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2023 Reftek Colt Seismometer Exploratory Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated three Colt broadband seismometers designed and manufactured by Reftek. The purpose of this seismometer evaluation is to measure performance characteristics in areas such as power consumption, sensitivity, frequency response, full scale, self-noise, dynamic range, calibration system response, and passband. The Colt model of sensors are being evaluated to explore the potential for a future seismometer Type Approval process in the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

ACKNOWLEDGEMENTS

The evaluation of the Colt seismometers was sponsored under a Fund-In Agreement between Sandia National Laboratories and the Preparatory Commission to the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO PrepCom).

We would like to thank Reftek for providing the sensors to evaluate.

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ACRONYMS AND TERMS

Acronym/Term	Definition
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO PrepCom	Preparatory Commission to the Comprehensive Nuclear-Test-Ban Treaty Organization
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
GPS	Global Position System
GNSS	Global Navigation Satellite System
HNM	High Noise Model
IMS	International Monitoring System
LNM	Low Noise Model
PSD	Power Spectral Density
SI	International System of Units
SNL	Sandia National Laboratories

1 INTRODUCTION

The evaluation of the Colt seismometers was performed to determine the sensors' performance characteristics relative to the manufacturer's specifications and IMS requirements. Figure 1 shows the seismometers included in the evaluation. Left to right are Colt seismometers 213010, 213011 and 213012.

Figure 1 Colt Seismometers Included in the Evaluation

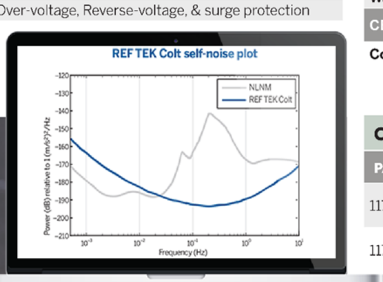
The Colt's specifications along with the IMS minimum requirements for primary and auxiliary seismological stations are shown in the figures below.

REF TEK COLT

BROADBAND SEISMOMETER

SPECIFICATIONS

ELECTRICAL	
Sensor Type	Symmetrical Configuration (3 Component), Orthogonal Output
Feedback	Force balance with capacitive transducer
Bandwidth	0.0083 (120 seconds) – 80 Hz (Flat velocity response) 0.0167 (60 seconds) – 80 Hz (Flat velocity response)
Dynamic Range	>140dB (0.01 -0.05Hz); >160 dB (1–10 Hz)
Self-Noise	Below NLNM from 40 seconds to 10 Hz
Clip Level	>10 mm/s (@1 Hz)
Nominal Sensitivity	2000 V/m/s s ±0.5% (see supplied test sheet for precise value)
Full Scale Output	40 Volts Peak-Peak (Differential Output)
Output Impedance	<100 Ohms
Parasitic Resonances	>160 Hz
Cross Axis Coupling	<1%
Linearity	<–60 dB
Total Harmonic Distortion	<–60 dB
Calibration Constant	10 m/s2/A (nominal)
Calibration Input	Calibration current on 3 components simultaneously
Calibration Enable Capability	Active Low on Pin L to stay enable
Cal Coil	Single Cal signal input, isolated until cal enable line activated
Mass Position Outputs	±10 V
POWER	
Input Voltage	9–18 VDC
Consumption	<0.7 Watts
Protection	Over-voltage, Reverse-voltage, & surge protection



SPECIFICATIONS

MECHANICAL	
SIZE	
Without Handle & Feet	150 mm (5.9") Diameter x 192 mm (7.6") Height
With Handle & Feet	150 mm (5.9") Diameter x 258 mm (10.2") Height
Weight	5.5 kg (12 lbs)
Leveling	Integrated bubble level and three adjustable leveling feet with locknuts
Leveling Tilt Range	±3.0
Alignment	Handle of top of case parallel to the North-South Axis Removable N/S pins screw into the base for additional alignment guidance
Mass Lock/Unlock	Automatic unlock when sensor powers on (Unlock on Active LOW for more than 6 sec on Pin U) Automatic lock when sensor powers off (Unlock on Active LOW for more than 6 sec on Pin K) Lock/Unlock can also be done via logic level commands from digitizer
Mass Centering	Automatic when sensor powers on (Start after unlock, Active LOW pulse on Pin M) Manual upon logic level command from Digitizer
Mass Centering Range	± 2.0° (Auto-centering by motors)
Mass Temperature Sensitivity	+/- 20°C without mass re-centering
ENVIRONMENTAL	
Operating Temp.	–25 °C to +60 °C
Storage Temp.	–55 °C to +80 °C
Watertight Integrity	IP67
CERTIFICATIONS	
Compliance	CE, RoHS

ORDERING INFORMATION

PART NO.	DESCRIPTION
117400-120	REF TEK Colt broadband seismometer, 120 seconds to 80 Hz
117400-60	REF TEK Colt broadband seismometer, 60 seconds to 80 Hz

NORTH AMERICA
75 MacDonald Ave Unit 1
Dartmouth, Nova Scotia
B3B 1T8 Canada

sales@reftek.com

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1/18/2023

Figure 2 Colt Technical Specifications (from Reftek Datasheet)

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

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

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

Figure 3 Minimum Requirements for Primary and Auxiliary Seismological Station Specifications (CTBT/WGB/TL-11,17/15/Rev.5)

2 TEST PLAN

2.1 Test Facility

Testing 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 seismometers, infrasound sensors, preamplifiers, digitizing waveform recorders, and analog-to-digital converters/high-resolution digitizers for geophysical applications.

Tests are based on ISO 16063-11: Primary vibration calibration by laser interferometry, ISO 16063-21: Vibration calibration by comparison to a reference transducer, and ISO 16063-45: In-situ calibration of transducers with built in calibration coil. In addition, where appropriate, tests are ensured to be consistent with the Institute of Electrical and Electronics Engineers (IEEE) Standard 1057 for Digitizing Waveform Recorders and Standard 1241 for Analog to Digital Converters. The analysis based on these standards is performed in the frequency domain or time domain as required. When appropriate, instrumentation calibration was traceable to the SI.

The seismometers were evaluated on the FACT site's seismic calibration shake table system, shown in Figure 4, and in the subterranean bunker shown in Figure 5 and Figure 6.

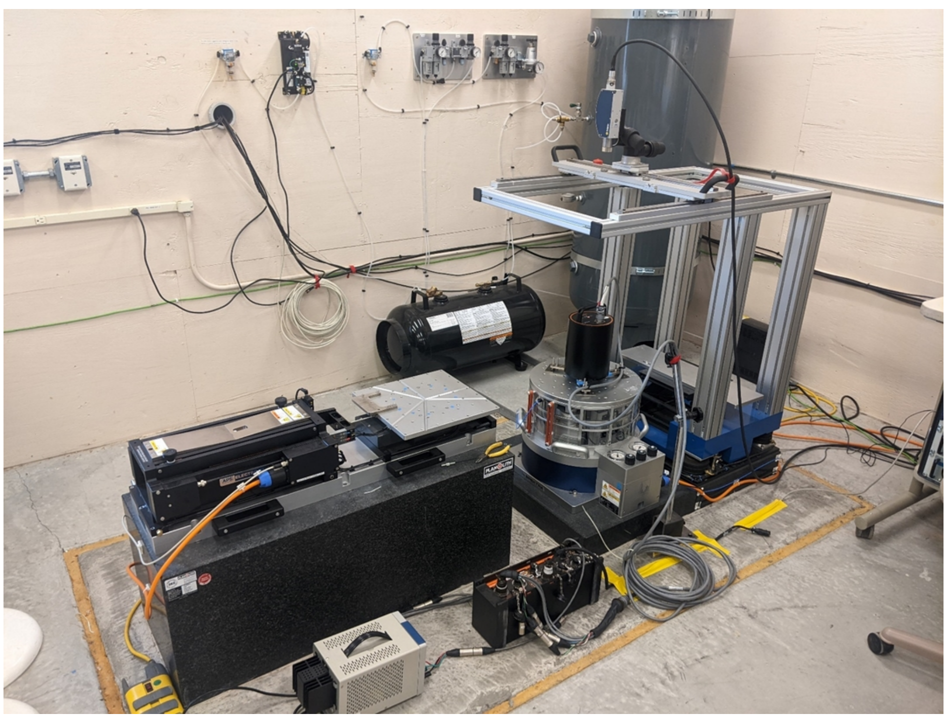


Figure 4 FACT Site Seismic Calibration System

Figure 5 FACT Site Subterranean Bunker

Figure 6 Equipment Operating in the FACT Bunker

The seismometers were all powered from a laboratory power supply configured to output 12 V unless noted otherwise.

Figure 7 Lab Power Supply

2.2 Scope

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

Table 1 Tests Performed

Test
Power Consumption
Primary Sensitivity at 1Hz
Primary Frequency Response (Tonal, 0.1 – 20 Hz)
Reference Sensitivity at 1Hz
Reference Frequency Response
Passband
Sensitivity vs power supply voltage
Sensitivity vs input amplitude
Full Scale
Self-Noise
Dynamic Range
Calibrator Frequency Response

2.3 Timeline

Testing was performed at Sandia National Laboratories from October 12 to December 8, 2023.

Table 2 Timeline of Testing

Day	Time (Local)	Description
October 12, 2023	Morning	Start Electrical Calibration Tests: • Long and short duration Pseudo Random Binary and Sine Signal Calibrations • Verification of UVW and Calibration Enable control lines
October 16, 2023	Afternoon	Complete Electrical Calibration Tests
October 24, 2023	Morning	Start shake table tests: • Primary Sensitivity • Primary Frequency Response • Sensitivity vs power supply voltage • Sensitivity vs input amplitude • Full Scale
November 2, 2023	Afternoon	Complete shake table testing
November 27, 2023	Morning	Install sensors in FACT bunker for: • Reference Sensitivity • Reference Frequency Response • Self-Noise
December 5, 2023	Morning	Complete Reference Sensitivity, Reference Frequency Response and Self Noise
December 7, 2023	Afternoon	Power Testing Control line verification
December 8, 2023	Morning	Complete power testing

2.4 Evaluation Frequencies

The frequency range of the measurements is from 0.02 Hz to 20 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 = -17, -16, …, 12, 13. The nominal center frequency values, in Hz, are:

0.02	0.025	0.0315	0.04	0.05	0.063	0.08	0.1	0.125	0.16
0.2	0.25	0.315	0.4	0.5	0.63	0.8	1	1.25	1.6
2	2.5	3.15	4	5	6.3	8	10	12.5	16
20									

3 TEST EVALUATION

3.1 Power Consumption

The Power Consumption test is used to measure the amount of power that a sensor consumes during operation. Power use in several operational modes such as steady state, start-up, locking, unlocking, and recentering, are measured to understand the range of power consumption levels. The sensor is also tested at low and high input voltage levels to ensure it functions properly across the specified operating range.

3.1.1 Measurand

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

3.1.2 Configuration

The seismometer is connected to a power supply, current meter, and voltage meter as shown in the diagram below. It is also connected to a seismic datalogger so that sensor control commands can be issued.

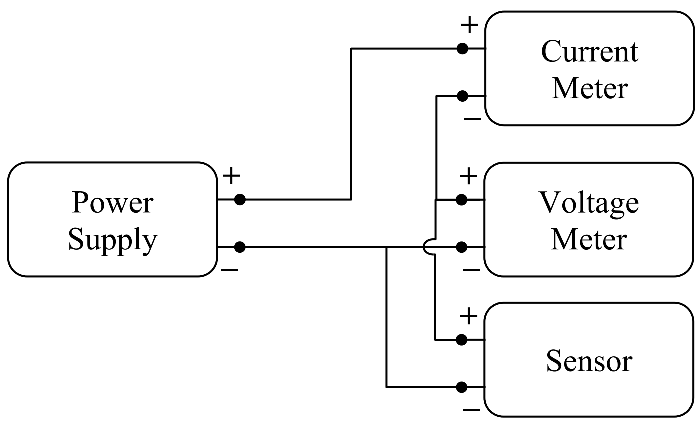


Figure 8 Power Consumption Configuration Diagram

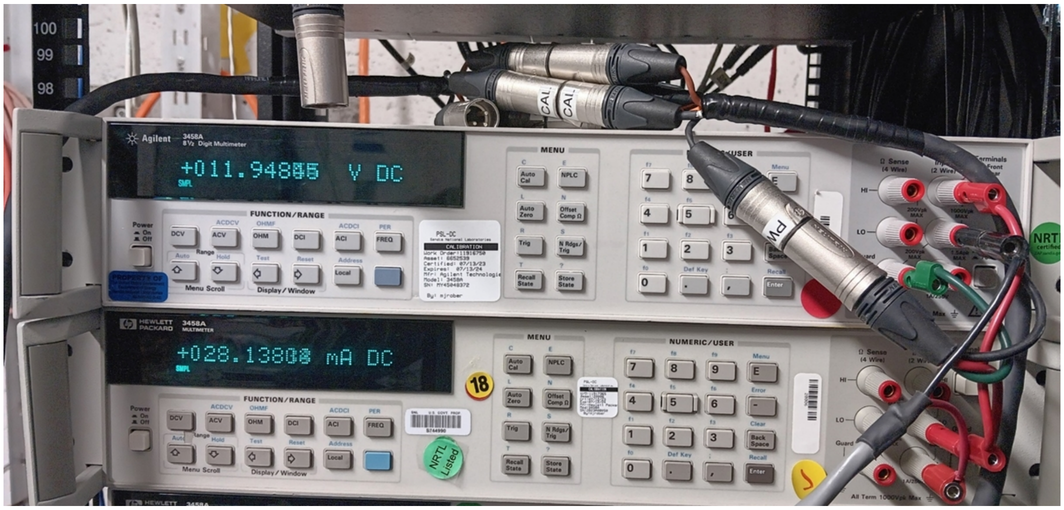


Figure 9 Power Consumption Configuration Picture

Table 3 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Power Supply	Protek DC Power Supply 3003B	N/A	12 V
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage Mode
Current Meter	HP 3458A	2823A08050	DC Current Mode

The voltage and current meters have active calibrations from the Primary Standard Laboratory at SNL.

3.1.3 Analysis

Measurements of the average current and voltage from the power supply are taken from the respective meters, preferably from a time-series recording:

$$V \text{ and } I$$

The average power in watts is then calculated as the product of the current and voltage:

$$P = V * I$$

3.1.4 Result

The figures below show representative waveform time series for the recordings of voltage and current made on the reference meters. The window regions bounded by the red lines indicate the segments of data used to evaluate the power consumption of the sensor.

Figure 10 shows Colt 213012's steady state voltage and current waveforms. Figure 11 shows its voltage and current waveforms during start up. Figure 12 shows the voltage and current waveforms during a re-center operation. Figure 13 shows the unit's voltage and current waveforms during a lock operation.

