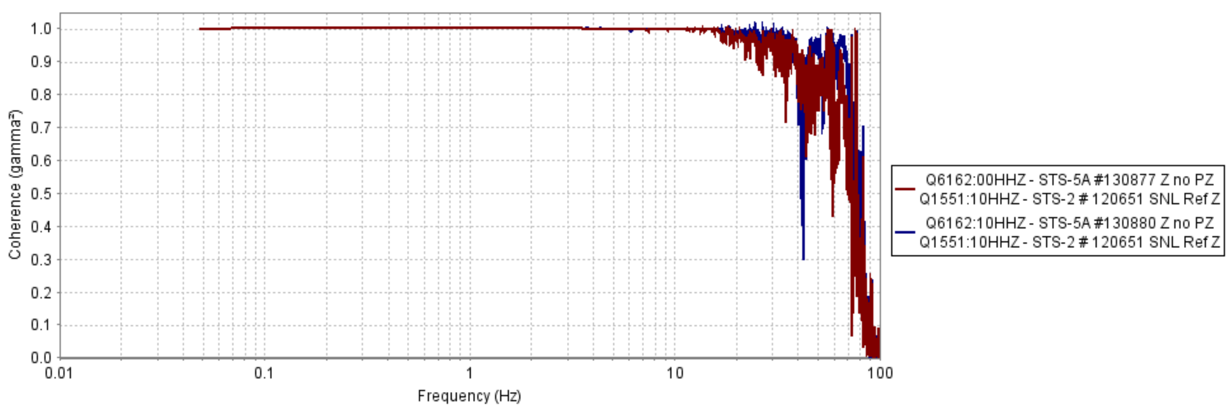



**Figure 53 High Frequency Response Coherence**

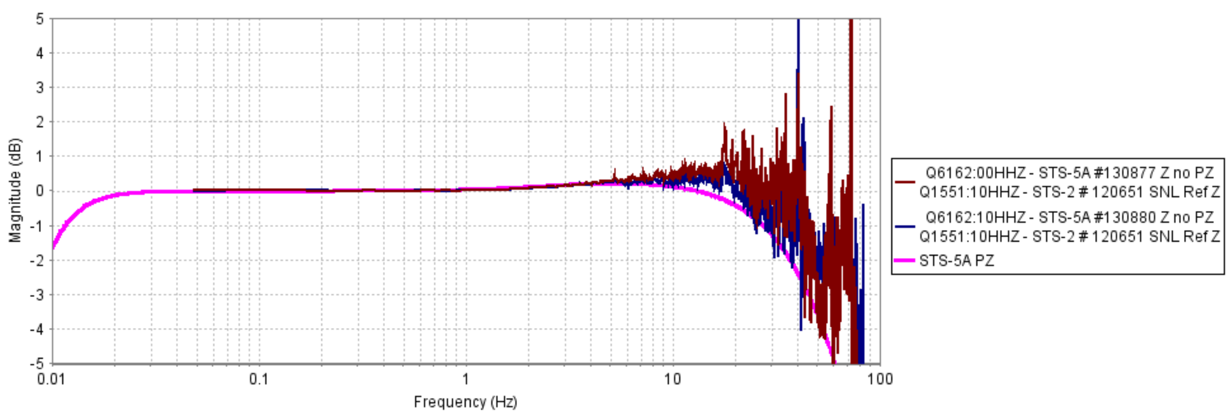



**Figure 54 High Frequency Amplitude Response**

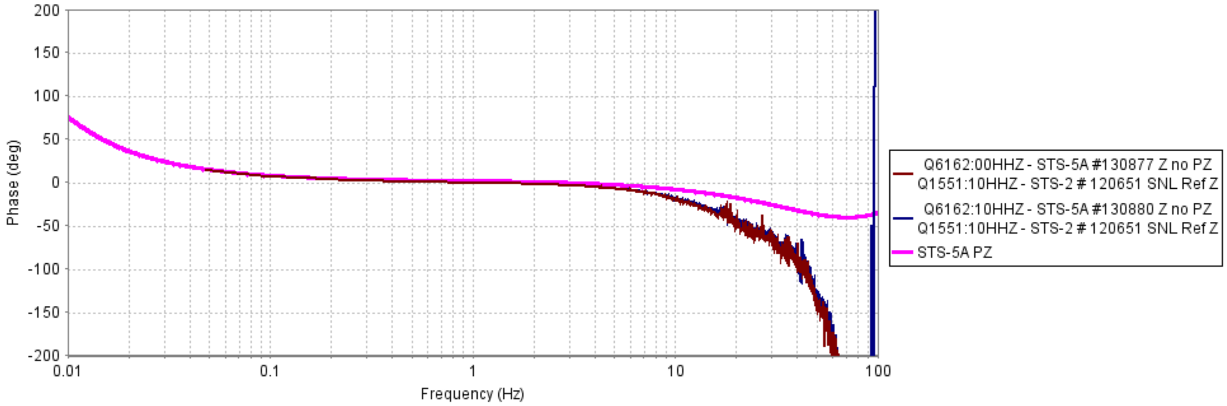



**Figure 55 High Frequency Phase Response**

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

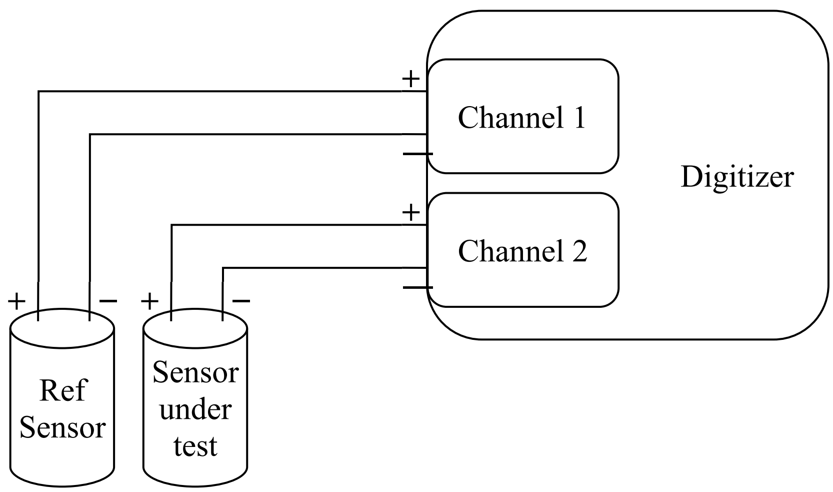



**Figure 56 Passband Configuration Diagram**

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 19 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 | Kinemetrics STS-5A | # 130877, 130880 | 1500 V/(m/s) |
| Sensor Digitizers | Kinemetrics Q330 | # 6162 | 200 Hz, 40 Vpp |

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

### 3.5.3 Analysis

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

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

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

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

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

### 3.5.4 Result

The figures below show the expanded sections of the low and high frequency passband roll-off from the amplitude response data.