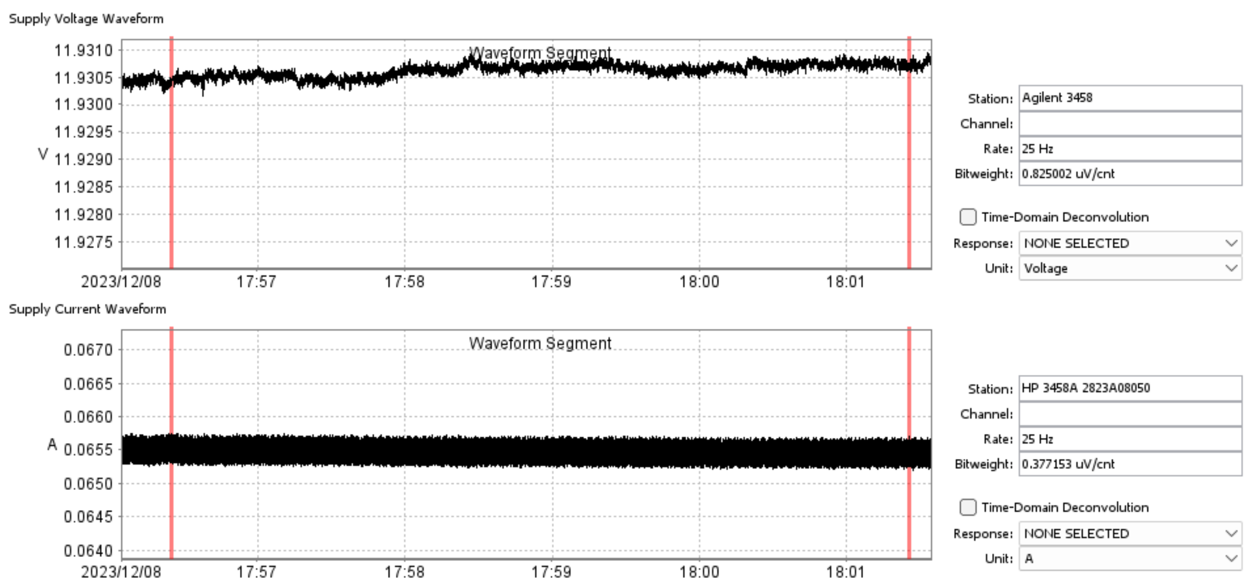


Figure 10 Colt 213012 Voltage and Current Waveforms in Steady State Operation

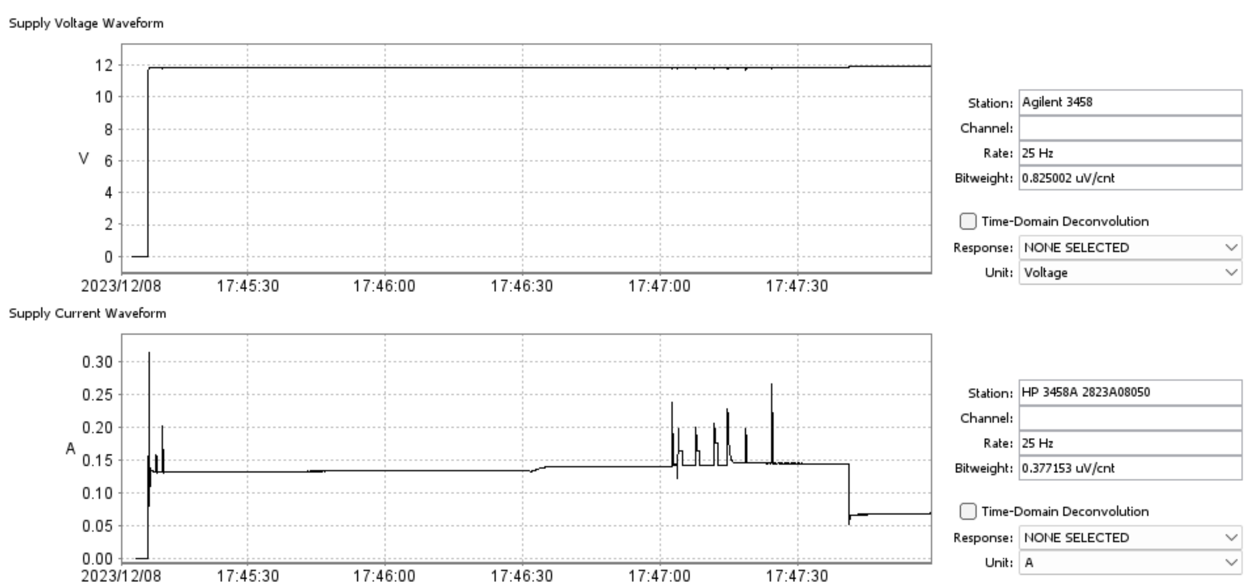


Figure 11 Colt 213012 Voltage and Current Waveforms During Start Up

Figure 12 Colt 213012 Voltage and Current Waveforms During Recenter Operation

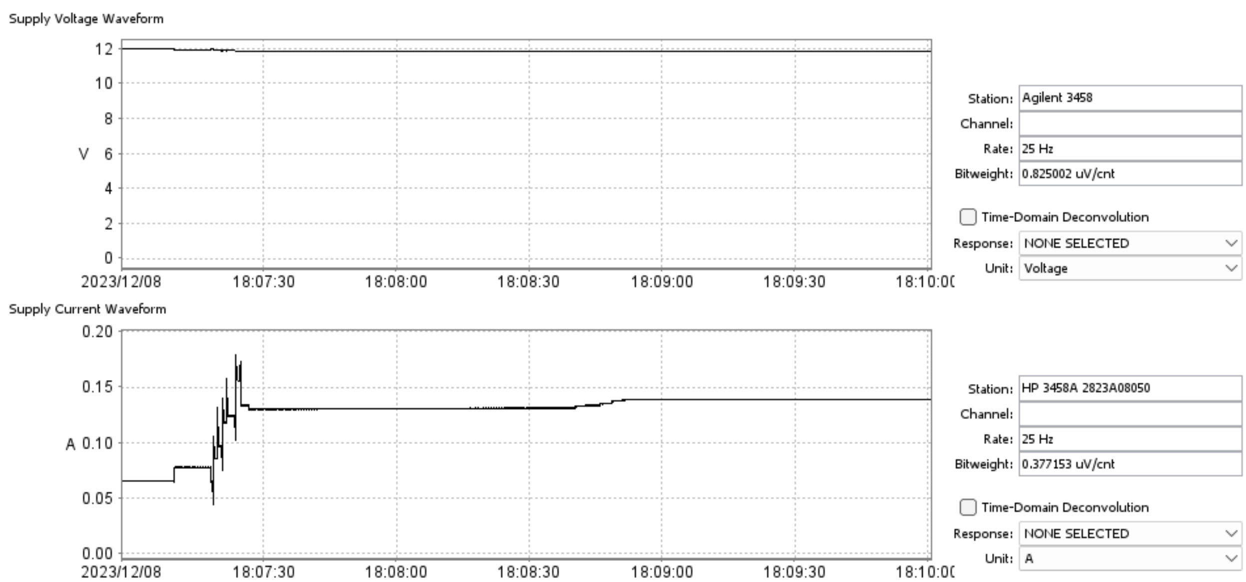


Figure 13 Colt 213012 Voltage and Current Waveforms During Lock Operation

The resulting voltage, current, and power consumption levels are shown in

Table 4, below. In addition, the peak current use of the three sensors for each test is listed in Table 5. Table 5 also lists the operation the sensor was performing when the peak current value was reached.

Table 4 Power Consumption Results: Steady State

Sensor	Supply Voltage	Supply Voltage Std Dev	Supply Current	Supply Current Std Dev	Power	Power Std Dev
Colt 213010	9.41 V	0.35 mV	82.68 mA	0.32 mA	0.78 W	2.99 mW
	11.93 V	0.09 mV	65.93 mA	0.14 mA	0.79 W	1.74 mW
	17.96 V	0.24 mV	47.45 mA	0.23mA	0.85 W	4.14 mW
Colt 213011	9.40 V	0.22mV	83.52 mA	0.44 mA	0.79 W	4.17 mW
	11.93 V	0.09 mV	66.28 mA	0.14 mA	0.79 W	1.63 mW
	17.95 V	0.11 mV	47.12 mA	0.09 mA	0.85 W	1.64 mW
Colt 213012	9.41 V	0.41 mV	83.75 mA	0.40 mA	0.79 W	3.76 mW
	11.93 V	0.12mV	65.45 mA	0.14 mA	0.78 W	1.66 mW
	17.96 V	0.14 mV	46.31 mA	0.09 mA	0.83 W	1.64 mW

Table 5 Peak Current Use

Sensor	Supply Voltage	Peak Current Use	Operation
Colt 213010	9.41 V	0.30 A	Lock
	11.93 V	0.25 A	Startup/Unlock
	17.96 V	0.20 A	Startup/Unlock
Colt 213011	9.40 V	0.32 A	Startup/Unlock
	11.93 V	0.27 A	Startup/Unlock
	17.95 V	0.21 A	Startup/Unlock
Colt 213012	9.41 V	0.37 A	Startup/Unlock
	11.93 V	0.31 A	Startup/Unlock
	17.96 V	0.24 A	Startup/Unlock

The specification sheet for the Colt states that the unit consumes less than 0.7W of power in typical operation. All three Colts were found to have slightly higher power consumption with values ranging from 0.78 to 0.85W. Power consumption was about 50mW higher when the sensors operated near the maximum input voltage rating of 18V.

All sensors operated successfully when tested at 9.5V, 12V and 18V. At each test voltage the sensors were first started up and unlocked (the unlock operation begins automatically after power is applied). They were then operated at steady state for several minutes and then a recenter command was issued. At the end of the test the sensors were commanded to lock their masses via toggling of a control line.

The peak current use by any of the three sensors was 0.37A which occurred during the startup and unlock period of Colt 213012 when it was operating at 9.41V. This value is an average of the current usage during a 0.04s acquisition window from the current meter. This current peak occurred for a single sample only and likely represents a small in-rush current when the sensor is unlocking its masses.

3.2 Primary Sensitivity

The sensitivity of a sensor is defined as the ratio between the change in the output voltage and the corresponding change in the quantity being measured, velocity in the case of the Colt seismometers. For primary sensitivity, the reference measurement of the quantity being measured must be directly traceable to SI units (e.g., use of a laser vibrometer for motion measurements).

3.2.1 Measurand

The quantity being measured is the sensor's sensitivity in V/(m/s) and phase shift in degrees at a reference frequency of 1Hz.

3.2.2 Configuration

The sensor is placed on a seismic calibration table and subjected to a sinusoidal velocity with a frequency of 1Hz and an amplitude set to 10% of the sensor's specified full-scale velocity. All available axes of the sensor are tested. For the Colt sensors their vertical, north-south, and east-west sensitivities were independently tested utilizing vertical and horizontal axis shake tables. Figure 14, below, provides a block diagram of the horizontal shake table system. Figure 15 illustrates how the sensors were clamped to the testing surfaces of the shake tables. Figure 16 shows photos of the Colt sensors installed on the horizontal and vertical calibration tables.

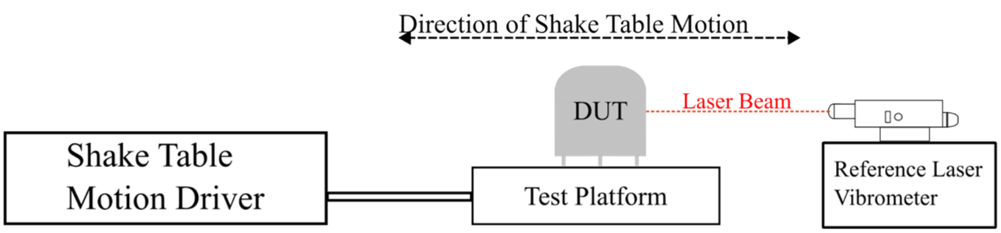


Figure 14 Horizontal Sensitivity Testbed

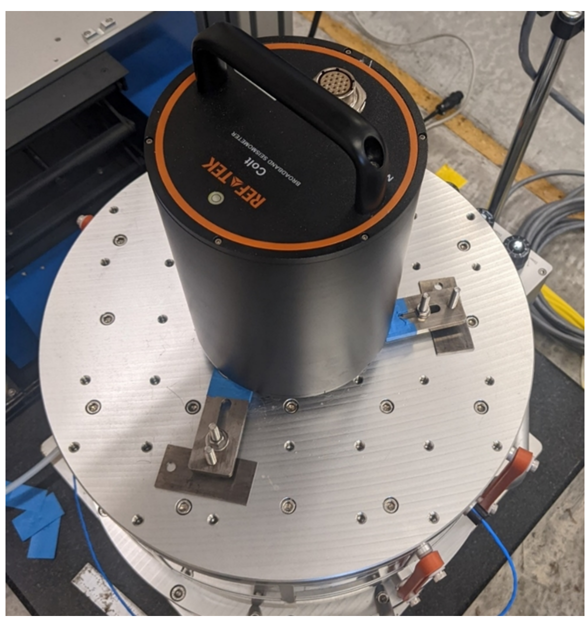


Figure 15 Colt Sensor Clamped to the Vertical Shake Table

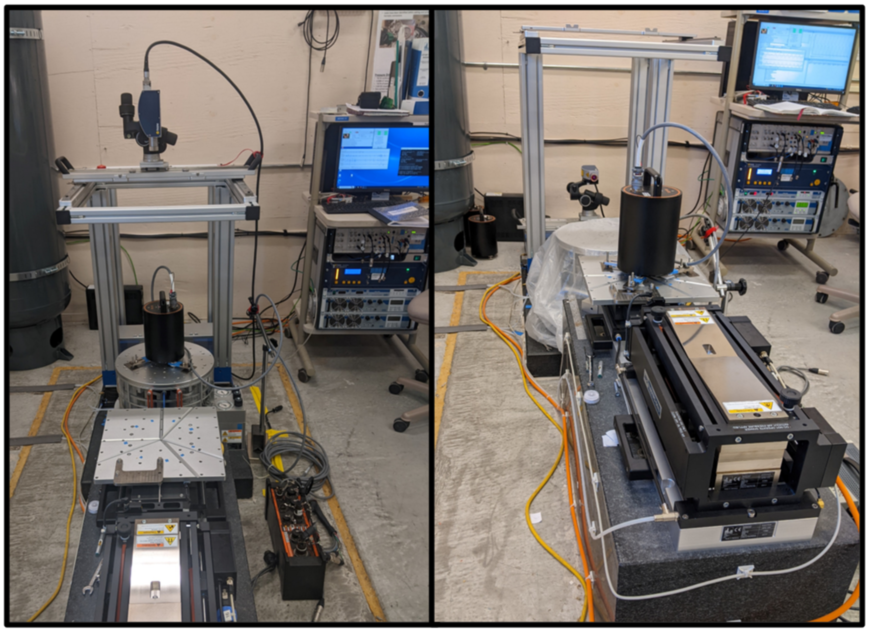


Figure 16 Colt sensors on vertical shake table (left) and horizontal shake table (right)

Table 6 Sensitivity Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.00 mm/s Frequency = 1Hz Pressure = 823.3 ± 6.2hPa Temperature = 21.1 ± 2.7C Humidity = 18.8 ± 8.4%

The Spektra CS-18P Seismic Calibration system provides integrated control, data acquisition, and signal analysis to perform a primary measurement of a seismometer's amplitude and phase response at discrete test frequencies. A laser vibrometer is utilized to provide a calibrated and traceable measurement of the velocity of the sensor under test (SUT). The SUT is clamped to the surface of the shake table for both horizontal and vertical testing as shown in Figure 15.

3.2.3 Analysis

The Spektra CS-18P system performs the analysis of data internally by fitting a sine equation to both the SUT's output and the output of the reference laser vibrometer.

The sensor amplitude sensitivity in Volts / (m/s) is computed using the amplitude of the fitted sinusoidal equations:

$$Sensitivity = \frac{Voltage_{SUT}}{Velocity_{Laser}}$$

The sensor phase shift in degrees is computed using the phase of the fitted sinusoidal equations:

$$Phase = \theta_{SUT} - \theta_{ref}$$

3.2.4 Result

The following table contains the measured amplitude and phase response of the sensors when excited with 1Hz velocity signals. Also included are the nominal 1Hz response values provided by the manufacturer.

Table 7 Primary Sensitivity and Phase at 1Hz

Vertical Axis							
Sensor	Test Velocity (mm/s)	**Amplitude Response (V/m/s)**			**Phase Response (Degrees)**		
		Measured	Nominal	Uncertainty (k=2, %)	Measured	Nominal	Uncertainty (k=2)
Colt 213010	1.00	2006.25	2011.81	0.7%	0.06	-0.04	1.0
Colt 213011	1.00	1995.10	2000.97	0.7%	0.04	-0.04	1.0
Colt 213012	1.00	1994.80	1999.81	0.7%	0.05	-0.04	1.0
North-South Axis							
Sensor	Test Velocity (mm/s)	**Amplitude Response (V/m/s)**			**Phase Response (Degrees)**		
		Measured	Nominal	Uncertainty (k=2, %)	Measured	Nominal	Uncertainty (k=2)
Colt 213010	1.00	2017.70	2015.26	0.7%	0.05	-0.04	1.0
Colt 213011	1.00	2006.60	1998.85	0.7%	0.04	-0.04	1.0
Colt 213012	1.00	2002.70	1992.05	0.7%	0.02	-0.04	1.0
East-West Axis							
Sensor	Test Velocity (mm/s)	**Amplitude Response (V/m/s)**			**Phase Response (Degrees)**		
		Measured	Nominal	Uncertainty (k=2, %)	Measured	Nominal	Uncertainty (k=2)
Colt 213010	1.00	1977.80	2008.57	0.7%	0.04	-0.04	1.0
Colt 213011	1.00	1988.60	1999.64	0.7%	0.02	-0.04	1.0
Colt 213012	1.00	1993.55	2003.36	0.7%	0.05	-0.04	1.0

The measured amplitude response values are all within 1.5% of the nominal. The measured phase values are all within 0.10 degrees of the nominal value. The measured sensitivity values at 1 Hz are all consistent with the nominal values, accounting for the uncertainty in the measurements.

3.3 Primary Frequency Response

The sensor frequency response is defined as the linear time-invariant (LTI) change in the sensor's output signal amplitude and phase relative to an input velocity signal. When determining primary frequency response, the reference measurement of the input velocity signal must be directly traceable to the SI (e.g., by a calibrated laser vibrometer).

3.3.1 Measurand

Response, including the amplitude expressed in dB relative to the nominal amplitude at the reference frequency of 1Hz and the absolute phase expressed in degrees, over the defined frequencies.

3.3.2 Configuration

The sensor is placed on a seismic calibration table and subjected to sinusoidal velocities with a frequency ranging from 0.1Hz up to 20Hz. The amplitude of the signal is set to 10% of the sensor's specified full-scale velocity. At higher frequencies the velocity amplitude may be reduced to ensure that the acceleration rating of the sensor is not exceeded. Figure 17, below, provides a block diagram of the horizontal shake table system. All three axes of the sensor are tested.

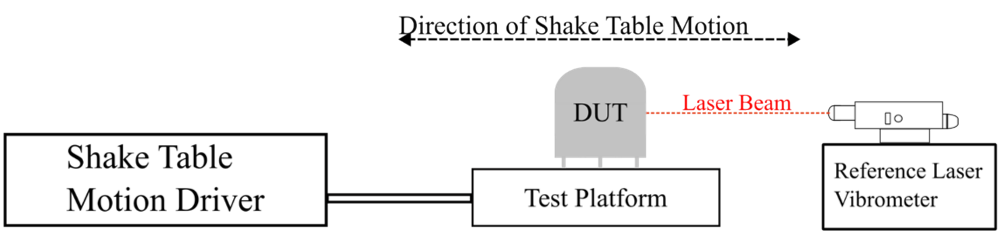


Figure 17 Primary Frequency Response Configuration Diagram

Table 8 Primary Frequency Response Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.00 mm/s Frequency = 0.1 – 20Hz Pressure = 823.3 ± 6.2hPa Temperature = 21.1 ± 2.7C Humidity = 18.8 ± 8.4%

The SUT is clamped to the surface of the shake table for both horizontal and vertical testing as shown in Figure 15.

3.3.3 Analysis

The Spektra seismometer calibrator performs the analysis of data internally by fitting a sine function to both the sensor output and a primary measurement of the sensor displacement, which is converted to velocity.

The sensor amplitude sensitivity in Volts / (m/s) is computed for each frequency that the Spektra system operates at:

$$Sensitivity = \frac{Voltage_{SUT}}{Velocity_{Laser}}$$

The amplitude sensitivity at each frequency is converted to a measurement of decibels relative to the amplitude sensitivity at the reference frequency of 1 Hz.

$$Amplitude\ Response(f) = 10 \cdot \log_{10}\left(\frac{Sensitivity(f)}{Sensitivity(f_{ref})}\right)^2$$

The sensor phase sensitivity in degrees is likewise computed for each operational frequency:

$$Phase = \theta_{SUT} - \theta_{ref}$$

Upon completion of the frequency response test, the Spektra system generates a frequency, amplitude, and phase (FAP) table.

3.3.4 Result

The following plots show the amplitude and phase responses obtained with the CS-18P system for the three axes of the sensors (vertical, north-south and east-west). The nominal response of the sensor, provided by Reftek, is included in the following plots as a black line. For the amplitude response plots, the amplitude data is shown with units of dB and has been normalized to the nominal 1 Hz sensitivity. Hence the nominal response curve in the following plots will have an amplitude response of 0 dB at 1 Hz.

The vertical axis of the sensors was evaluated from 0.5Hz to 20Hz while the North/South and East/West axes were evaluated from 0.1 Hz to 20 Hz. The specified k=2 uncertainties for the CS-18P system are shows as shaded regions around the response trace for each sensor. The vertical shake table generates a significant magnetic field during operation which impacted the sensors' measured amplitude response at frequencies below 0.5Hz. For this reason, vertical axis response data below 0.5Hz are not presented.