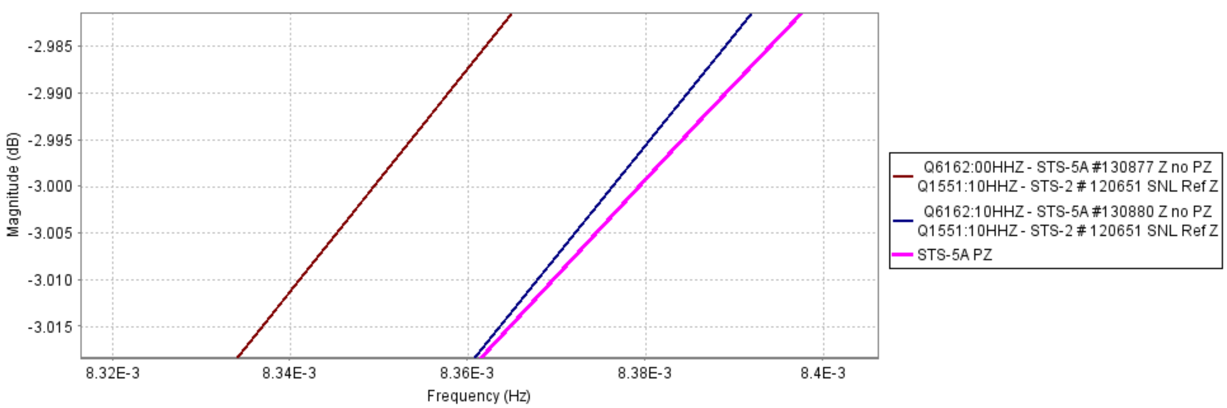



**Figure 57 Passband Z Low Frequency**

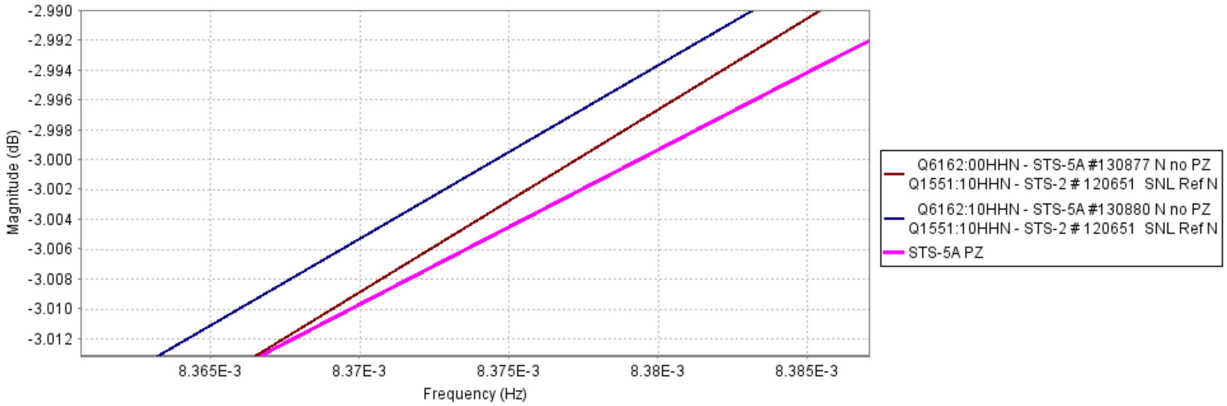



**Figure 58 Passband N Low Frequency**

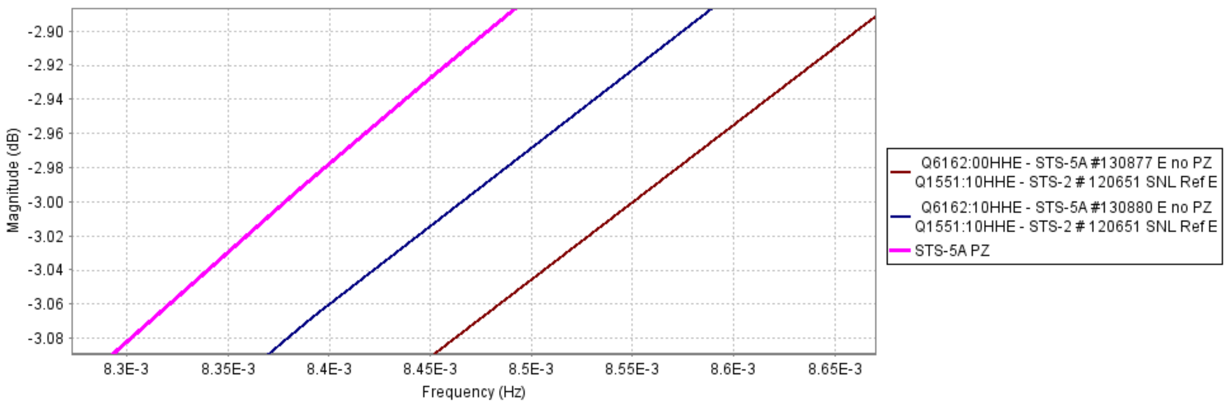



**Figure 59 Passband E Low Frequency**

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 20 Passband**

| | Chanel | Low Frequency | High Frequency |
|---|---|---|---|
| Nominal | | 0.0833 Hz (120 sec) | 50 Hz |
| STS5A #130877 | Z | 0.0835 Hz | > 20 Hz |
| | N | 0.0838 Hz | > 20 Hz |
| | E | 0.0855 Hz | > 20 Hz |
| STS5A #130880 | Z | 0.0838 Hz | > 20 Hz |
| | N | 0.0837 Hz | > 20 Hz |
| | E | 0.0845 Hz | > 20 Hz |

We can observe that the low frequency corner matches very closely with the nominal 120 second, or 0.0833 Hz, corner specified for the STS 5A. 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 that is internally looped back and recorded as shown in the diagram below.

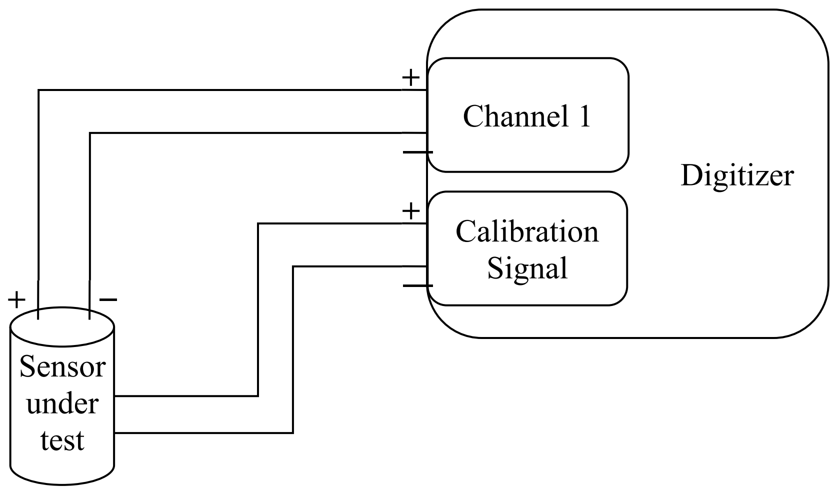



**Figure 60 Calibrator Sensitivity Configuration Diagram**

**Table 21 Calibrator Sensitivity Testbed Equipment**

| | Manufacturer / Model | Serial Number | Nominal Configuration |
|---|---|---|---|
| Sensor under test | Kinematics STS-5A | # 130877, 130880 | 1500 V/(m/s) |
| Sensor Digitizers | Kinemetrics Q330 | # 6162 | 200 Hz, 40 Vpp |

The digitizer is configured to generate a 1 Hz sinusoid for 5 minutes 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 Kinemetrics Q330 digitizers have the ability to generate a variety of signals for calibration (Sinsuoidal, Broadband, and Step). In addition, the Q330 digitizers have the ability to loop back back the calibration signal to one of the recording channels. However, it is necessary to designate one of the existing recording channels for this purpose.

The figure below shows a representative waveform time series for the recording made of the seismometer calibration. The reference waveform on top is the vertical seismometer output and the test waveform on the bottom is the calibration input signal. The window regions bounded by the blue lines indicate the segment of data used for analysis.

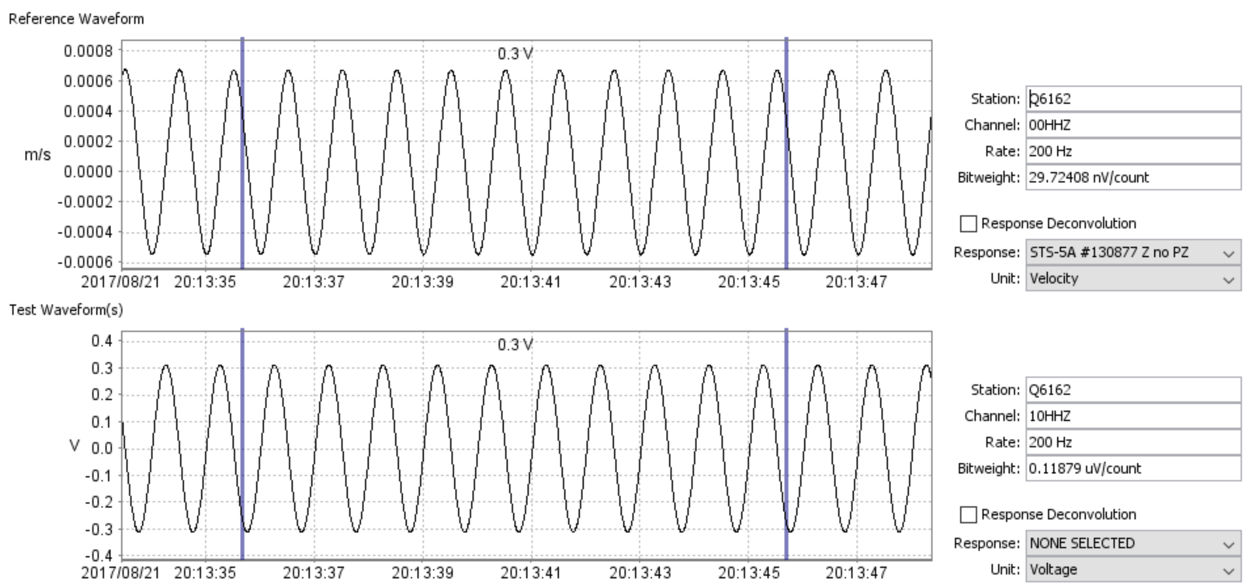



**Figure 61 Calibrator Sensitivity Time Series - #130877**

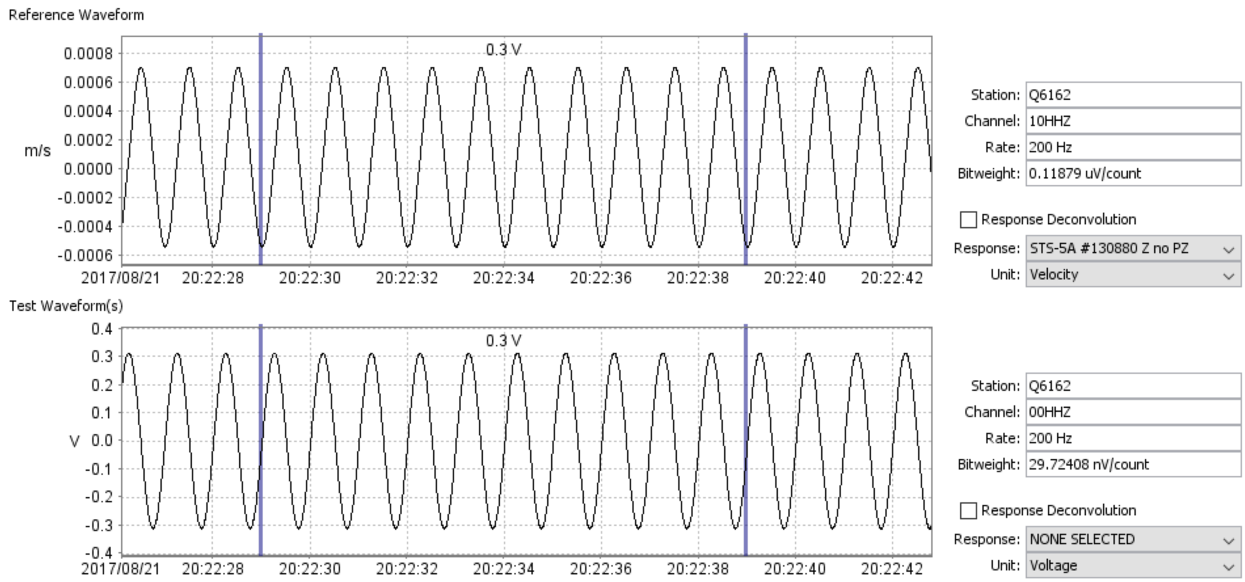



**Figure 62 Calibrator Sensitivity Time Series - #130880**

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

**Table 22 Calibrator Sensitivity**

| | #130877 | #130880 |
|---|---|---|
| Input Voltage | 0.3121 V | 0.3121 V |
| Input Frequency | 1.0 Hz | 1.0 Hz |
| | | |
| Output Voltage | 0.9035 V | 0.9245 V |
| Seismometer Sensitivity | 1508 V/(m/s) | 1510 V/(m/s) |
| Output Velocity | 5.991E-4 m/s | 6.123E-4 m/s |
| | | |
| Calibrator Sensitivity | 82.92 V/(m/s^2) | 81.11 V/(m/s^2) |

For a simultaneous calibration of all three U, V, and W axes, the resulting vertical calibrator sensitivities were determined to be 82.92 V/(m/s$^2$) and 81.11 V/(m/s$^2$) for #130877 and #130880, respectively.

## 3.7 Calibrator Frequency Response Verification

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

### *3.7.1 Measurand*

The quantity being measured is the seismometer calibration frequency response.