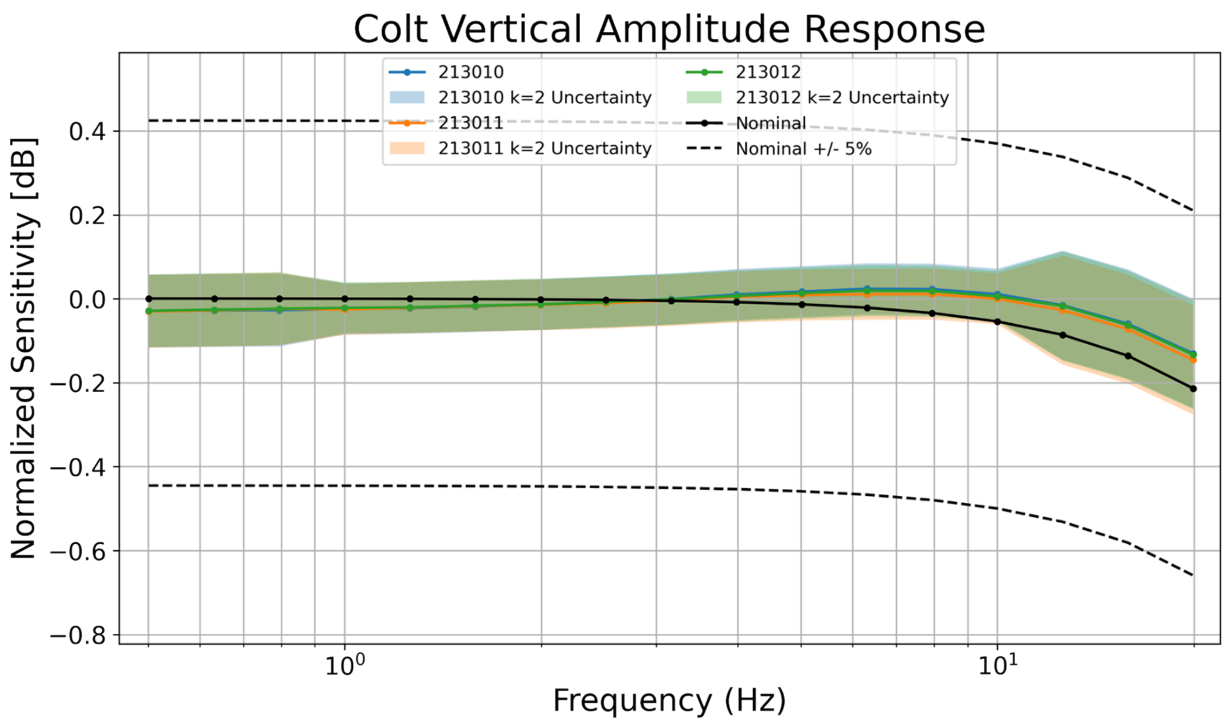


Figure 18 Vertical Amplitude Response

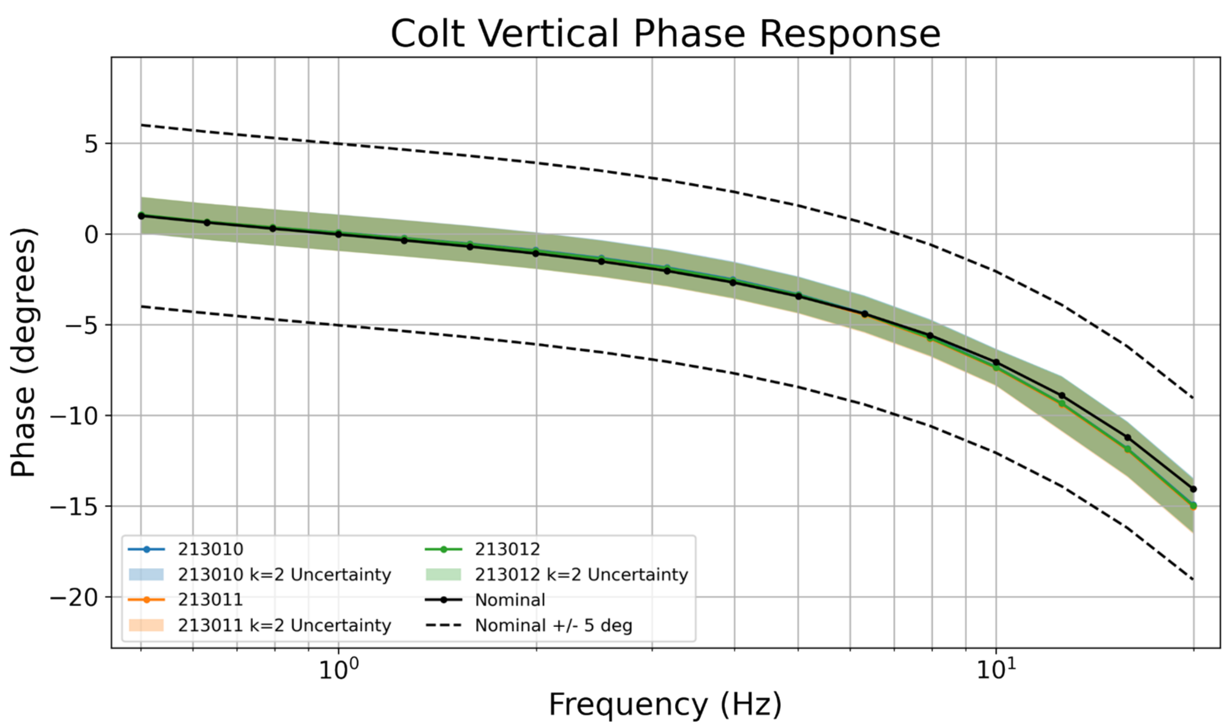


Figure 19 Vertical Phase Response

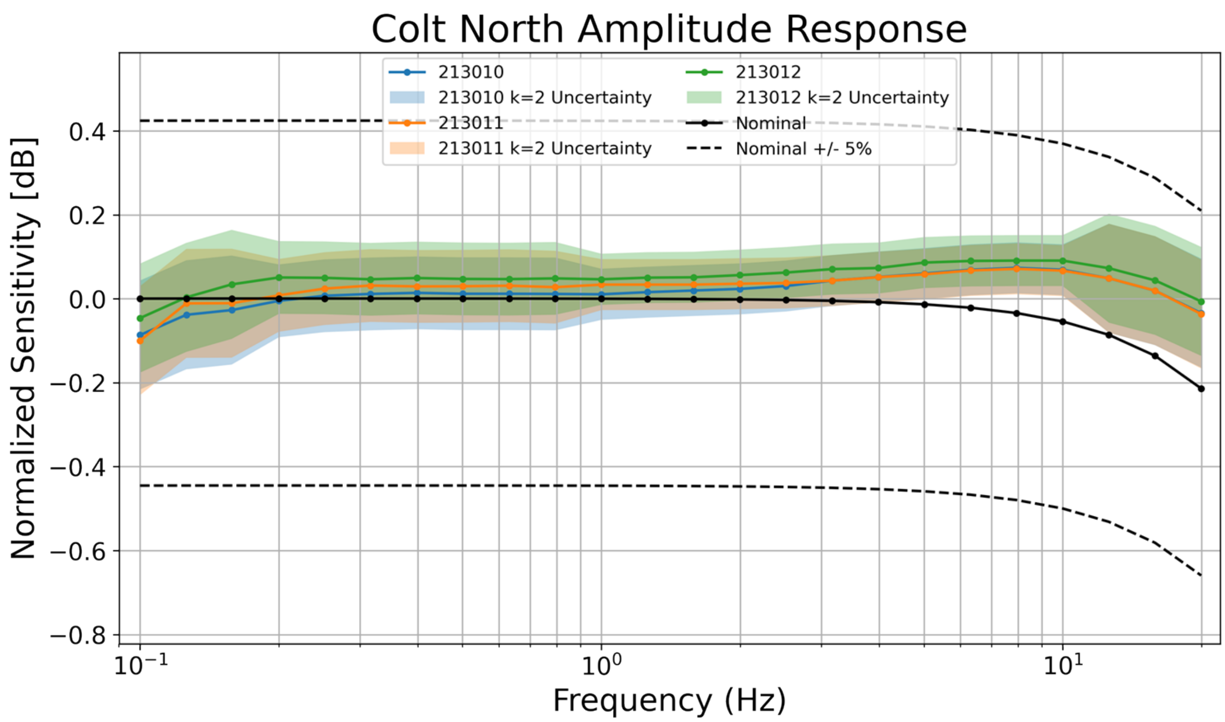


Figure 20 North-South Amplitude Response

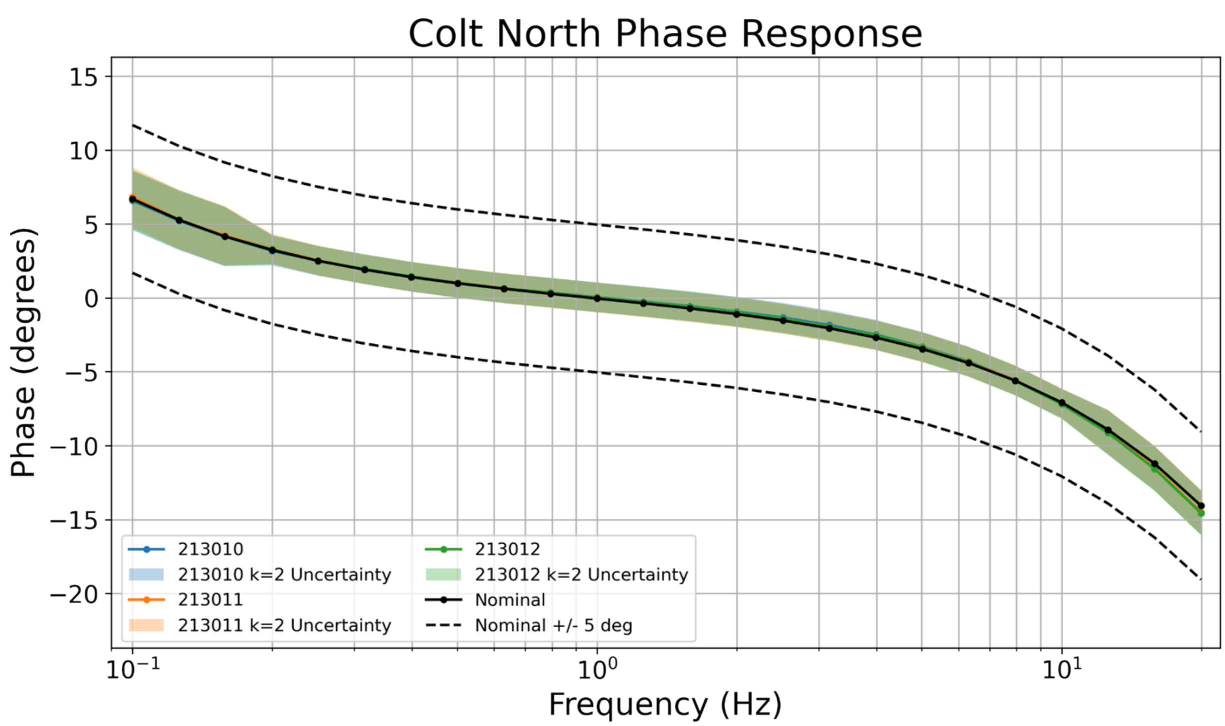


Figure 21 North-South Phase Response

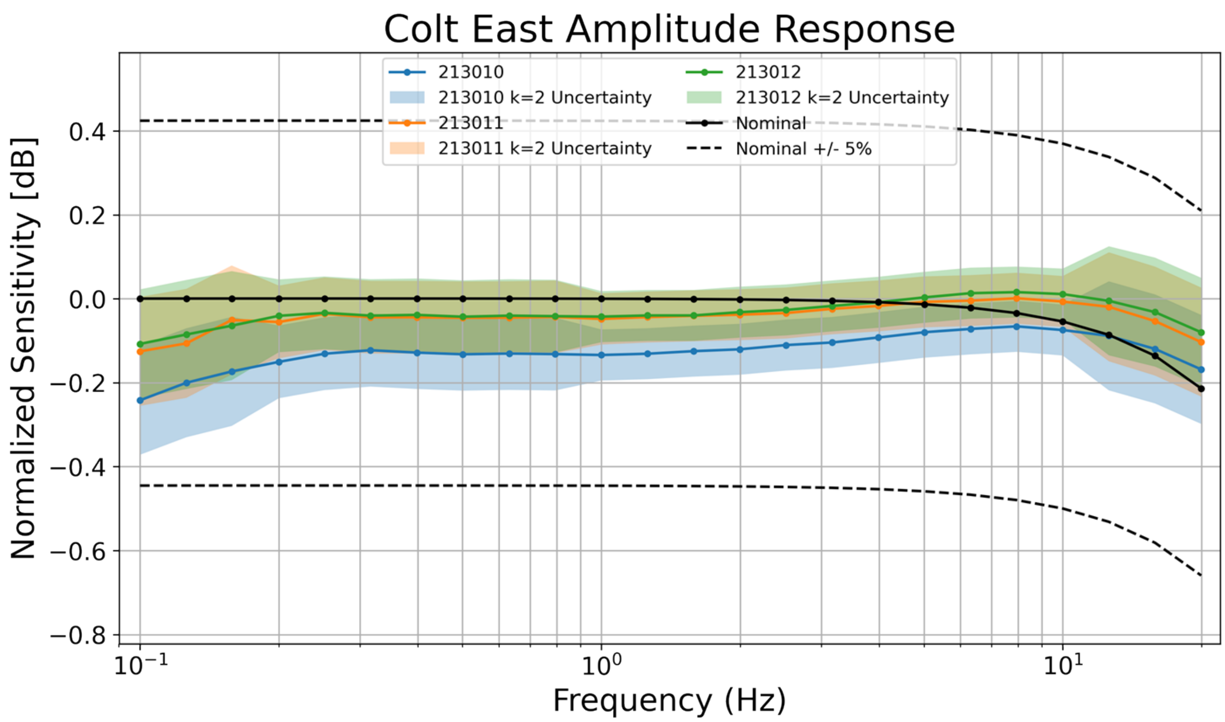


Figure 22 East-West Amplitude Response

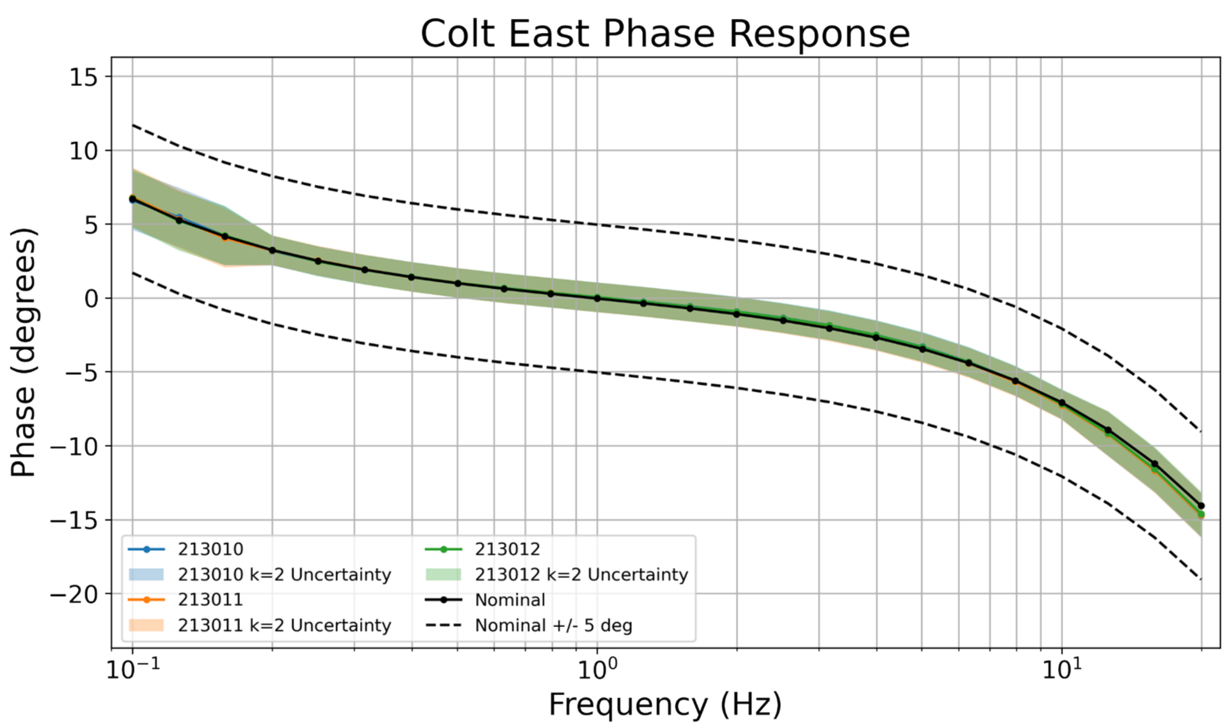


Figure 23 East-West Phase Response

The amplitude response of all three Colts closely matches the nominal amplitude response for all frequencies evaluated. The measured amplitude response generally has a slight increase for frequencies above 1 Hz, but the increase is small and does not result in the sensors operating outside of the +/-5% of nominal IMS requirement. The measured phase response of all three Colts closely matches the nominal phase response for all evaluated frequencies.

The following tables contains the values used to generate the above plots.