### *3.7.2 Configuration*

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

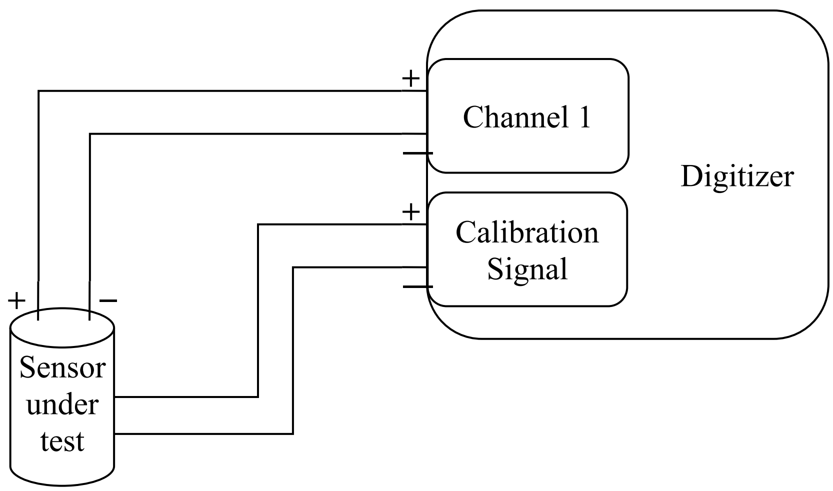



**Figure 63 Calibrator Frequency Response Configuration Diagram**

**Table 23 Calibrator Frequency Response Testbed Equipment**

| | Manufacturer / Model | Serial Number | Nominal Configuration |
|---|---|---|---|
| Sensor under test | Kinemetrics STS-5A | # 130877, 130880 | 1500 V/(m/s) |
| Sensor Digitizers | Kinemetrics Q330 | # 6162 | 200 Hz, 40 Vpp |

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

### *3.7.3 Analysis*

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

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

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

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

### 3.7.4 Result

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

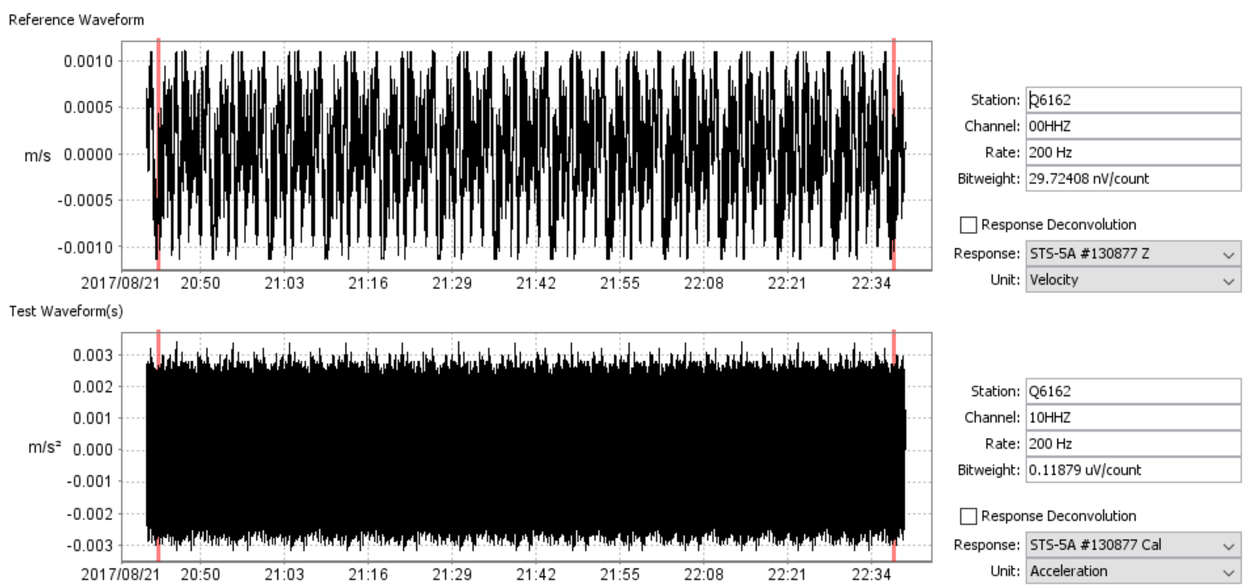



**Figure 64 Calibrator Frequency Response Time Series**

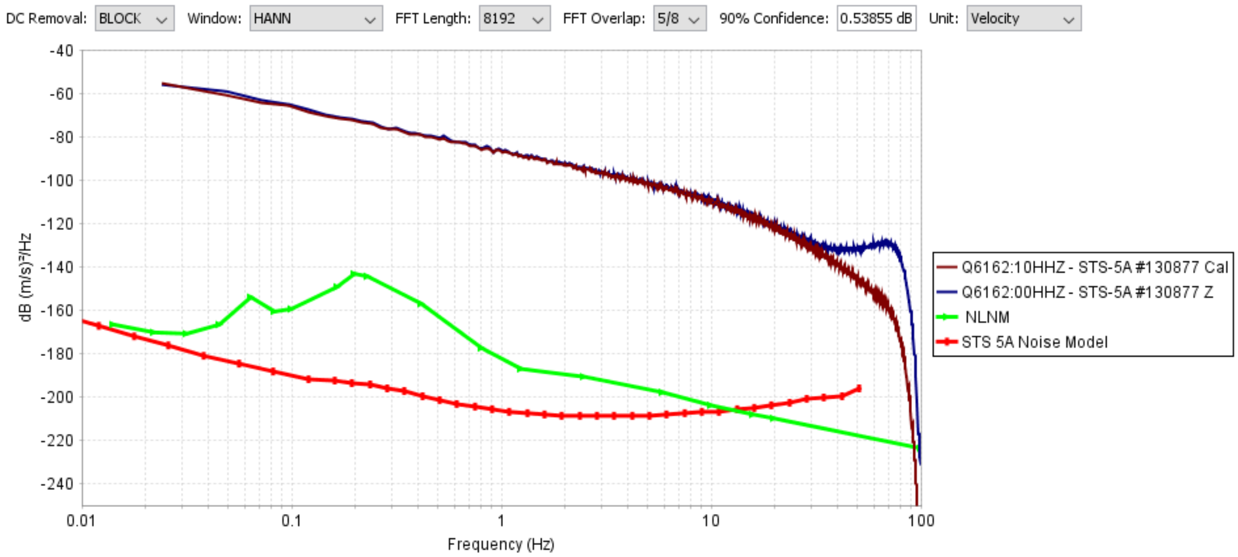



**Figure 65 Calibrator Frequency Response Power Spectra**

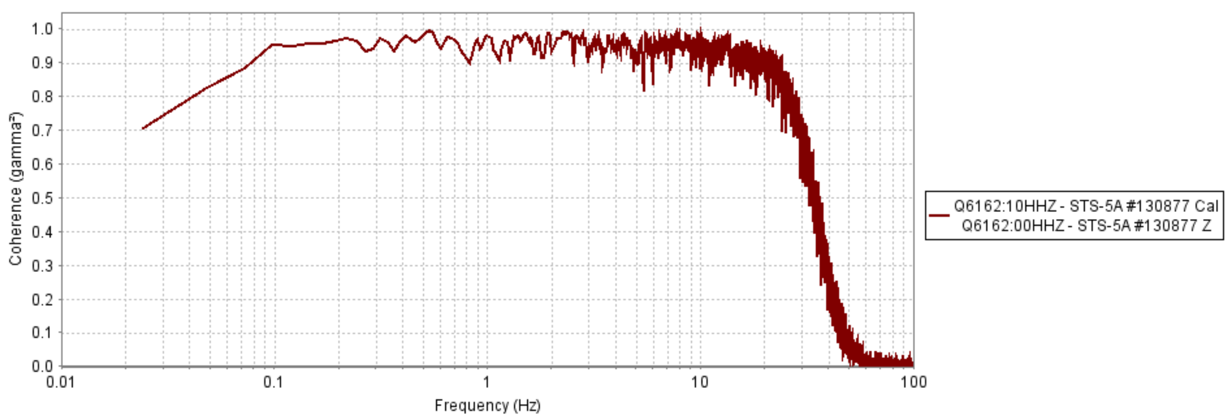



**Figure 66 Calibrator Frequency Response Coherence**

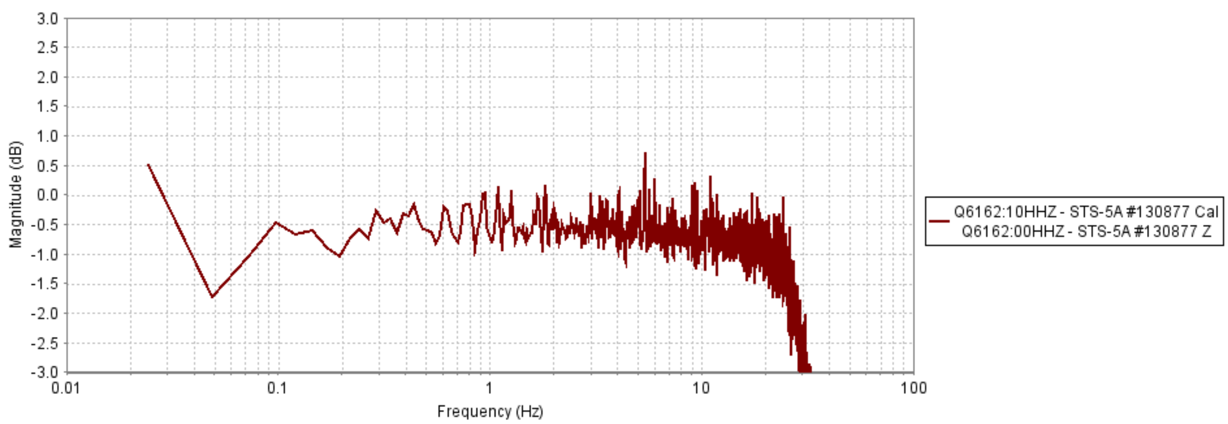



**Figure 67 Calibrator Frequency Response Amplitude Response**

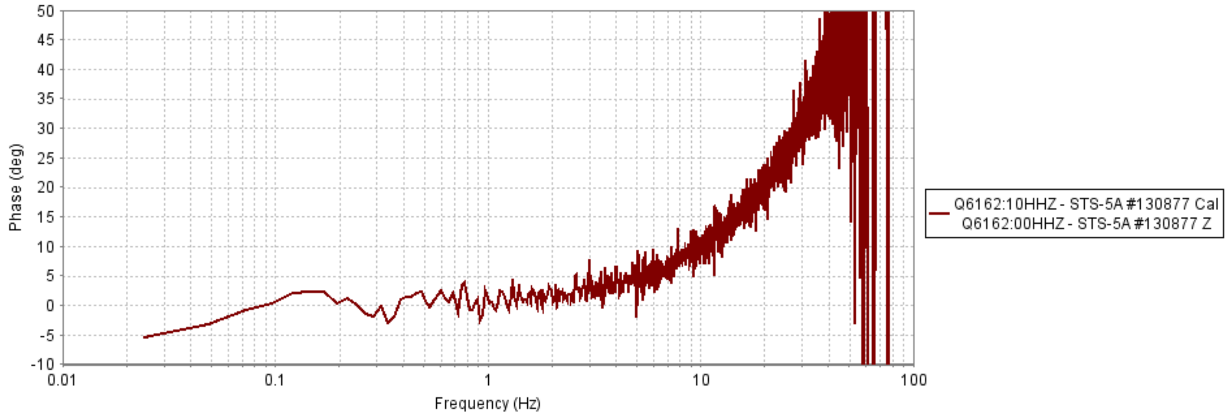



**Figure 68 Calibrator Frequency Response Phase Response**

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

**Table 24 Calibrator Frequency Response**

| | STS-5A #130877 | | STS-5A #130880 | |
|---|---|---|---|---|
| Frequency | Amplitude | Phase | Amplitude | Phase |
| 0.1000 Hz | -0.48 dB | 0.15 deg | -0.60 dB | -6.87 deg |
| 0.1250 Hz | -0.48 dB | 1.98 deg | -0.60 dB | -3.50 deg |
| 0.1600 Hz | -0.90 dB | 2.14 deg | -1.00 dB | -2.33 deg |
| 0.2000 Hz | -0.90 dB | 1.11 deg | -1.00 dB | -1.85 deg |
| 0.2500 Hz | -0.73 dB | -0.08 deg | -0.78 dB | -2.89 deg |
| 0.3150 Hz | -0.40 dB | -2.04 deg | -0.47 dB | -4.29 deg |
| 0.4000 Hz | -0.37 dB | 0.92 deg | -0.44 dB | -0.67 deg |
| 0.5000 Hz | -0.60 dB | 1.25 deg | -0.58 dB | -0.22 deg |
| 0.6300 Hz | -0.70 dB | 1.17 deg | -0.77 dB | 0.15 deg |
| 0.8000 Hz | -0.41 dB | 0.19 deg | -0.74 dB | -0.29 deg |
| 1.0000 Hz | -0.43 dB | 0.19 deg | -0.63 dB | -0.24 deg |
| 1.2500 Hz | -0.45 dB | 1.57 deg | -0.68 dB | 1.14 deg |
| 1.6000 Hz | -0.63 dB | 0.98 deg | -0.78 dB | 1.47 deg |
| 2.0000 Hz | -0.47 dB | 1.40 deg | -0.67 dB | 2.12 deg |
| 2.5000 Hz | -0.60 dB | 1.69 deg | -0.80 dB | 2.75 deg |
| 3.1500 Hz | -0.52 dB | 2.32 deg | -0.80 dB | 4.36 deg |
| 4.0000 Hz | -0.63 dB | 3.13 deg | -0.93 dB | 5.84 deg |
| 5.0000 Hz | -0.45 dB | 4.46 deg | -0.86 dB | 8.35 deg |
| 6.3000 Hz | -0.58 dB | 5.63 deg | -1.01 dB | 10.99 deg |
| 8.0000 Hz | -0.71 dB | 7.58 deg | -0.99 dB | 14.89 deg |
| 10.0000 Hz | -0.73 dB | 9.92 deg | -0.97 dB | 19.52 deg |

There does appear to be a difference between the calibrator sensitivity obtained from the sinusoid and the frequency response at 1 Hz of between -0.43 and -0.63 dB. There is no explanation for this difference.

# 4 SUMMARY

**Sensitivity**
The STS-5A seismometers were found to have sensitivities at 1 Hz of between 1505 and 1510 V/(m/s). These values differ by between 0.33 % and 0.67 % of the nominal 1500 V/(m/s) and are within the +/- 1% tolerance quoted by Kinemetrics.

**Self-Noise**
All three STS-5A 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, 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 120.5 and 145.4 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 STS-5A seismometers were found to have calibrator sensitivities at 1 Hz of 82.92 V/(m/s$^2$) and 81.11 V/(m/s$^2$) for #130877 and #130880, respectively.