Table 9 Primary Vertical Amplitude Response

Primary Vertical Amplitude Response of Colt Sensors					
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Uncertainty k=2 [dB]
0.50	-0.029	-0.030	-0.029	0.000	0.087
0.63	-0.028	-0.028	-0.026	0.000	0.087
0.79	-0.027	-0.024	-0.024	0.000	0.087
1.00	-0.024	-0.026	-0.022	0.000	0.061
1.26	-0.023	-0.022	-0.020	0.000	0.061
1.59	-0.019	-0.018	-0.017	-0.001	0.061
2.00	-0.014	-0.015	-0.014	-0.002	0.061
2.51	-0.007	-0.010	-0.008	-0.003	0.061
3.16	-0.001	-0.004	-0.001	-0.005	0.061
3.98	0.010	0.004	0.006	-0.008	0.061
5.01	0.017	0.009	0.013	-0.013	0.061
6.31	0.024	0.011	0.019	-0.021	0.061
7.94	0.023	0.011	0.018	-0.034	0.061
10.00	0.011	0.000	0.006	-0.054	0.061
12.59	-0.016	-0.027	-0.017	-0.086	0.130
15.85	-0.060	-0.073	-0.063	-0.136	0.130
19.95	-0.131	-0.146	-0.134	-0.214	0.130

Table 10 Primary North-South Amplitude Response

Primary North-South Amplitude Response of Colt Sensors					
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Uncertainty k=2 [dB]
0.10	-0.086	-0.100	-0.046	0.000	0.130
0.13	-0.038	-0.011	0.003	0.000	0.130
0.16	-0.027	-0.011	0.034	0.001	0.130
0.20	-0.005	0.008	0.051	0.001	0.087
0.25	0.007	0.024	0.050	0.001	0.087
0.32	0.011	0.031	0.046	0.000	0.087
0.40	0.014	0.029	0.049	0.000	0.087
0.50	0.012	0.030	0.047	0.000	0.087
0.63	0.012	0.031	0.047	0.000	0.087
0.79	0.011	0.028	0.048	0.000	0.087
1.00	0.011	0.034	0.046	0.000	0.061
1.26	0.016	0.034	0.050	0.000	0.061
1.59	0.020	0.034	0.051	-0.001	0.061
2.00	0.023	0.036	0.056	-0.002	0.061
2.51	0.030	0.038	0.062	-0.003	0.061
3.16	0.043	0.043	0.071	-0.005	0.061
3.98	0.052	0.051	0.073	-0.008	0.061
5.01	0.060	0.058	0.086	-0.013	0.061
6.31	0.069	0.067	0.090	-0.021	0.061
7.94	0.074	0.071	0.091	-0.034	0.061
10.00	0.069	0.067	0.091	-0.054	0.061
12.59	0.049	0.049	0.073	-0.086	0.130
15.85	0.019	0.019	0.044	-0.136	0.130
19.95	-0.034	-0.036	-0.006	-0.214	0.130

Table 11 Primary East-West Amplitude Response

Primary East-West Amplitude Response of Colt Sensors					
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Uncertainty k=2 [dB]
0.10	-0.242	-0.125	-0.108	0.000	0.130
0.13	-0.200	-0.106	-0.085	0.000	0.130
0.16	-0.173	-0.051	-0.064	0.001	0.130
0.20	-0.150	-0.056	-0.041	0.001	0.087
0.25	-0.131	-0.036	-0.034	0.001	0.087
0.32	-0.123	-0.044	-0.040	0.000	0.087
0.40	-0.128	-0.044	-0.038	0.000	0.087
0.50	-0.132	-0.045	-0.043	0.000	0.087
0.63	-0.131	-0.045	-0.040	0.000	0.087
0.79	-0.132	-0.043	-0.042	0.000	0.087
1.00	-0.134	-0.048	-0.043	0.000	0.061
1.26	-0.131	-0.044	-0.040	0.000	0.061
1.59	-0.125	-0.041	-0.040	-0.001	0.061
2.00	-0.120	-0.038	-0.032	-0.002	0.061
2.51	-0.110	-0.034	-0.027	-0.003	0.061
3.16	-0.104	-0.024	-0.017	-0.005	0.061
3.98	-0.092	-0.017	-0.009	-0.008	0.061
5.01	-0.080	-0.008	0.003	-0.013	0.061
6.31	-0.072	-0.005	0.013	-0.021	0.061
7.94	-0.066	0.001	0.016	-0.034	0.061
10.00	-0.075	-0.007	0.011	-0.054	0.061
12.59	-0.089	-0.019	-0.005	-0.086	0.130
15.85	-0.120	-0.053	-0.032	-0.136	0.130
19.95	-0.168	-0.103	-0.080	-0.214	0.130

Table 12 Primary Vertical Phase Response

Primary Vertical Phase Response of Colt Sensors					
Frequency (Hz)	Colt 213010 (deg)	Colt 213011 (deg)	Colt 213012 (deg)	Nominal (deg)	Uncertainty k=2 (deg)
0.50	1.01	1.02	1.04	0.99	1.00
0.63	0.66	0.66	0.66	0.62	1.00
0.79	0.35	0.35	0.35	0.28	1.00
1.00	0.06	0.04	0.05	-0.04	1.00
1.26	-0.24	-0.25	-0.26	-0.37	1.00
1.59	-0.56	-0.58	-0.58	-0.71	1.00
2.00	-0.91	-0.94	-0.95	-1.09	1.00
2.51	-1.34	-1.39	-1.38	-1.53	1.00
3.16	-1.86	-1.92	-1.90	-2.05	1.00
3.98	-2.52	-2.58	-2.57	-2.68	1.00
5.01	-3.35	-3.41	-3.38	-3.45	1.00
6.31	-4.40	-4.47	-4.42	-4.41	1.00
7.94	-5.71	-5.79	-5.74	-5.59	1.00
10.00	-7.33	-7.40	-7.36	-7.07	1.00
12.59	-9.34	-9.41	-9.35	-8.92	1.50
15.85	-11.84	-11.91	-11.87	-11.21	1.50
19.95	-14.94	-15.04	-14.99	-14.06	1.50

Table 13 Primary North-South Phase Response

Primary North-South Phase Response of Colt Sensors					
Frequency (Hz)	Colt 213010 (deg)	Colt 213011 (deg)	Colt 213012 (deg)	Nominal (deg)	Uncertainty k=2 (deg)
0.10	6.58	6.83	6.65	6.70	2.00
0.13	5.23	5.29	5.30	5.28	2.00
0.16	4.15	4.23	4.16	4.16	2.00
0.20	3.19	3.31	3.28	3.23	1.00
0.25	2.52	2.54	2.50	2.51	1.00
0.32	1.93	1.93	1.96	1.91	1.00
0.40	1.42	1.43	1.45	1.41	1.00
0.50	1.00	1.03	1.02	0.99	1.00
0.63	0.65	0.66	0.64	0.62	1.00
0.79	0.35	0.32	0.35	0.28	1.00
1.00	0.05	0.04	0.02	-0.04	1.00
1.26	-0.25	-0.29	-0.27	-0.37	1.00
1.59	-0.56	-0.62	-0.59	-0.71	1.00
2.00	-0.92	-0.98	-0.95	-1.09	1.00
2.51	-1.33	-1.41	-1.42	-1.53	1.00
3.16	-1.84	-1.94	-1.93	-2.05	1.00
3.98	-2.49	-2.54	-2.53	-2.68	1.00
5.01	-3.30	-3.32	-3.35	-3.45	1.00
6.31	-4.30	-4.32	-4.35	-4.41	1.00
7.94	-5.57	-5.57	-5.61	-5.59	1.00
10.00	-7.14	-7.13	-7.19	-7.07	1.00
12.59	-9.09	-9.08	-9.13	-8.92	1.50
15.85	-11.54	-11.49	-11.56	-11.21	1.50
19.95	-14.55	-14.49	-14.55	-14.06	1.50

Table 14 Primary East-West Phase Response

Primary East-West Phase Response of Colt Sensors					
Frequency (Hz)	Colt 213010 (deg)	Colt 213011 (deg)	Colt 213012 (deg)	Nominal (deg)	Uncertainty k=2 (deg)
0.10	6.61	6.82	6.75	6.70	2.00
0.13	5.45	5.32	5.20	5.28	2.00
0.16	4.20	4.05	4.22	4.16	2.00
0.20	3.19	3.21	3.23	3.23	1.00
0.25	2.48	2.52	2.47	2.51	1.00
0.32	1.91	1.93	1.90	1.91	1.00
0.40	1.44	1.42	1.42	1.41	1.00
0.50	1.01	1.02	1.01	0.99	1.00
0.63	0.66	0.64	0.67	0.62	1.00
0.79	0.35	0.35	0.34	0.28	1.00
1.00	0.04	0.02	0.05	-0.04	1.00
1.26	-0.25	-0.27	-0.26	-0.37	1.00
1.59	-0.58	-0.60	-0.60	-0.71	1.00
2.00	-0.93	-0.96	-0.93	-1.09	1.00
2.51	-1.35	-1.41	-1.37	-1.53	1.00
3.16	-1.86	-1.94	-1.86	-2.05	1.00
3.98	-2.51	-2.58	-2.52	-2.68	1.00
5.01	-3.31	-3.40	-3.33	-3.45	1.00
6.31	-4.33	-4.41	-4.35	-4.41	1.00
7.94	-5.60	-5.67	-5.60	-5.59	1.00
10.00	-7.21	-7.26	-7.18	-7.07	1.00
12.59	-9.21	-9.21	-9.16	-8.92	1.50
15.85	-11.66	-11.68	-11.59	-11.21	1.50
19.95	-14.72	-14.70	-14.61	-14.06	1.50

3.4 Reference Sensitivity

The sensitivity of a sensor is defined as the ratio between the change in the sensor's output voltage and the corresponding change in the quantity being measured. For reference sensitivity, a reference seismometer is utilized to determine the quantity being measured. Since the output of the reference seismometer is not directly traceable to the SI, this test is considered a reference measurement as opposed to a primary measurement.

3.4.1 Measurand

The quantity being measured is the sensor's sensitivity in V/(m/s) and phase in degrees at a reference frequency of 1Hz.

3.4.2 Configuration

The sensor(s) under test and a reference sensor with known response characteristics are placed on a seismic pier. Data is collected continuously and signal sources such as earthquakes are used to determine the relative response between the sensor(s) under test and the reference sensor. Figure 24 shows a block diagram of the test and Figure 25 is a photo of how the sensors were installed in the FACT bunker. Figure 24 shows sensors with a single output signal. For the Colt sensors, which have three output signals, a three-axis reference sensor is used and all output signals from all sensors are simultaneously recorded with multiple digitizers.

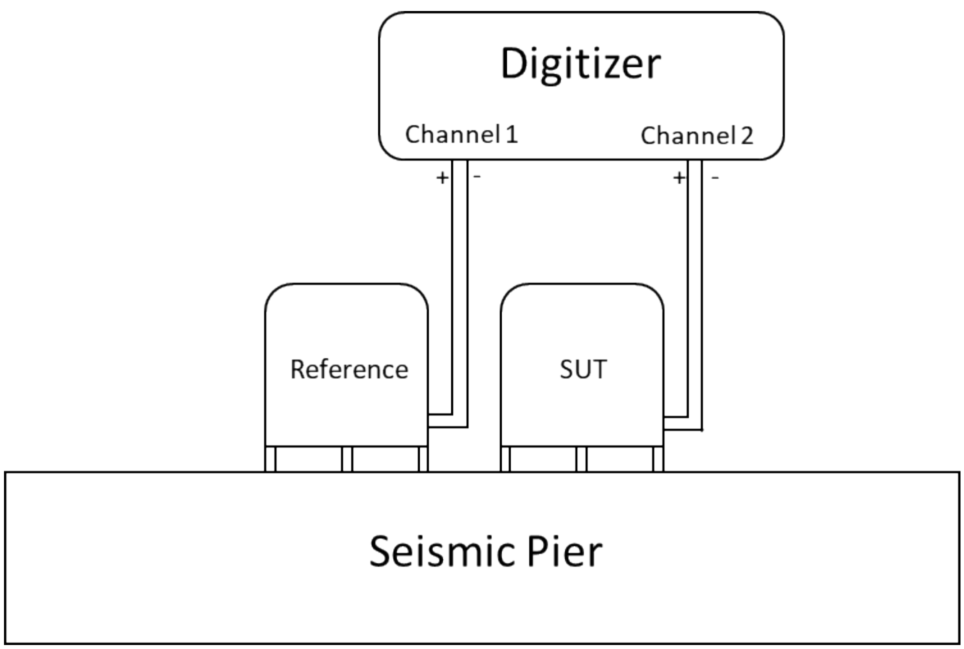


Figure 24 Reference Sensitivity Configuration Diagram

Figure 25 Sensors installed in the bunker

Table 15 Reference Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	Streckeisen / STS-2 G3	120651	1500 V/(m/s) at 1Hz
Seismic Pier	SNL	Bunker	23C
Reference Digitizer	Quanterra / Q330HR	1551	200 Hz, 20x gain
SUT Digitizer 1	Reftek / Wrangler	3052D	200Hz, 64x gain Port A: Colt 213011 Port B: Colt 213012
SUT Digitizer 2	Reftek / Wrangler	3052C	200Hz, 64x gain Port A: Colt 213010 Port B: None

The reference digitizer records the output of the reference sensor and the SUT digitizers record the output of the sensors under test.

3.4.3 Analysis

The bit-weights for each digitizer are applied to the recorded data:

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

The input signal to both the reference sensor and SUT are assumed to be identical since they are both installed in the same location and exposed to the same ground motion. This assumption allows for the sensors, input signal, output signals and linearly additive noise sources to be expressed in the frequency domain as:

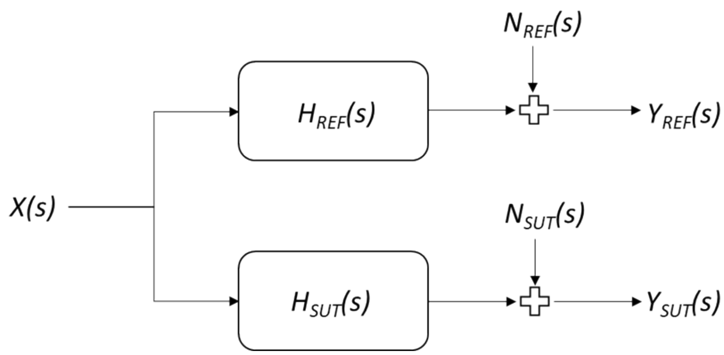


Figure 26 Diagram of two sensors with a common input signal

In equation form, the output signals of the refence seismometer and the SUT are expressed as:

$$Y_{REF}(s) = H_{REF}(s) * X(s) + N_{REF}(s)$$

$$Y_{SUT}(s) = H_{SUT}(s) * X(s) + N_{SUT}(s)$$

Following the analysis presented in (Holcomb, 1989) and (Merchant, 2011) for the distributed noise model, in which the noise sources are assumed to be independent but equal in power, the relative transfer function between the reference and sensor under test is:

$$H_{Relative}(s) = \frac{P^*_{YrefYsut}}{P_{YrefYref} - P_{nn}}$$

Here, $P^*_{YrefYsut}$ represents the complex conjugate of the cross power spectral density between the output of the reference and the sensor under test. $P_{YrefYref}$ is the auto power spectral density of the output of the reference. P_{nn} is the power spectral density of the independent noise. P_{nn} itself can be estimated as:

$$P_{nn} = \frac{1}{2}\left(P_{YrefYref} + P_{YsutYsut}\right) - \sqrt{\frac{1}{4}\left(P_{YrefYref} - P_{YsutYsut}\right)^2 + |P_{YrefYsut}|^2}$$

3.4.4 Result

The figure below shows the vertical axis time series data recorded by the reference sensor and SUTs after a M4.0 earthquake occurred in West Texas on 12/4/2023 at 23:59:09UTC. Details on the earthquake are available at the USGS: https://earthquake.usgs.gov/earthquakes/eventpage/tx2023xtoa/.

A two-minute analysis window is defined around the event, marked by the red lines in the below figure. All sensors were sampled at 200sps.

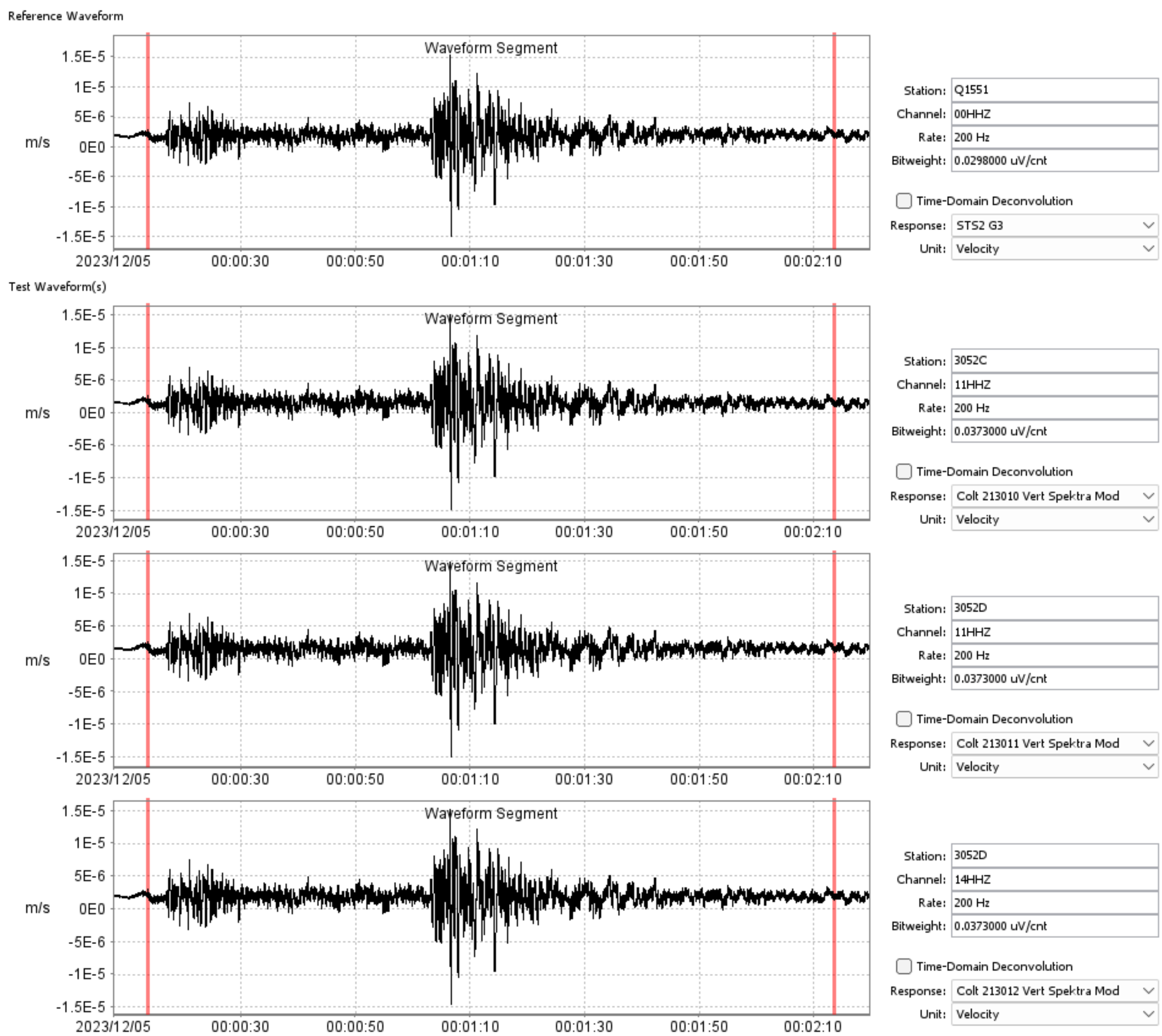


Figure 27 Reference Sensitivity Time Series

The top waveform is the STS-2 reference sensor and the lower three are Colts 213010, 213011, and 213012 respectively. For the frequency domain analysis, the two minutes of earthquake data were processed with windows of 1024 samples and 5/8 window overlaps which provided sufficient data segments. The response results from these segments were averaged to obtain the relative transfer functions. The reference sensor is corrected with the nominal poles and zeros and a 1Hz sensitivity value that was previously measured with the CS-18P system. The 1Hz sensitivity values along with the nominal poles and zeros are shown in Table 49 and Figure 69 of the Appendix.