**Calibrator Response Verification**
The STS-5A seismometer calibration frequency responses were able to be measured over 0.1 Hz to 10 Hz. The resulting amplitude response were off by about 0.5 dB from the values obtained from the Calibrator Sensitivity test.

# 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.

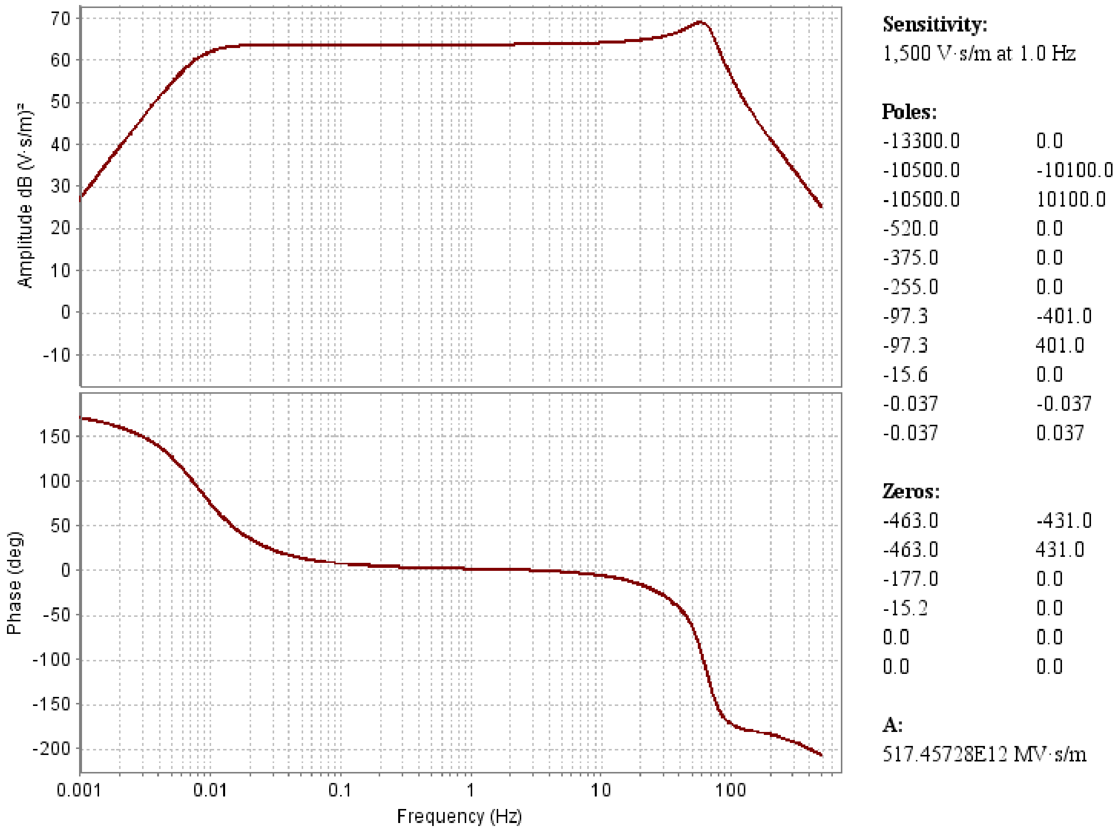
8. Merchant, B. John, and Darren M. Hart (2011), *Component Evaluation Testing and Analysis Algorithms*, SAND2011-8265.

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

## Kinematrics STS-2 #120651 SNL Reference Response

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

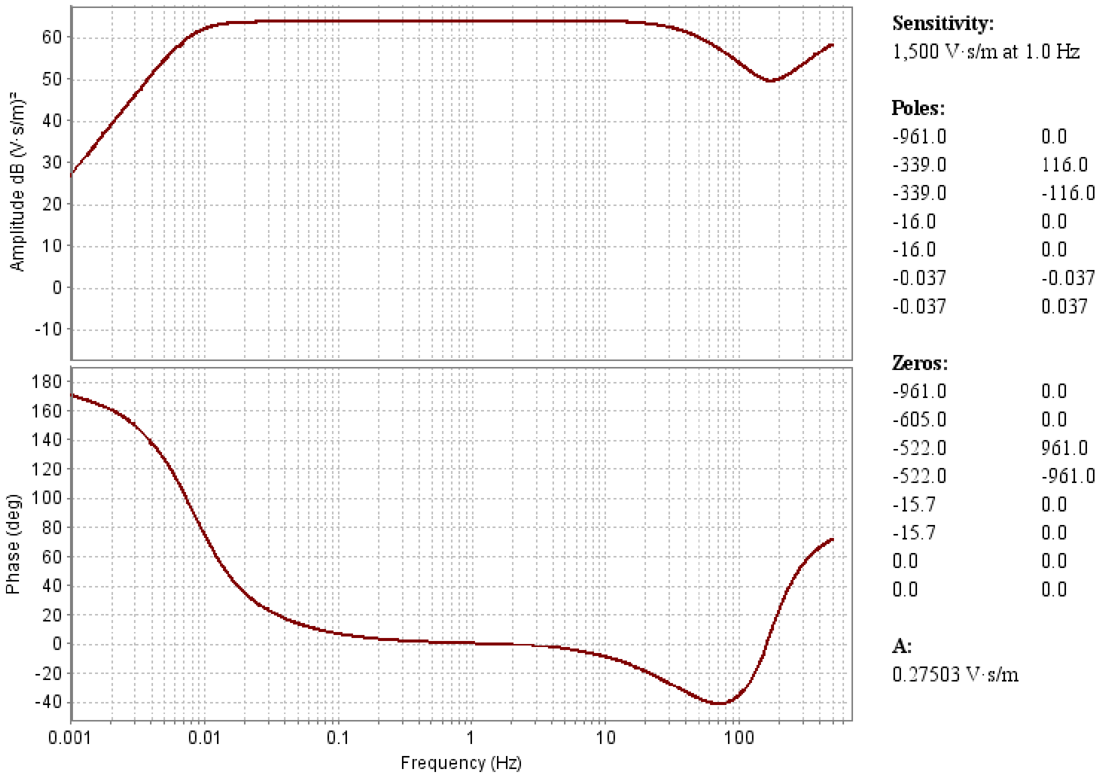



The reference STS-2 was calibrated at the USGS Albuquerque Seismic Laboratory (ASL) in November, 2016 using their step-table, a Lennartz CT-E1 step calibration table. The resulting sensitivities at 1 Hz for the reference STS-2 #120651 are shown below:

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

# Kinematics STS-5A Response

The Kinematics STS-5A poles and zeros, provided by Kinematics, along with the sensitivity of 1500 V/(m/s) are shown below.



# 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<br>05752 |
| Custodian | Slad, George William |
| Location | SNLNM/TA1/758/1044 |
| Date of Receipt | September 13, 2016 |
| Dates Tested (Start – End) | September 30, 2016 - September 30, 2016 |
| Date Approved | October 12, 2016 |
| Calibration Expiration Date | October 12, 2017 |

### Calibration Description

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

## Calibration Specifications and Results

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

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

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

NOTE: 700 V RMS maximum on 1000 VAC range

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

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

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

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

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665


# Calibration Data Report

## Primary Electrical Lab

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

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

COMMENTS:

### Standards Used

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

### Test Results

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

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

SOFTWARE USED: Met/Cal Version 8.3.2

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

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

The internal temperature of the 3458A is 36.2 deg.C
DC Volts
```

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

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 | |

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Test Results

| Test Description | True Value | Lower Limit | Measured Value | Upper Limit | Units | TUR | % Tol | Status |
|---|---|---|---|---|---|---|---|---|
| 10.00000 V @ 40 Hz | 10.000220 | 9.99552 | 10.00043 | 10.00492 | V | >10 | 4 | |
| 10.00000 V @ 20 kHz | 10.000190 | 9.99549 | 9.99959 | 10.00489 | V | >10 | 13 | |
| 10.00000 V @ 50 kHz | 10.000207 | 9.99001 | 10.00030 | 10.01041 | V | >10 | 1 | |
| 10.00000 V @ 100 kHz | 9.999795 | 9.97960 | 9.99935 | 10.01999 | V | >10 | 2 | |
| 10.00000 V @ 300 kHz | 10.001654 | 9.90064 | 9.99865 | 10.10267 | V | >10 | 3 | |
| 100.0000 V @ 10 Hz | 100.00266 | 99.8007 | 100.0055 | 100.2047 | V | >10 | 1 | |
| 100.0000 V @ 40 Hz | 100.00218 | 99.9552 | 100.0044 | 100.0492 | V | >10 | 5 | |
| 100.0000 V @ 20 kHz | 100.00295 | 99.9559 | 100.0003 | 100.0500 | V | >10 | 6 | |
| 100.0000 V @ 50 kHz | 100.00901 | 99.9070 | 100.0129 | 100.1110 | V | >10 | 4 | |
| 100.0000 V @ 100 kHz | 100.01336 | 99.8113 | 100.0096 | 100.2154 | V | >10 | 2 | |
| 100.0000 V @ 200 kHz | 100.06044 | 99.0498 | 100.0300 | 101.0710 | V | >10 | 3 | |
| 700.0000 V @ 40 Hz | 700.01590 | 699.4359 | 700.0061 | 700.5959 | V | >10 | 2 | |
| 700.0000 V @ 20 kHz | 700.02470 | 699.4447 | 699.7809 | 700.6047 | V | >10 | 42 | |
| FREQUENCY | | | | | | | | |
| 10.00000 Hz @ 1 V | | 9.995000 | 10.000099 | 10.005000 | Hz | >10 | 2 | |
| 40.00000 Hz @ 1 V | | 39.996000 | 40.000415 | 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 | 500.003401 | 500.050000 | kHz | >10 | 7 | |
| 1.000000 MHz @ 1 V | | 0.9999000 | 1.0000071 | 1.0001000 | MHz | >10 | 7 | |
| 2.000000 MHz @ 1 V | | 1.9998000 | 2.0000139 | 2.0002000 | MHz | >10 | 7 | |
| 4.000000 MHz @ 1 V | | 3.9996000 | 4.0000278 | 4.0004000 | MHz | >10 | 7 | |
| 6.000000 MHz @ 1 V | | 5.9994000 | 6.0000422 | 6.0006000 | MHz | >10 | 7 | |
| 8.000000 MHz @ 1 V | | 7.9992000 | 8.0000566 | 8.0008000 | MHz | >10 | 7 | |
| 10.000000 MHz @ 1 V | | 9.9990000 | 10.0000696 | 10.0010000 | MHz | >10 | 7 | |

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

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

## Equipment (Standard) Used

| Asset # | Description | Model | Expires |
|---|---|---|---|
| 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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*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<br>Metrologist | Aragon, Steven J.<br>Metrologist |

**End-of-Document**

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6652541_11682157

## Kinematrics STS-5A #130877

# Certificate of Calibration

**STRECKEISEN**
SEISMIC INSTRUMENTATION

Type: STS-5a Serial No: 130877 Date: June 30, 2015

### Basic Properties:

- ☑ Axes Purity (orthogonality; x, y horizontal, z vertical): Maximum deviation ±0.6°
- ☑ Generator Constants for x, y, and z: 1500 V*sec/m ±15 V*sec/m
- ☑ Transfer Function of each sensor component (see below)

### Noise Performance:

- ☑ Instrumental Long-Period Noise (1 mHz - 30 mHz)
- ☑ Electronic Self-Noise (1 Hz - 50 Hz) per sensor component

### Miscellaneous:

- ☑ Air Tightness
- ☑ Digital Control Functions including Automatic Centering & Leveling

### Parameters Routinely Tested and Evaluated:

Notation conventions: 1. Individual parameter values are noted in *italic* letters. 2. "*N.E.*" = "Not Evaluated"

**Oscillator Frequency:** *22.00* kHz

**Initial Humidity:** *<3* %

**Electrical calibration transducer constant (CAL input to Z output, CS0 = CS1 = 0V or open):**

[(fraction of g)/V]: *N.E.* ±1 %, @ Period [s]: ---- $g = 9.81\ m/s^2$

### Transfer Function Parameters:

**1. Low-Frequency Corner Period and Damping Constant**

| Param. | U[1)] | | V[1)] | | W[1)] | | Lower Limit[2)] | | Upper Limit[2)] | |
|---|---|---|---|---|---|---|---|---|---|---|
| T[s], 1σ[%] | *119.9* | *0.023* | *119.9* | *0.021* | *119.5* | *0.021* | *118.8* | ---- | *121.2* | ---- |
| h, 1σ[%] | *0.708* | *0.030* | *0.709* | *0.027* | *0.706* | *0.027* | *0.7* | ---- | *0.714* | ---- |

1) Optimized for best fit between 5.86 mHz and 105.5 mHz, 2) According to specifications (±1 %)

**2. Preliminary upper frequency range poles and zeroes. Sensitivity coordinates of components.**

**Please notice!** The poles & zeroes have been evaluated using the mechanical core of this instrument together with an STS-2.5 case assembly instead of an STS-5a case assembly. Corresponding amplitudes and phases deviate <2 % and <2 °, respectively, between 1 Hz and 70 Hz. These deviations are accounted for by adding case-related amplitude and phase corrections to the measured transfer functions.

| Compo nent | C'mon Fact[3)] | [Hz], Note 4 | | | | | | | | | | Spher. Sens. Coord.[5)] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | z1 | z2 | zre3 | zim3 | z4=p4 | p1 | pre2 | pim2 | pre3 | pim3 | $Gc/Gc_0$ | φ [°] | θ [°] |