The coherency plots for the vertical, north-south, and east-west axes when the data are processed in this way are shown in Figure 28. Coherency is high from 0.2Hz to 30Hz.

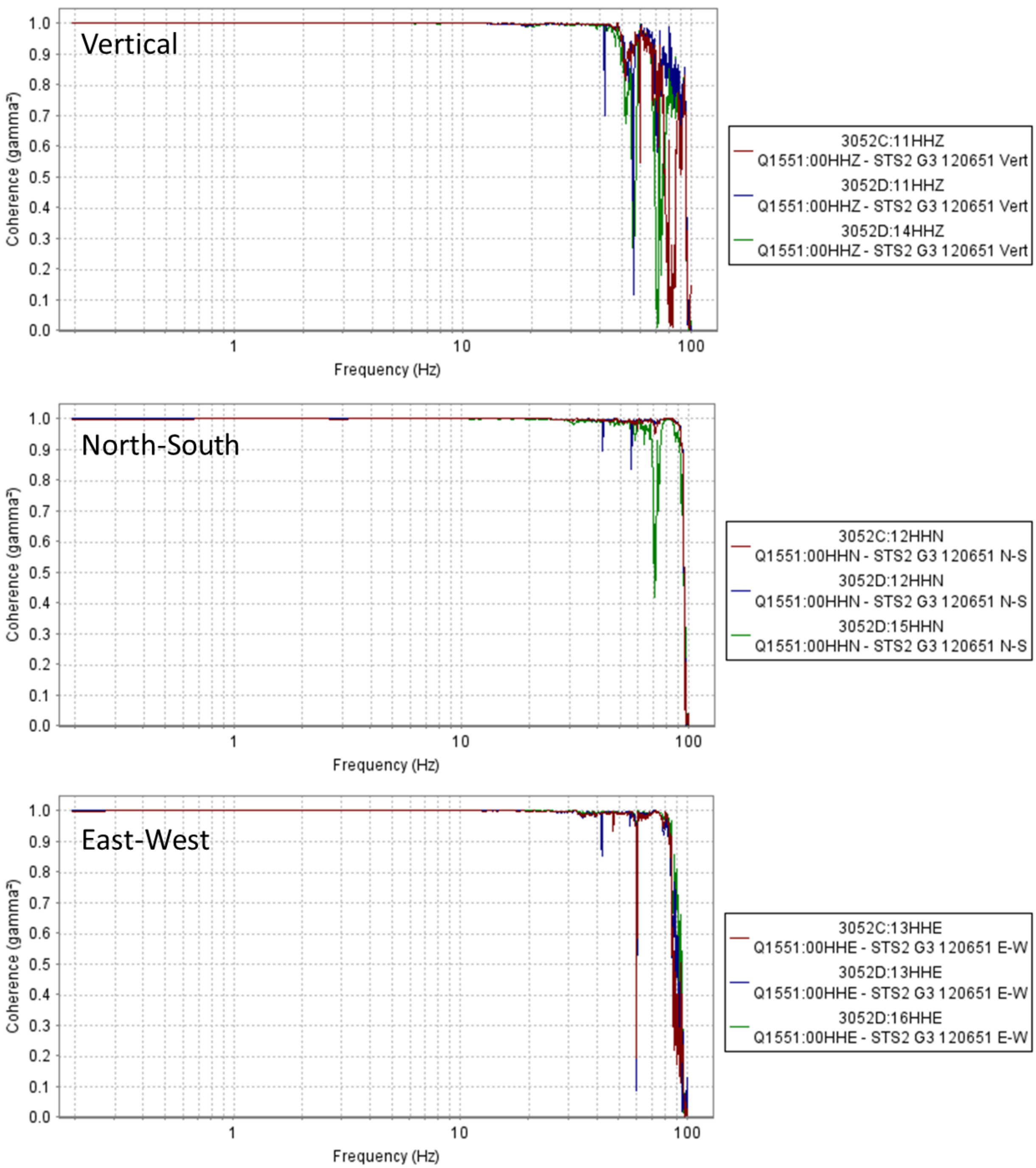


Figure 28 Coherence for M4.0 Earthquake

The relative response between the reference sensor and SUTs at 1Hz is calculated and summarized in the below tables. Also included in the tables are the nominal responses of the Colt sensors at 1Hz.

Table 16 Vertical Axis Response at 1 Hz

Vertical Axis				
	Amplitude Response (V/m/s)		Phase Response (Degrees)	
Sensor	Measured	Nominal	Measured	Nominal
Colt 213010	2000.76	2011.81	0.64	-0.04
Colt 213011	1982.15	2000.97	0.42	-0.04
Colt 213012	1979.42	1999.81	0.74	-0.04

Table 17 North-South Axis Response at 1 Hz

North-South Axis				
	Amplitude Response (V/m/s)		Phase Response (Degrees)	
Sensor	Measured	Nominal	Measured	Nominal
Colt 213010	2003.58	2015.26	0.40	-0.04
Colt 213011	1998.12	1998.85	0.34	-0.04
Colt 213012	1987.22	1992.05	0.41	-0.04

Table 18 East-West Axis Response at 1Hz

East-West Axis				
	Amplitude Response (V/m/s)		Phase Response (Degrees)	
Sensor	Measured	Nominal	Measured	Nominal
Colt 213010	1981.28	2008.57	0.39	-0.04
Colt 213011	1986.56	1999.64	0.41	-0.04
Colt 213012	1994.88	2003.36	0.39	-0.04

The measured amplitude response values are all within 1.4% of the nominal value. The measured phase response values are all within 0.78 degrees of the nominal value. The measured sensitivity values at 1 Hz are all consistent with the nominal values, however we do not have uncertainty estimates available for this method of calibration.

3.5 Reference Frequency Response

The frequency response of a sensor is defined as the linear time-invariant (LTI) change in the sensor's output signal amplitude and phase relative to an input velocity signal. For reference frequency response, a reference sensor whose output is not directly traceable to SI units is utilized to determine the input velocity signal.

3.5.1 Measurand

Response, including the amplitude relative to the nominal amplitude at the reference frequency of 1Hz, expressed in dB, and the phase expressed in degrees, over the defined frequencies.

3.5.2 Configuration

The sensor(s) under test and a reference sensor with known response characteristics are placed on a seismic pier. Data is collected continuously and signal sources such as earthquakes are used to determine the relative response between the sensor(s) under test and the reference sensor. Figure 29 shows a block diagram of the test. This diagram represents sensors with a single output signal. In the case of the Colt seismometers, the reference and SUTs are three component sensors, and each has three output signals that are simultaneously recorded with digitizers. A photo of how the sensors were installed for the test is shown in Figure 30.

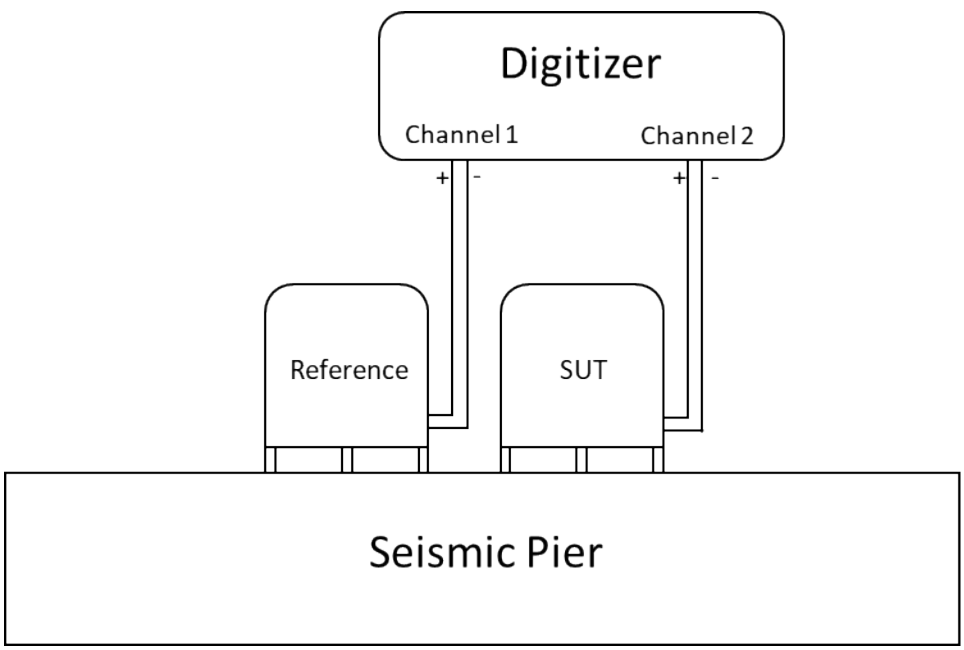


Figure 29 Reference Frequency Response Configuration Diagram


Figure 30 Sensors installed for Reference Frequency Response Test

Table 19 Reference Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	Streckeisen / STS-2 G3	120651	1500 V/(m/s) at 1Hz
Seismic Pier	SNL	Bunker	23C
Reference Digitizer	Quanterra / Q330HR	1551	200 Hz, 20x gain
SUT Digitizer 1	Reftek / Wrangler	3052D	200Hz, 64x gain Port A: Colt 213011 Port B: Colt 213012
SUT Digitizer 2	Reftek / Wrangler	3052C	200Hz, 64x gain Port A: Colt 213010 Port B: None

The reference digitizer records the output of the reference sensor and the SUT digitizers record the output of the sensors under test. The reference sensor recording is used for comparison against the sensor under test recording.

3.5.3 Analysis

The bit-weights for each digitizer are applied to the recorded data:

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

The input signal to both the reference sensor and SUT are assumed to be identical since they are both installed in the same location and exposed to the same ground motion. This assumption allows for the sensors, input signal, output signals and linearly additive noise sources to be expressed in the frequency domain as:

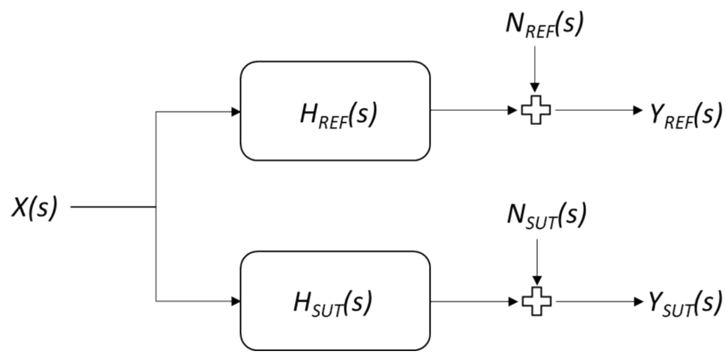


Figure 31 Diagram of two sensors with a common input signal

In equation form, the output signals of the refence seismometer and the SUT are expressed as:

$$Y_{REF}(s) = H_{REF}(s) * X(s) + N_{REF}(s)$$

$$Y_{SUT}(s) = H_{SUT}(s) * X(s) + N_{SUT}(s)$$

Following the analysis presented in (Holcomb, 1989) and (Merchant, 2011) for the distributed noise model, in which the noise sources are assumed to be independent but equal in power, the relative transfer function between the reference and sensor under test is:

$$H_{Relative}(s) = \frac{P^{*}_{YrefYsut}}{P_{YrefYref} - P_{nn}}$$

Here, $P^{*}_{YrefYsut}$ represents the complex conjugate of the cross power spectral density between the output of the reference and the sensor under test. $P_{YrefYref}$ is the auto power spectral density of the output of the reference. P_{nn} is the power spectral density of the independent noise. P_{nn} itself can be estimated as:

$$P_{nn} = \frac{1}{2}\left(P_{YrefYref} + P_{YsutYsut}\right) - \sqrt{\frac{1}{4}\left(P_{YrefYref} - P_{YsutYsut}\right)^{2} + |P_{YrefYsut}|^{2}}$$

3.5.4 Result

Two earthquakes were used to determine the reference frequency response of the SUTs from 0.02Hz to 20Hz. The first was a magnitude 7.6 in the Philippines that occurred on 12/2/2023 at 14:37:04UTC. This event was used to provide frequency response data from 0.02 Hz to 2.5Hz. Details on this event are available at:
https://earthquake.usgs.gov/earthquakes/eventpage/us7000lff4/.

The second event was the M4.0 event in West Texas that was also used for the reference sensitivity test. This event occurred on 12/4/2023 at 23:59:09UTC. This event provided frequency response data from 0.25Hz to 20Hz. Details on the event are available at:
https://earthquake.usgs.gov/earthquakes/eventpage/tx2023xtoa/.

Both events overlap from 0.25Hz to 2.5Hz which allows for verification of a stable response from one event to the next. Figure 28, shows the coherence for the M4.0 Texas event and Figure 32, below, shows the coherence for the M7.6 Philippines event.

The STS-2 sensor is instrument corrected using the nominal poles and zeros from the manufacturer. The gain that was measured when the sensor was calibrated on the CS-18 shake table system is used in place of the nominal gain value of 1500 V/(m/s). The 1Hz sensitivity values along with the nominal poles and zeros are shown in Table 49 and Figure 69 of the Appendix.

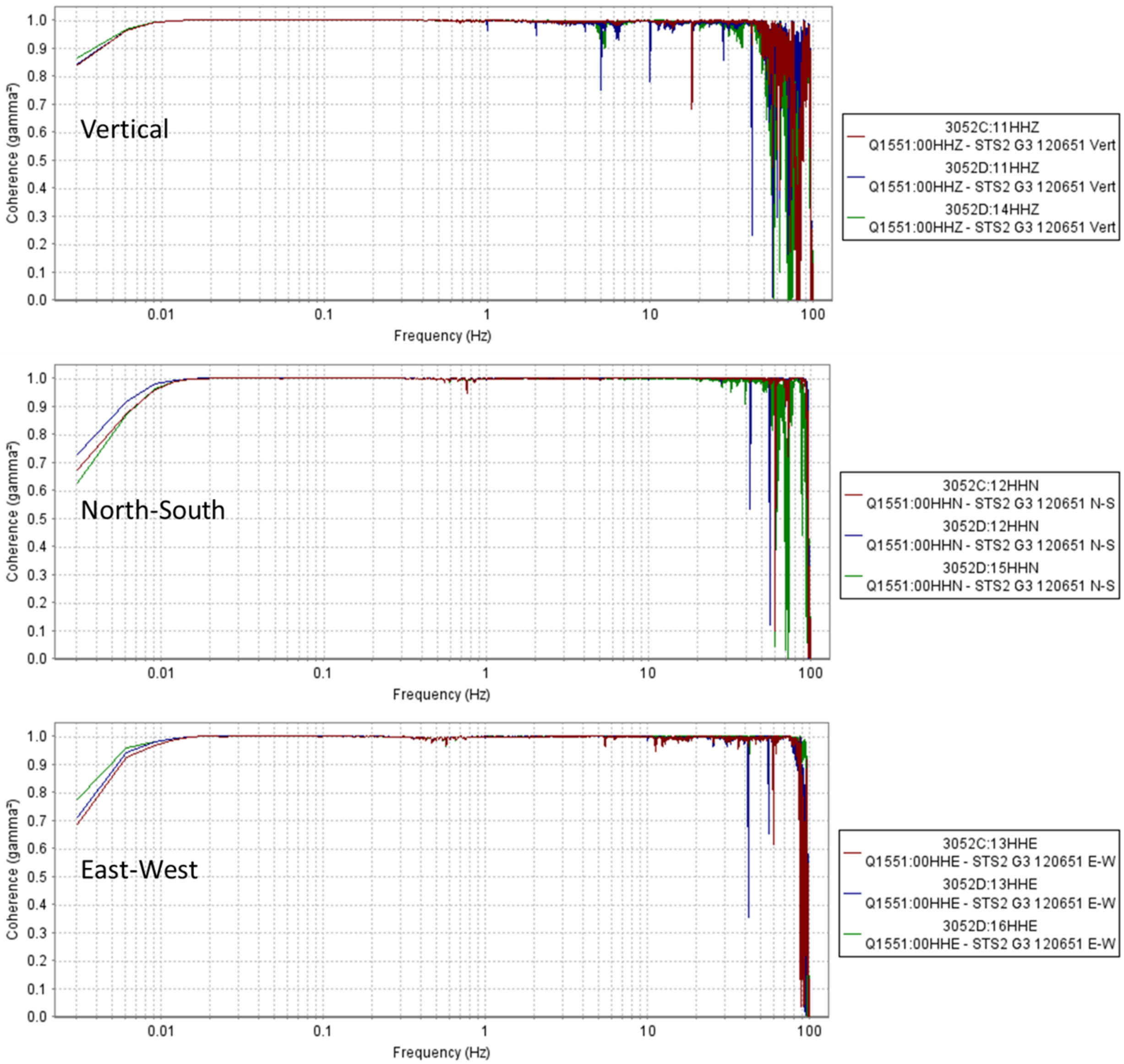


Figure 32 Coherence from the M7.6 Philippines Earthquake

Figure 33, Figure 34, and Figure 35, below, show the measured frequency response of the SUTs from 0.01Hz to 20Hz for all three axis. For comparison, the nominal response model of the sensors, provided by the manufacturer, is also included. Data from the M7.6 event is marked with triangles and data from the M4.0 event is marked with squares. For the amplitude response plots, the amplitude data are shown with units of dB and have been normalized to the nominal 1Hz sensitivity. Hence the nominal response curve in the following plots will have an amplitude response of 0dB at 1Hz.

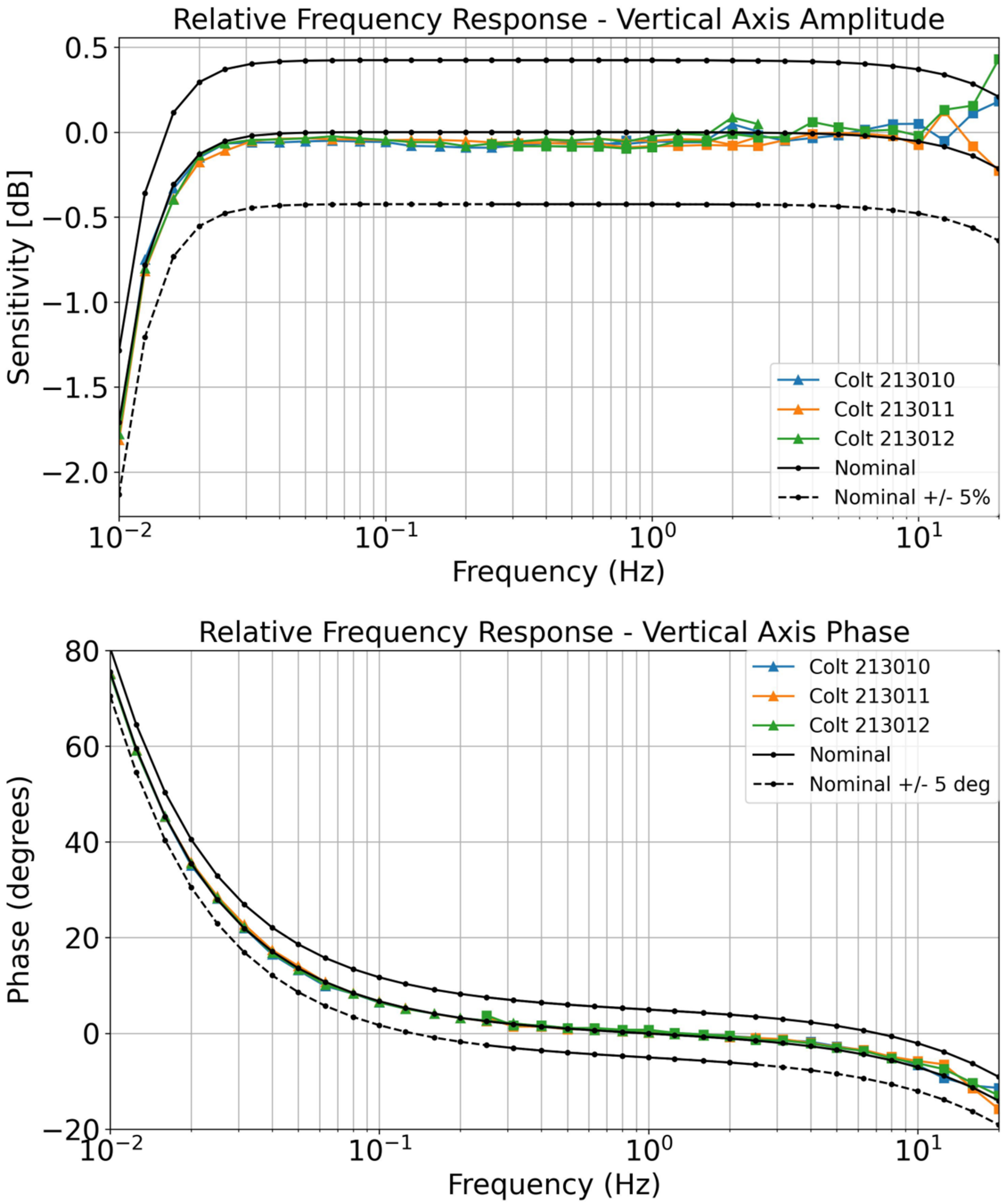
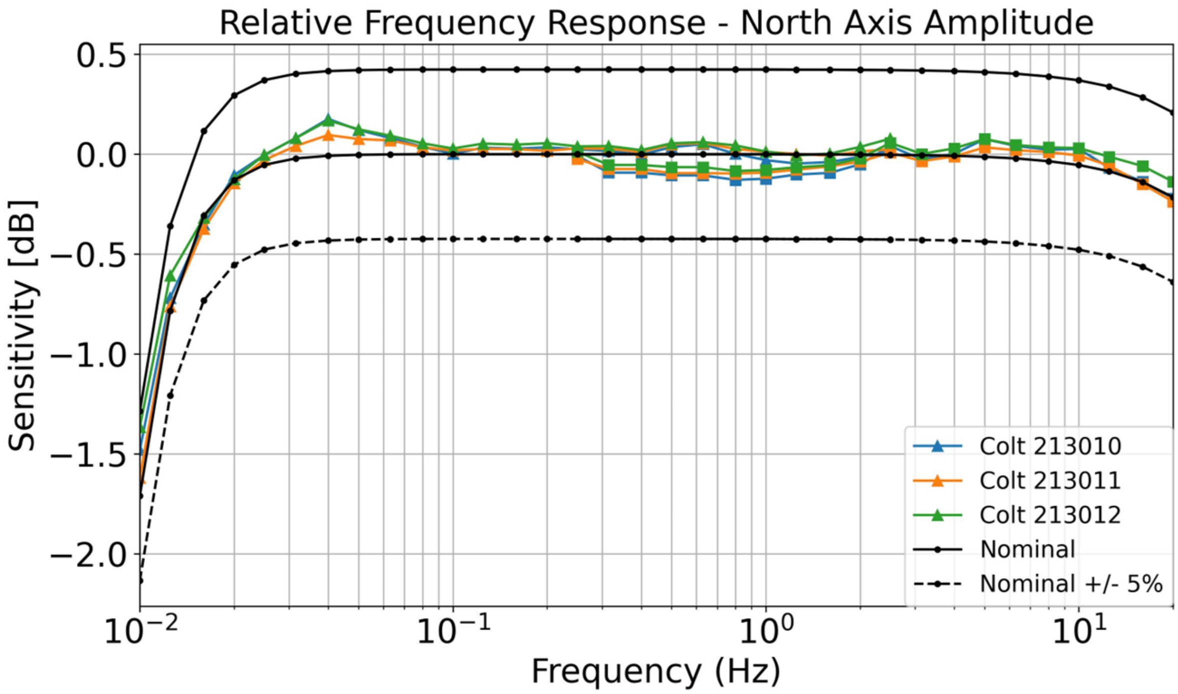


Figure 33 Vertical Axis Reference Frequency Response



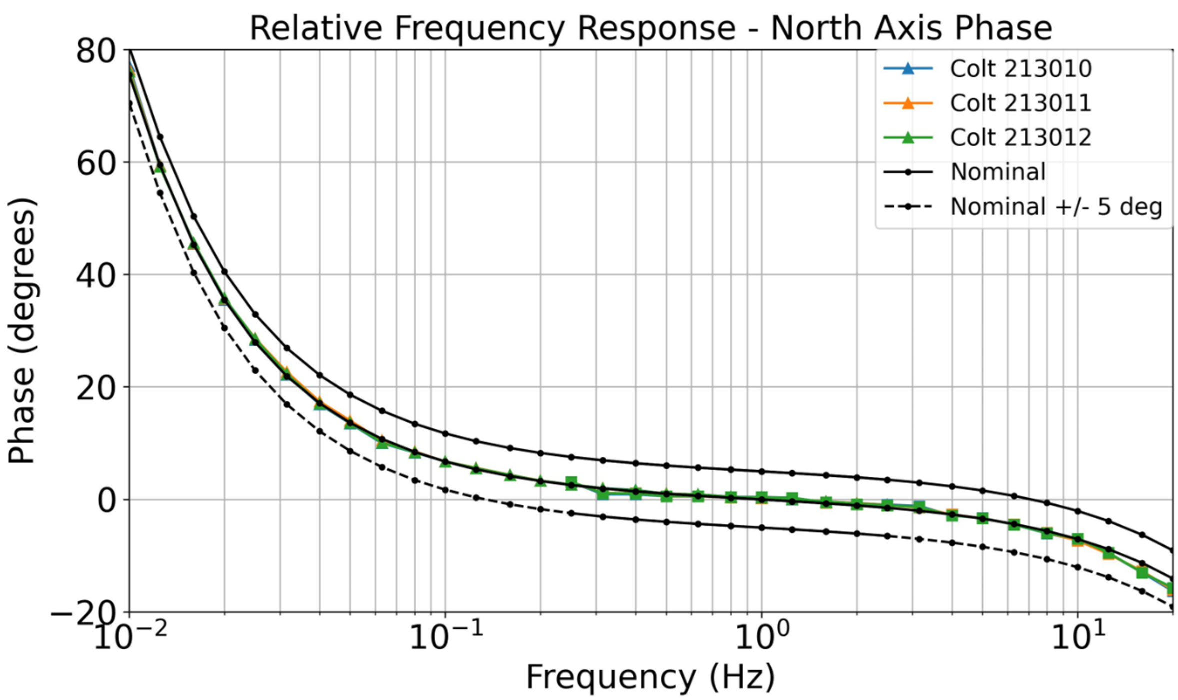
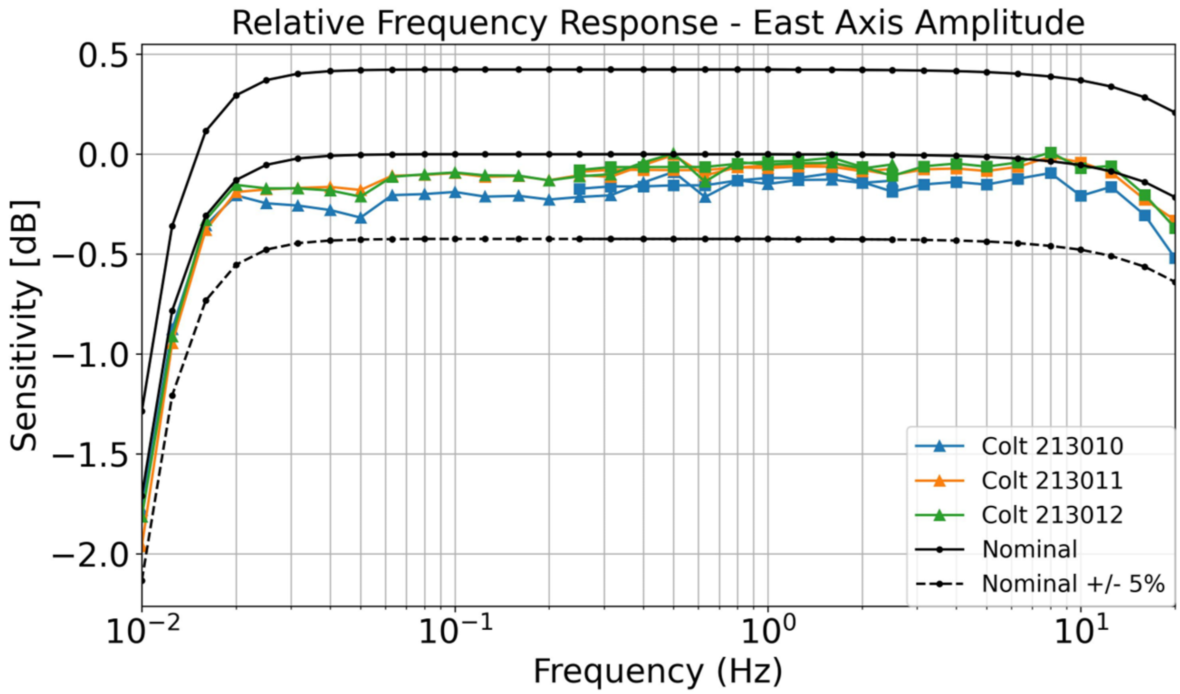


Figure 34 North/South Axis Reference Frequency Response



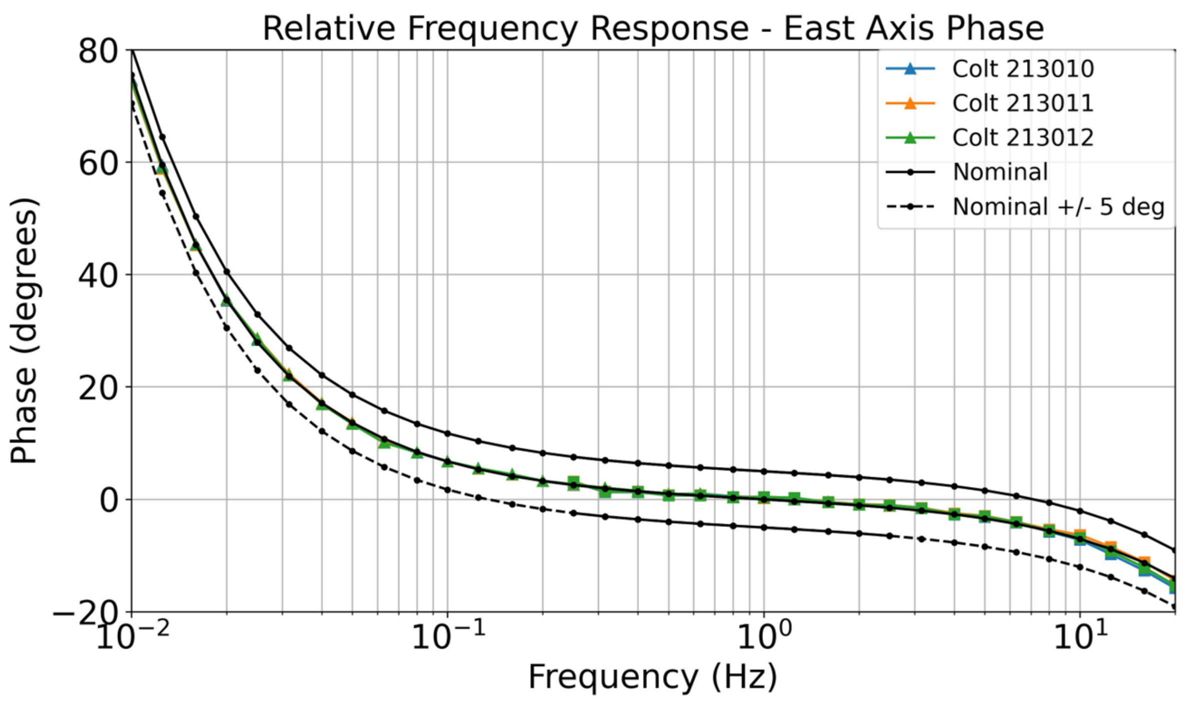


Figure 35 East/West Axis Reference Frequency Response

The above figures show that for almost all evaluated frequencies, the measured amplitude responses of the three Colt sensors closely match the nominal response model. The only exception is the vertical axis amplitude response above 10Hz for sensors 213010 and 213012. Above 10Hz both sensors' amplitude response diverges from the nominal and at 20Hz the measured amplitude response is more than 5% larger than nominal. This same pattern is not seen in the North-South or East-West axis. For the horizontal axis, the agreement between measured response and nominal response is excellent even at 20Hz. The discrepancy between the vertical axis amplitude response and horizontal axis response can be explained by more closely examining the coherency between the reference STS-2 sensor and the Colts for frequencies above 10Hz. Figure 36, below, shows how the vertical axis coherency begins to drop above 10Hz while the Horizontal axis coherency remains high. This drop in vertical axis coherency means that the measured amplitude response may not be accurate and may not properly represent the Colt's response above 10Hz.

The measured relative phase response of the three Colts closely matches the nominal response model for all evaluated frequencies.

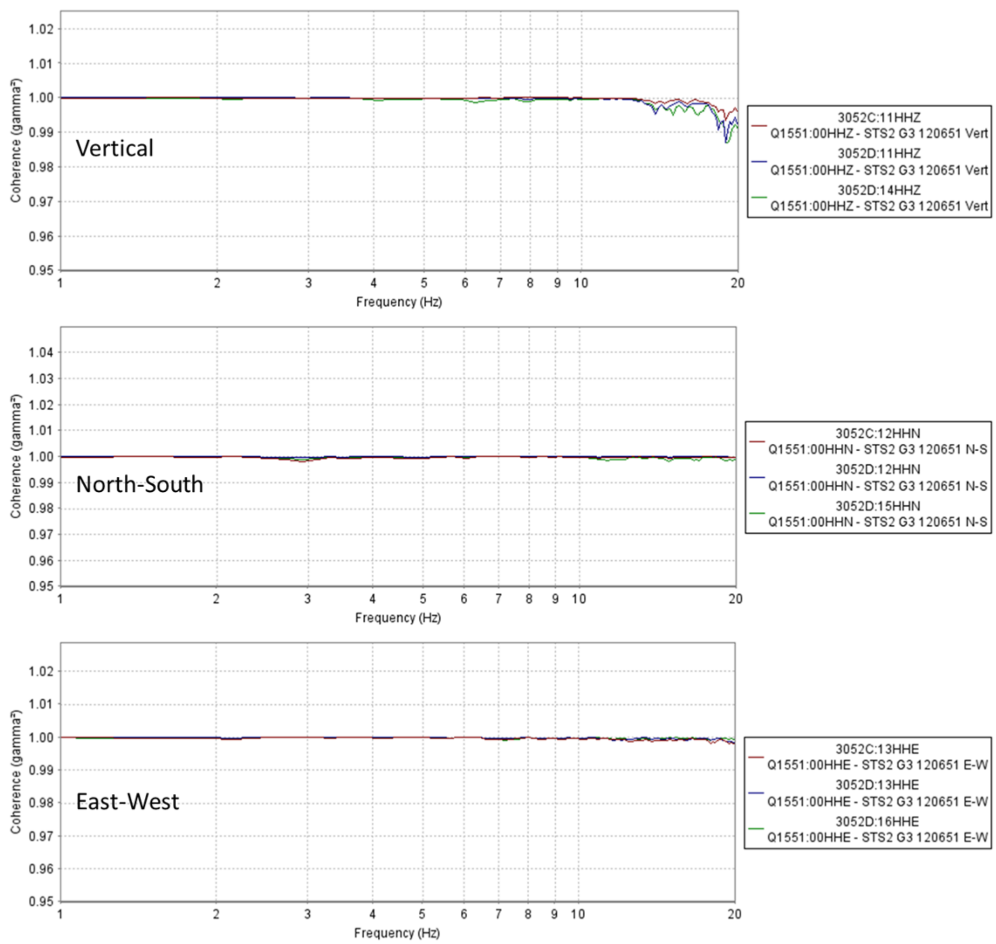


Figure 36 Coherency between reference STS-2 and Colts for M4.0 West Texas Event (1Hz to 20Hz)

The data used to generate the relative response figures are summarized in the tables below, in dB relative to the nominal sensitivity at 1 Hz for amplitude and degrees for phase.