| U | 2*π* … | 3.5 | 96.3 | 83.0 | 152.9 | *59.9* | *3.5917* | *81.18* | *0.00* | *16.22* | *103.35* | *0.8888* | *269.68* | *56.77* |
| V | 2*π* … | 3.5 | 96.3 | 83.0 | 152.9 | *59.5* | *3.5986* | *80.41* | *0.00* | *17.73* | *102.82* | *0.9089* | *149.78* | *56.25* |
| W | 2*π* … | 3.5 | 96.3 | 83.0 | 152.9 | *61.4* | *3.5953* | *81.20* | *0.00* | *14.82* | *104.45* | *0.8828* | *29.79* | *56.21* |

3) "Common factor". All t.f. parameter values to be multiplied with, when entering into the formula below.
4) The vertically written parameters are pre-established values, those parameters written in italics are optimized for best fit between 0.75 Hz and 70 Hz. For details please consult the STS-5a manual.
5) Spherical sensitivity coordinates deduced from absolute calibration. Gc = component generator constant, $Gc_0$ = 1500 V*s/m. φ = azimuth relative to orientation mark. θ = dip (Z direction = 0° with respect to plumb).

**Complete transfer function formula 0.001 ... 70 Hz:** Related to ground velocity, normalized to 1500 V*s/m

$$TF_{cal}(s) = -\frac{p_1^2 \cdot (p_{re2}^2 + p_{im2}^2)^3 (p_{re3}^2 + p_{im3}^2)}{z_1^2} \cdot \frac{(s+z_1)^2(s+z_4)}{(s+p_1)^2(s+p_{re2}+i \cdot p_{im2})^3(s+p_{re2}-i \cdot p_{im2})^3(s+p_{re3}+i \cdot p_{im3})(s+p_{re3}-i \cdot p_{im3})(s-p_4)}$$

$$TF_{corr}(s) = \frac{(s+z_2)(s+z_{re3}+i \cdot z_{im3})(s+z_{re3}-i \cdot z_{im3})}{z_2 \cdot (z_{re3}^2 + z_{im3}^2)}$$

$$TF_{LF}(s) = \frac{s^2}{\left(s^2 + 2 \cdot h \cdot \frac{2\pi}{T} \cdot s + \left(\frac{2\pi}{T}\right)^2\right)}$$

$$TF_{TOT}(s) = G \cdot TF_{LF}(s) \cdot TF_{cal}(s) \cdot TF_{corr}(s)$$

STRECKEISEN
SEISMIC INSTRUMENTATION
Streckeisen GmbH
Daettlikonerstr. 5
CH-8422 Pfungen

Test engineer

Nicolas Rüst

## Kinemetrics STS-5A #130880

# Certificate of Calibration

**STRECKEISEN**
SEISMIC INSTRUMENTATION

Type: STS-5a Serial No: 130880 Date: June 30, 2015

### Basic Properties:

- ☑ Axes Purity (orthogonality; x, y horizontal, z vertical): Maximum deviation ±0.6°
- ☑ Generator Constants for x, y, and z: 1500 V*sec/m ±15 V*sec/m
- ☑ Transfer Function of each sensor component (see below)

### Noise Performance:

- ☑ Instrumental Long-Period Noise (1 mHz - 30 mHz)
- ☑ Electronic Self-Noise (1 Hz - 50 Hz) per sensor component

### Miscellaneous:

- ☑ Air Tightness
- ☑ Digital Control Functions including Automatic Centering & Leveling

### Parameters Routinely Tested and Evaluated:

Notation conventions: 1. Individual parameter values are noted in *italic* letters. 2. "*N.E.*" = "Not Evaluated"

**Oscillator Frequency:** *22.00* kHz

**Initial Humidity:** *<3* %

**Electrical calibration transducer constant (CAL input to Z output, CS0 = CS1 = 0V or open):**

[(fraction of g)/V]: *N.E.* ±1 %, @ Period [s]: ---- $g = 9.81\ m/s^2$

### Transfer Function Parameters:

**1. Low-Frequency Corner Period and Damping Constant**

| Param. | U[1)] | | V[1)] | | W[1)] | | Lower Limit[2)] | | Upper Limit[2)] | |
|---|---|---|---|---|---|---|---|---|---|---|
| T[s], 1σ[%] | *119.8* | *0.020* | *119.2* | *0.025* | *119.8* | *0.018* | *118.8* | ---- | *121.2* | ---- |
| h, 1σ[%] | *0.706* | *0.026* | *0.706* | *0.032* | *0.706* | *0.024* | *0.7* | ---- | *0.714* | ---- |

1) Optimized for best fit between 5.86 mHz and 105.5 mHz, 2) According to specifications (±1 %)

**2. Preliminary upper frequency range poles and zeroes. Sensitivity coordinates of components.**

**Please notice!** The poles & zeroes have been evaluated using the mechanical core of this instrument together with an STS-2.5 case assembly instead of an STS-5a case assembly. Corresponding amplitudes and phases deviate <2 % and <2 °, respectively, between 1 Hz and 70 Hz. These deviations are accounted for by adding case-related amplitude and phase corrections to the measured transfer functions.

| Component | C'mon Fact[3)] | [Hz], Note 4 | | | | | | | | | | Spher. Sens. Coord.[5)] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | z1 | z2 | zre3 | zim3 | z4=p4 | p1 | pre2 | pim2 | pre3 | pim3 | $Gc/Gc_0$ | φ [°] | θ [°] |
| U | 2*π* ... | 3.5 | 96.3 | 83.0 | 152.9 | *59.8* | *3.6008* | *80.39* | *0.00* | *18.16* | *102.66* | *0.8943* | *269.74* | *57.18* |
| V | | | | | | *61.1* | *3.5959* | *80.00* | *8.54* | *13.02* | *103.43* | *0.8657* | *149.62* | *56.52* |
| W | | | | | | *61.5* | *3.5986* | *80.84* | *2.30* | *14.02* | *103.78* | *0.8762* | *29.81* | *56.74* |

3) "Common factor". All t.f. parameter values to be multiplied with, when entering into the formula below.

4) The vertically written parameters are pre-established values, those parameters written in italics are optimized for best fit between 0.75 Hz and 70 Hz. For details please consult the STS-5a manual.

5) Spherical sensitivity coordinates deduced from absolute calibration. Gc = component generator constant, $Gc_0$ = 1500 V*s/m. φ = azimuth relative to orientation mark. θ = dip (Z direction = 0° with respect to plumb).

**Complete transfer function formula 0.001 ... 70 Hz:** Related to ground velocity, normalized to 1500 V*s/m

$$TF_{cal}(s) = -\frac{p_1^2 \cdot (p_{re2}^2 + p_{im2}^2)^3 (p_{re3}^2 + p_{im3}^2)}{z_1^2} \cdot \frac{(s+z_1)^2 (s+z_4)}{(s+p_1)^2 (s+p_{re2}+i\cdot p_{im2})^3 (s+p_{re2}-i\cdot p_{im2})^3 (s+p_{re3}+i\cdot p_{im3})(s+p_{re3}-i\cdot p_{im3})(s-p_4)}$$

$$TF_{corr}(s) = \frac{(s+z_2)(s+z_{re3}+i\cdot z_{im3})(s+z_{re3}-i\cdot z_{im3})}{z_2 \cdot (z_{re3}^2 + z_{im3}^2)}$$

$$TF_{LF}(s) = \frac{s^2}{\left(s^2 + 2\cdot h \cdot \frac{2\pi}{T} \cdot s + \left(\frac{2\pi}{T}\right)^2\right.}$$

$$TF_{TOT}(s) = G \cdot TF_{LF}(s) \cdot TF_{cal}(s) \cdot TF_{corr}(s)$$

STRECKEISEN
SEISMIC INSTRUMENTATION
Streckeisen GmbH
Daettlikonerstr. 5
CH-8422 Pfungen

Test engineer

Nicolas Rüst

file: Cal025095 | Streckeisen GmbH | Daettlikonerstr. 5 | CH-8422 Pfungen | SWITZERLAND | phone +41(0)52 315 67 00 e-mail: info@streckeisen.biz Page 1/1

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