Table 20 Reference Vertical Response using M4.0 Event

Relative Vertical Response for M4.0 West Texas Earthquake								
	Vertical Amplitude Response				Vertical Phase Response			
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Colt 213010 (degrees)	Colt 213011 (degrees)	Colt 213012 (degrees)	Nominal (degrees)
0.25	-0.07	-0.07	-0.07	0.00	3.58	3.25	3.76	2.52
0.32	-0.08	-0.06	-0.08	0.00	1.69	1.41	1.66	1.92
0.40	-0.08	-0.06	-0.08	0.00	1.69	1.41	1.66	1.40
0.50	-0.08	-0.07	-0.08	0.00	0.96	0.85	1.10	0.99
0.63	-0.08	-0.07	-0.08	0.00	0.96	0.85	1.10	0.62
0.80	-0.05	-0.09	-0.10	0.00	0.64	0.42	0.74	0.27
1.00	-0.05	-0.08	-0.09	0.00	0.64	0.42	0.74	-0.04
1.25	-0.06	-0.08	-0.05	0.00	0.08	-0.02	0.09	-0.36
1.60	-0.06	-0.08	-0.05	0.00	-0.24	-0.36	-0.24	-0.73
2.00	-0.01	-0.08	-0.01	0.00	-0.49	-0.62	-0.48	-1.10
2.50	-0.02	-0.08	-0.03	0.00	-1.28	-0.97	-1.39	-1.52
3.15	-0.05	-0.05	-0.03	0.00	-1.44	-1.21	-1.47	-2.04
4.00	-0.03	-0.01	0.06	-0.01	-1.76	-1.99	-2.11	-2.70
5.00	-0.02	0.00	0.03	-0.01	-2.71	-2.87	-2.99	-3.45
6.30	0.02	-0.01	0.01	-0.02	-3.54	-3.44	-3.68	-4.40
8.00	0.05	-0.02	0.01	-0.03	-4.92	-4.91	-5.22	-5.64
10.00	0.05	-0.08	-0.02	-0.05	-6.65	-5.76	-6.27	-7.07
12.50	-0.05	0.12	0.13	-0.09	-9.35	-6.48	-7.46	-8.85
16.00	0.11	-0.08	0.16	-0.14	-10.92	-11.46	-10.37	-11.32
20.00	0.18	-0.23	0.43	-0.22	-11.41	-15.82	-12.98	-14.09

Table 21 Reference North-South Response using M4.0 Event

Relative North-South Response for M4.0 West Texas Earthquake								
	North-South Amplitude Response				North-South Phase Response			
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Colt 213010 (degrees)	Colt 213011 (degrees)	Colt 213012 (degrees)	Nominal (degrees)
0.25	-0.01	-0.02	0.01	0.00	3.07	3.04	3.12	2.52
0.32	-0.09	-0.07	-0.05	0.00	0.88	1.10	1.06	1.92
0.40	-0.09	-0.07	-0.05	0.00	0.88	1.10	1.06	1.40
0.50	-0.11	-0.09	-0.06	0.00	0.51	0.52	0.56	0.99
0.63	-0.11	-0.09	-0.06	0.00	0.51	0.52	0.56	0.62
0.80	-0.13	-0.10	-0.08	0.00	0.37	0.31	0.38	0.27
1.00	-0.12	-0.09	-0.08	0.00	0.37	0.31	0.38	-0.04
1.25	-0.10	-0.08	-0.07	0.00	0.28	0.09	0.25	-0.36
1.60	-0.09	-0.06	-0.06	0.00	-0.57	-0.57	-0.57	-0.73
2.00	-0.05	-0.04	-0.02	0.00	-0.91	-0.91	-0.91	-1.10
2.50	0.04	0.01	0.06	0.00	-0.93	-1.08	-1.09	-1.52
3.15	-0.03	-0.03	0.00	0.00	-1.21	-1.46	-1.37	-2.04
4.00	0.00	-0.01	0.03	-0.01	-2.87	-2.70	-2.87	-2.70
5.00	0.08	0.03	0.08	-0.01	-3.32	-3.38	-3.36	-3.45
6.30	0.04	0.02	0.05	-0.02	-4.51	-4.46	-4.51	-4.40
8.00	0.02	0.01	0.03	-0.03	-6.06	-5.96	-5.99	-5.64
10.00	0.03	-0.01	0.03	-0.05	-7.25	-7.33	-7.00	-7.07
12.50	-0.07	-0.06	-0.01	-0.09	-9.62	-9.72	-9.47	-8.85
16.00	-0.14	-0.15	-0.06	-0.14	-13.02	-12.77	-13.05	-11.32
20.00	-0.22	-0.24	-0.14	-0.22	-16.34	-16.12	-15.74	-14.09

Table 22 Reference East-West Response using M4.0 Event

Relative East-West Response for M4.0 West Texas Earthquake								
	East-West Amplitude Response				East-West Phase Response			
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Colt 213010 (degrees)	Colt 213011 (degrees)	Colt 213012 (degrees)	Nominal (degrees)
0.25	-0.17	-0.09	-0.08	0.00	3.03	3.15	3.06	2.52
0.32	-0.16	-0.08	-0.06	0.00	1.25	1.36	1.30	1.92
0.40	-0.16	-0.08	-0.06	0.00	1.25	1.36	1.30	1.40
0.50	-0.16	-0.08	-0.06	0.00	0.67	0.72	0.67	0.99
0.63	-0.16	-0.08	-0.06	0.00	0.67	0.72	0.67	0.62
0.80	-0.13	-0.07	-0.05	0.00	0.39	0.41	0.39	0.27
1.00	-0.12	-0.06	-0.04	0.00	0.39	0.41	0.39	-0.04
1.25	-0.12	-0.06	-0.03	0.00	0.23	0.20	0.24	-0.36
1.60	-0.10	-0.05	-0.02	0.00	-0.53	-0.50	-0.56	-0.73
2.00	-0.14	-0.08	-0.06	0.00	-0.94	-0.88	-0.98	-1.10
2.50	-0.19	-0.10	-0.11	0.00	-1.09	-1.04	-1.07	-1.52
3.15	-0.15	-0.08	-0.06	0.00	-1.50	-1.54	-1.59	-2.04
4.00	-0.14	-0.07	-0.05	-0.01	-2.70	-2.49	-2.67	-2.70
5.00	-0.15	-0.08	-0.06	-0.01	-3.14	-2.97	-3.05	-3.45
6.30	-0.12	-0.06	-0.04	-0.02	-4.17	-4.05	-4.10	-4.40
8.00	-0.09	-0.01	0.01	-0.03	-5.80	-5.37	-5.61	-5.64
10.00	-0.21	-0.04	-0.07	-0.05	-7.23	-6.35	-6.85	-7.07
12.50	-0.16	-0.09	-0.06	-0.09	-9.78	-8.48	-9.24	-8.85
16.00	-0.30	-0.23	-0.20	-0.14	-12.73	-11.18	-12.18	-11.32
20.00	-0.52	-0.33	-0.37	-0.22	-15.84	-14.44	-15.33	-14.09

Table 23 Reference Vertical Response using M7.6 Event

Relative Vertical Response for M7.6 Philippines Earthquake								
	Vertical Amplitude Response				Vertical Phase Response			
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Colt 213010 (degrees)	Colt 213011 (degrees)	Colt 213012 (degrees)	Nominal (degrees)
0.010	-1.776	-1.813	-1.778	-1.709	75.288	75.228	75.017	75.458
0.013	-0.750	-0.818	-0.801	-0.783	59.051	59.177	59.048	59.482
0.016	-0.332	-0.391	-0.397	-0.308	45.174	45.283	45.310	45.295
0.020	-0.149	-0.177	-0.138	-0.129	35.056	35.767	35.449	35.476
0.025	-0.067	-0.110	-0.066	-0.053	28.158	28.640	28.277	27.920
0.032	-0.061	-0.052	-0.046	-0.021	21.934	22.730	22.127	21.892
0.040	-0.060	-0.039	-0.042	-0.008	16.477	17.396	16.788	17.090
0.050	-0.054	-0.036	-0.037	-0.003	13.165	14.071	13.365	13.592
0.063	-0.051	-0.042	-0.024	-0.001	9.876	10.705	10.134	10.735
0.080	-0.055	-0.043	-0.037	0.000	8.280	8.431	8.294	8.413
0.100	-0.058	-0.047	-0.046	0.000	6.421	6.670	6.515	6.696
0.125	-0.081	-0.045	-0.058	0.000	5.149	5.302	5.120	5.320
0.160	-0.084	-0.046	-0.060	0.000	4.091	4.083	4.124	4.109
0.200	-0.091	-0.051	-0.083	0.000	3.197	3.171	3.198	3.235
0.250	-0.091	-0.060	-0.068	0.000	2.645	2.556	2.648	2.523
0.315	-0.078	-0.057	-0.055	0.000	2.042	1.899	2.078	1.918
0.400	-0.065	-0.048	-0.042	0.000	1.452	1.451	1.530	1.402
0.500	-0.062	-0.052	-0.049	0.000	1.077	0.994	1.091	0.992
0.630	-0.067	-0.039	-0.037	0.000	0.656	0.698	0.659	0.620
0.800	-0.069	-0.048	-0.056	0.000	0.410	0.439	0.459	0.271
1.000	-0.055	-0.052	-0.025	0.000	0.172	0.124	0.179	-0.041
1.250	-0.057	-0.041	-0.009	-0.001	-0.148	-0.138	-0.184	-0.356
1.600	-0.047	-0.045	-0.017	-0.001	-0.392	-0.439	-0.435	-0.725
2.000	0.048	-0.075	0.087	-0.002	-0.580	-0.811	-0.610	-1.096
2.500	0.003	-0.027	0.047	-0.003	-0.872	-1.221	-1.106	-1.521

Table 24 Reference North-South Response using M7.6 Event

Relative North-South Response for M7.6 Philippines Earthquake								
	North-South Amplitude Response				North-South Phase Response			
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Colt 213010 (degrees)	Colt 213011 (degrees)	Colt 213012 (degrees)	Nominal (degrees)
0.010	-1.480	-1.620	-1.364	-1.709	77.069	76.497	76.086	75.458
0.013	-0.720	-0.761	-0.606	-0.783	59.413	59.322	59.157	59.482
0.016	-0.352	-0.374	-0.318	-0.308	45.370	45.490	45.648	45.295
0.020	-0.105	-0.144	-0.125	-0.129	35.444	35.649	35.776	35.476
0.025	-0.004	-0.029	-0.003	-0.053	28.359	28.641	28.553	27.920
0.032	0.081	0.042	0.080	-0.021	22.124	22.657	22.301	21.892
0.040	0.177	0.096	0.169	-0.008	16.896	17.390	17.007	17.090
0.050	0.121	0.076	0.125	-0.003	13.482	13.984	13.592	13.592
0.063	0.082	0.069	0.093	-0.001	9.970	10.468	10.076	10.735
0.080	0.037	0.035	0.055	0.000	8.302	8.483	8.367	8.413
0.100	0.003	0.019	0.029	0.000	6.717	6.717	6.725	6.696
0.125	0.032	0.027	0.053	0.000	5.489	5.591	5.537	5.320
0.160	0.028	0.025	0.048	0.000	4.322	4.334	4.317	4.109
0.200	0.034	0.017	0.055	0.000	3.291	3.299	3.281	3.235
0.250	0.024	0.029	0.039	0.000	2.597	2.594	2.614	2.523
0.315	0.016	0.027	0.041	0.000	1.951	1.931	1.962	1.918
0.400	-0.002	0.011	0.020	0.000	1.651	1.552	1.591	1.402
0.500	0.035	0.050	0.055	0.000	0.977	1.003	0.962	0.992
0.630	0.050	0.056	0.060	0.000	0.845	0.827	0.859	0.620
0.800	0.002	0.026	0.044	0.000	0.433	0.419	0.415	0.271
1.000	-0.030	0.012	0.014	0.000	0.404	0.193	0.301	-0.041
1.250	-0.047	0.001	-0.006	-0.001	-0.050	0.044	0.005	-0.356
1.600	-0.039	-0.008	0.003	-0.001	-0.430	-0.414	-0.389	-0.725
2.000	-0.013	0.014	0.036	-0.002	-0.718	-0.672	-0.745	-1.096
2.500	0.013	0.025	0.078	-0.003	-0.973	-1.001	-1.057	-1.521

Table 25 Reference East-West Response using M7.6 Event

Relative East-West Response for M7.6 Philippines Earthquake								
	East-West Amplitude Response				East-West Phase Response			
Frequency (Hz)	Colt 213010 [dB]	Colt 213011 [dB]	Colt 213012 [dB]	Nominal [dB]	Colt 213010 (degrees)	Colt 213011 (degrees)	Colt 213012 (degrees)	Nominal (degrees)
0.010	-1.780	-1.960	-1.814	-1.709	74.735	74.135	74.425	75.458
0.013	-0.876	-0.946	-0.911	-0.783	59.392	58.770	59.070	59.482
0.016	-0.356	-0.379	-0.328	-0.308	45.280	45.211	45.298	45.295
0.020	-0.206	-0.189	-0.153	-0.129	35.312	35.495	35.561	35.476
0.025	-0.246	-0.176	-0.171	-0.053	28.363	28.654	28.548	27.920
0.032	-0.257	-0.169	-0.171	-0.021	22.084	22.292	22.043	21.892
0.040	-0.279	-0.163	-0.181	-0.008	17.095	17.135	16.913	17.090
0.050	-0.317	-0.179	-0.212	-0.003	13.608	13.682	13.372	13.592
0.063	-0.205	-0.108	-0.113	-0.001	10.203	10.308	10.032	10.735
0.080	-0.199	-0.104	-0.101	0.000	8.258	8.364	8.358	8.413
0.100	-0.189	-0.094	-0.091	0.000	6.711	6.742	6.728	6.696
0.125	-0.212	-0.113	-0.106	0.000	5.465	5.417	5.515	5.320
0.160	-0.208	-0.109	-0.107	0.000	4.362	4.371	4.410	4.109
0.200	-0.227	-0.130	-0.131	0.000	3.223	3.216	3.268	3.235
0.250	-0.214	-0.105	-0.111	0.000	2.518	2.584	2.647	2.523
0.315	-0.206	-0.113	-0.100	0.000	1.872	1.922	2.018	1.918
0.400	-0.142	-0.054	-0.041	0.000	1.311	1.378	1.476	1.402
0.500	-0.088	-0.004	0.004	0.000	0.857	0.898	0.909	0.992
0.630	-0.214	-0.106	-0.137	0.000	0.983	0.842	0.926	0.620
0.800	-0.130	-0.065	-0.039	0.000	0.496	0.358	0.336	0.271
1.000	-0.149	-0.069	-0.052	0.000	0.251	0.197	0.287	-0.041
1.250	-0.129	-0.062	-0.045	-0.001	-0.014	-0.058	-0.045	-0.356
1.600	-0.127	-0.062	-0.042	-0.001	-0.496	-0.517	-0.552	-0.725
2.000	-0.144	-0.085	-0.072	-0.002	-0.955	-0.910	-0.977	-1.096
2.500	-0.132	-0.073	-0.051	-0.003	-1.182	-1.153	-1.124	-1.521

3.7 Passband

The passband of a sensor is defined to be the frequency range over which the sensor can measure with a nominally constant sensitivity. The upper and lower frequency bounds of the passband are defined as the points at which the sensors amplitude response is 3 dB below, or 0.707x of, the measured sensitivity at a given frequency. This definition of passband is consistent with the definition of bandwidth for digitizers (IEEE Std 1241-2000 section 4.7.1).

3.5.5 Measurand

The upper and lower frequency bounds of the passband are defined as the points at which the sensors amplitude response is 3 dB below, or 0.707x of, the measured sensitivity at 1Hz.

3.5.6 Configuration

There is no test configuration for the passband test. The amplitude response used in computing the passband is determined in section 3.5.

3.5.7 Analysis

The passband limits are determined by interpolating between frequency points at which the amplitude response was measured to determine the frequencies at which the amplitude response is 3 dB below, or 0.707x of, the sensitivity at the calibration frequency.

3.5.8 Result

The following table contains the passband limits of the Colt sensors.

Table 26 Passband

	Lower Limit	Upper Limit
Colt 213010 (all axes)	<0.02	> 20 Hz
Colt 213011 (all axes)	<0.02	> 20 Hz
Colt 213012 (all axes)	<0.02	> 20 Hz

All the Colt sensors had -3dB low frequency corners below 0.02Hz and -3dB high frequency corners above 20Hz. This was true for the vertical, north-south, and east-west axes of the sensors.

3.6 Sensitivity vs Power Supply Voltage

The sensitivity vs power supply voltage test investigates if the sensor's performance is dependent on the input voltage supplied to the instrument. The seismometer is installed on a vertical shake table and connected to a laboratory DC power supply. The sensor is then operated at different voltages ranging from the minimum specified operating voltage to the maximum. At each input voltage setpoint, the seismometer is calibrated at 1Hz and 10Hz.

3.6.1 Measurand

The quantity being measured is the change in ground motion sensitivity as a function of the sensor's power supply voltage. The amplitude response of the sensor at different power supply voltages is expressed with units of dB and is normalized using the sensor's nominal amplitude response at 1Hz. The phase response of the sensor at different input voltages is expressed with units of degrees.

3.6.2 Configuration

The sensor is placed on a vertical seismic calibration table and subjected to a sinusoidal velocity at 1Hz and then at 10Hz. The amplitude of the input signal is set to 10% of the sensor's specified full-scale velocity. This calibration is repeated as the input voltage provided to the seismometer is varied from the minimum specified operating voltage up to the maximum (or up to 30V which is the limit of the laboratory DC power supply). The Spektra CS-18P system records the output of the seismometer and the reference laser vibrometer and calculates the 1Hz and 10Hz amplitude response and phase response of the sensor.

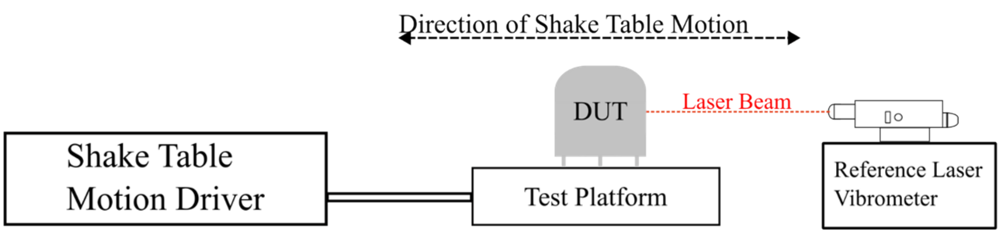


Figure 37 Sensitivity vs Input Voltage Configuration Diagram

Table 27 Sensitivity vs Input Voltage Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.00 mm/s Power Supply Voltage = 9V to 18V Frequency = 1Hz and 10Hz Pressure = 819.0 ± 2.1hPa Temperature = 22.5 ± 1.0C Humidity = 25.8 ± 1.9%

3.6.3 Analysis

The Spektra seismometer calibrator performs the analysis of data internally by fitting a sine function to both the sensor output and a primary measurement of the sensor displacement, which is converted to velocity.

The sensor amplitude sensitivity in Volts / (m/s) is computed for each frequency that the Spektra system operates at:

$$Sensitivity = \frac{Voltage_{SUT}}{Velocity_{Laser}}$$

The sensor phase sensitivity in degrees is likewise computed for each operational frequency:

$$Phase = \theta_{SUT} - \theta_{ref}$$

Upon completion of the frequency response test, the Spektra system generates a frequency, amplitude, and phase (FAP) table.

3.6.4 Result

The following figures shows the change in amplitude and phase for the three Colt sensors at 1 Hz and 10 Hz when the input voltage ranged from 9 V to 18 V. For the amplitude response plots, the amplitude data is shown with units of dB and has been normalized to the nominal 1 Hz sensitivity. Hence the nominal response curve in the following plots will have an amplitude response of 0 dB at 1 Hz. Note that there is a difference in the Colt's nominal phase response between 1 Hz and 10 Hz, which is why the plots of phase have a trend that this unrelated to any change due to the power supply voltage.

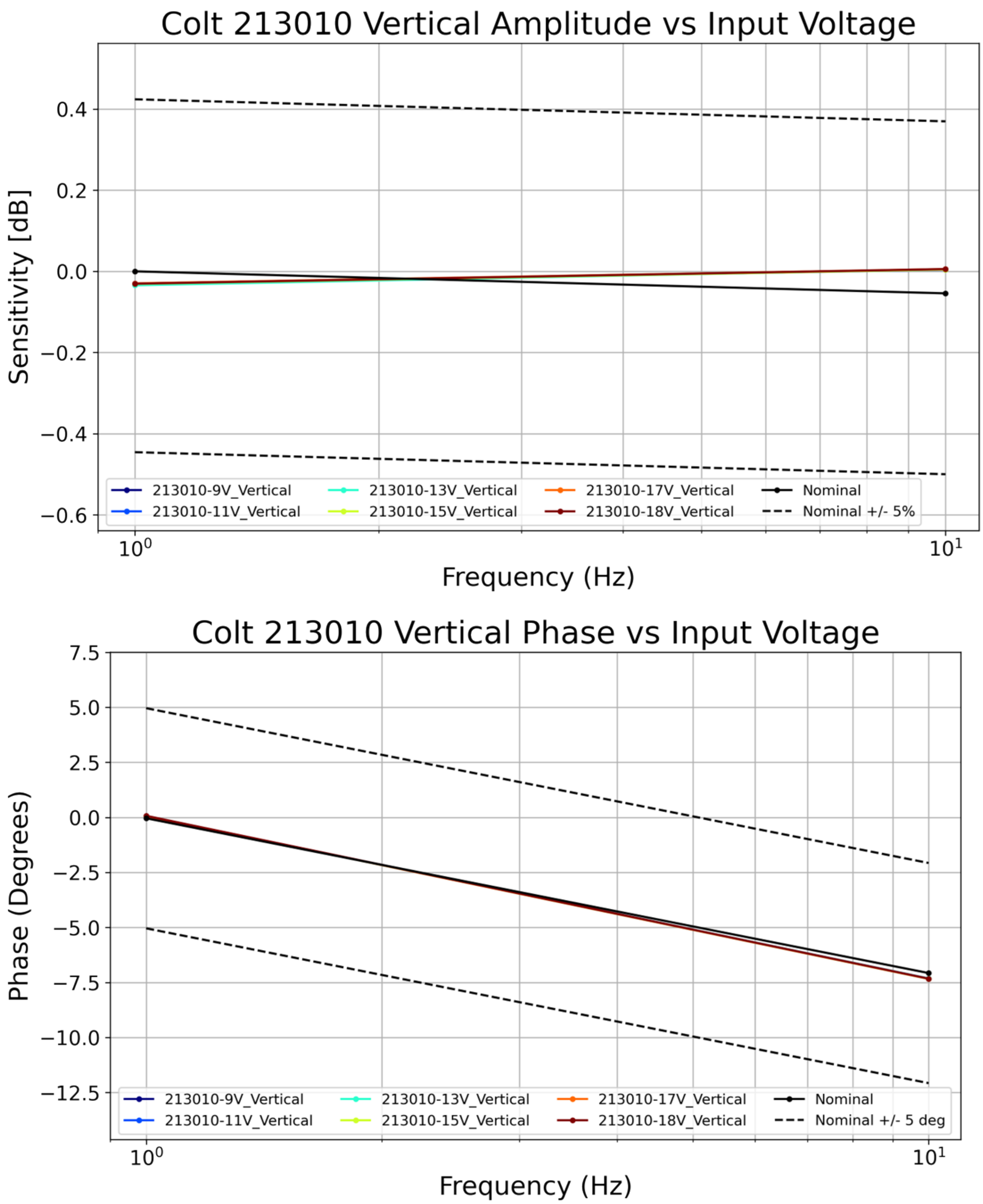


Figure 38 Colt 213010 Vertical Axis Response vs Input Voltage

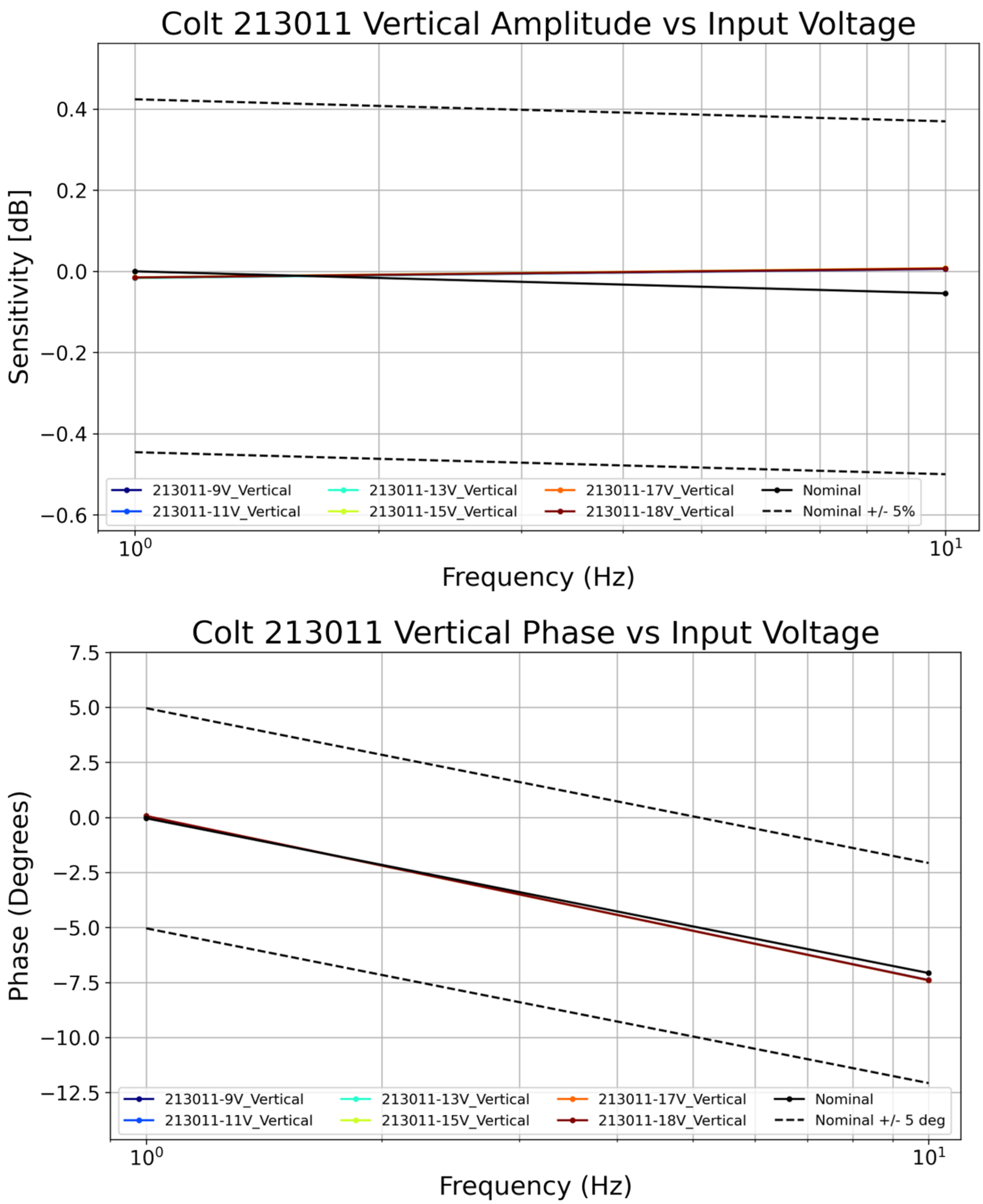
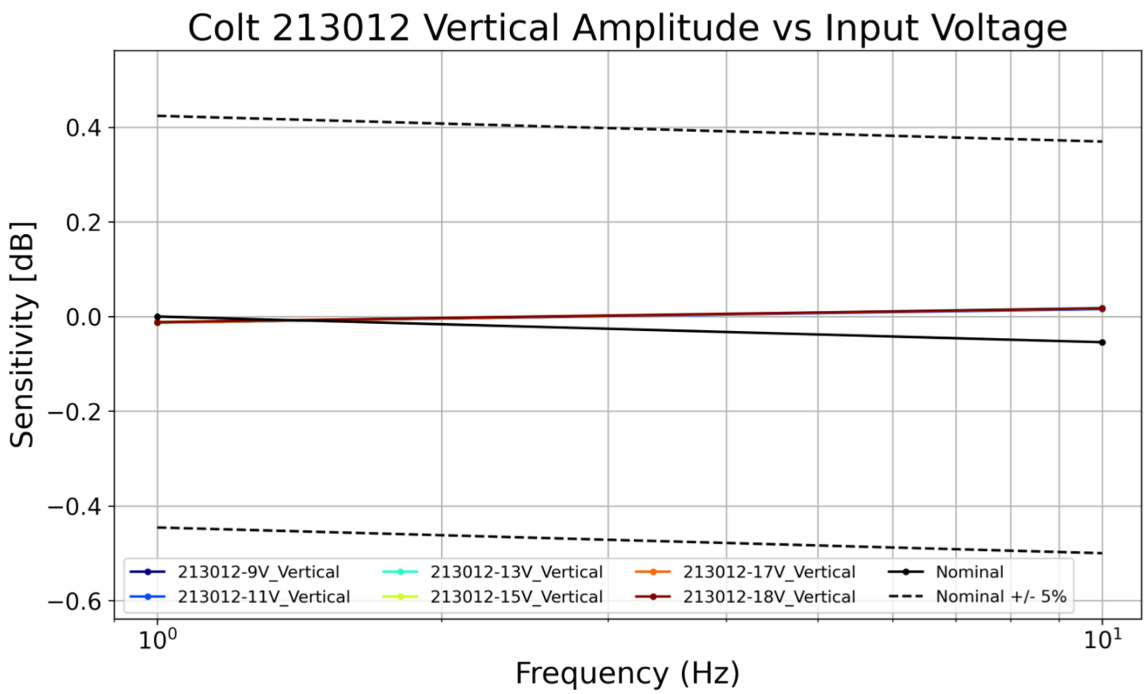


Figure 39 Colt 213011 Vertical Axis Response vs Input Voltage



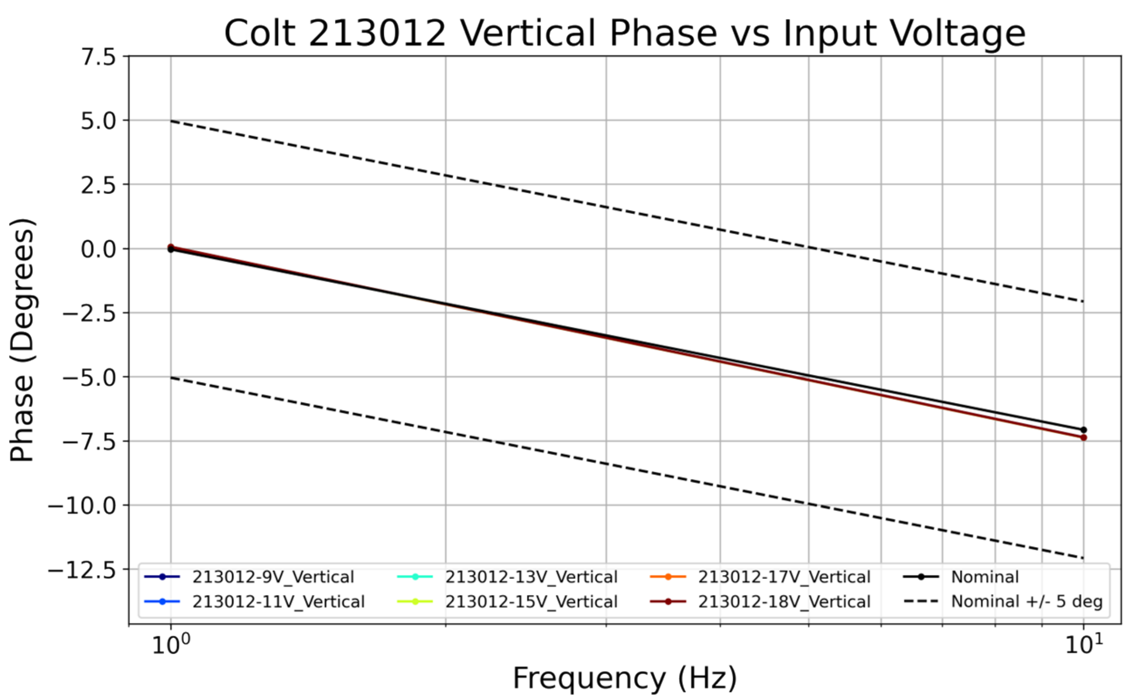


Figure 40 Colt 213012 Vertical Axis Response vs Input Voltage

We observe that there is no significant variation in the 1Hz and 10Hz amplitude or phase response due to changes in the power supply voltage from 9V to 18V.

The following tables contain the data used to generate the above plots. The k=2 measurement uncertainties at 1 Hz and 10Hz are 0.7% for amplitude and 1.0 degrees for phase.

Table 28 Change in Response vs Power Supply Voltage

Response vs Input Voltage - Vertical Axis				
Colt 213010				
	1Hz		10Hz	
Power Supply Voltage	Amplitude (V/(m/s))	Phase (degrees)	Amplitude (V/(m/s))	Phase (degrees)
9	2004.85	0.06	2013.00	-7.33
11	2004.90	0.06	2012.70	-7.32
13	2003.85	0.06	2013.00	-7.32
15	2004.65	0.06	2012.80	-7.34
17	2004.95	0.06	2013.10	-7.33
18	2004.75	0.07	2013.10	-7.33
Nominal	2011.81	-0.04	1999.28	-7.07
Colt 213011				
	1Hz		10Hz	
Power Supply Voltage	Amplitude (V/(m/s))	Phase (degrees)	Amplitude (V/(m/s))	Phase (degrees)
9	1997.20	0.04	2002.30	-7.39
11	1997.20	0.05	2002.40	-7.40
13	1997.15	0.05	2002.60	-7.40
15	1997.55	0.06	2002.80	-7.40
17	1997.45	0.05	2002.70	-7.40
18	1997.45	0.06	2002.50	-7.40
Nominal	2000.97	-0.04	1988.51	-7.07
Colt 213012				
	1Hz		10Hz	
Power Supply Voltage	Amplitude (V/(m/s))	Phase (degrees)	Amplitude (V/(m/s))	Phase (degrees)
9	1996.75	0.05	2003.60	-7.37
11	1996.75	0.06	2003.40	-7.36
13	1996.65	0.06	2004.00	-7.37
15	1997.15	0.05	2003.70	-7.37
17	1996.80	0.06	2003.70	-7.37
18	1997.10	0.06	2003.80	-7.37
Nominal	1999.81	-0.04	1987.36	-7.07

3.7 Sensitivity vs Input Amplitude

The sensitivity vs input amplitude test measures the linearity of the sensor's output with respect to the amplitude of the input signal. The seismometer is placed on a shake table and exposed to ground motion signals ranging from 10% to 98% of its specified full-scale input range. For each input amplitude step, the ground motion signal frequency is varied from 1Hz to 10Hz or greater.

3.7.1 Measurand

The quantity being measured is the change in sensitivity versus ground motion amplitude. The amplitude response of the sensor at different input amplitude levels is expressed with units of dB and is normalized using the sensor's nominal amplitude response at 1Hz. The phase response of the sensor at different input amplitude levels is expressed with units of degrees.

3.7.2 Configuration

The sensors are placed one at a time on a seismic calibration table and subjected to sinusoidal velocity signals. The sensors are tested at 10%, 15%, 25%, 50%, 75%, 90% and 98% of their full-scale velocity range. For each amplitude step, the sensors are calibrated from 1Hz to 10Hz or greater. The SPEKTRA CS-18P system records the output of the seismometer and the reference laser vibrometer and calculates the amplitude response and phase response of the sensor for each amplitude step. The vertical, north-south, and east-west axis of each sensor are independently evaluated.

The full-scale level of the Colt seismometer is specified as 10.0 mm/s up to 20Hz and then 125.6gal above 20Hz. The high frequency test limit was set to 10Hz for the 75%, 90% and 98% of full-scale tests to ensure that the sensors were not operated above the 125.6gal limit.

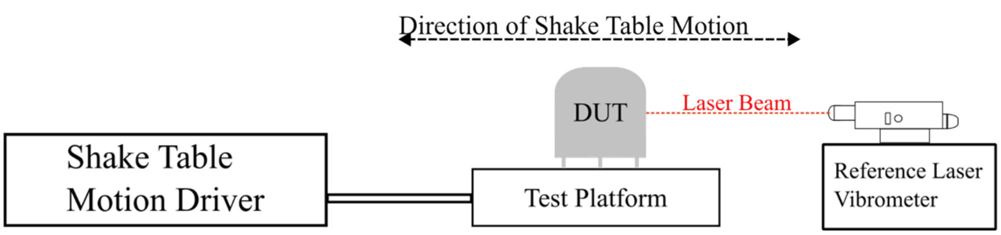


Figure 41 Sensitivity vs Input Amplitude Test Configuration

Table 29 Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.00 to 9.84 mm/s Input Voltage = 12V Frequency = 1Hz to >=10Hz Pressure = 823.1 ± 5.9hPa Temperature = 21.7 ± 3.7C Humidity = 18.3 ± 8.9%

3.7.3 Analysis

The Spektra seismometer calibrator performs the analysis of data internally by fitting a sine function to both the sensor output and a primary measurement of the sensor displacement, which is converted to velocity.

The sensor amplitude sensitivity in Volts / (m/s) is computed for each frequency that the Spektra system operates at:

$$Sensitivity = \frac{Voltage_{SUT}}{Velocity_{Laser}}$$

The sensor phase sensitivity in degrees is likewise computed for each operational frequency:

$$Phase = \theta_{SUT} - \theta_{ref}$$

Upon completion of the frequency response test, the Spektra system generates a frequency, amplitude, and phase (FAP) table.

3.7.4 Result

The figures below show how the amplitude and phase response of each axis of the three sensors changed with the input signal amplitude. These plots show data from 1Hz to 10Hz. The legend indicates the percent of full scale that each colored trace represents. When the input signal amplitude was less than 75% of full scale, the sensors were evaluated to 20Hz. This higher frequency data is included in the tables at the end of this section.

For the amplitude response plots, the amplitude data is shown with units of dB and has been normalized to the nominal 1Hz sensitivity. Hence the nominal response curve in the following plots will have an amplitude response of 0dB at 1Hz.

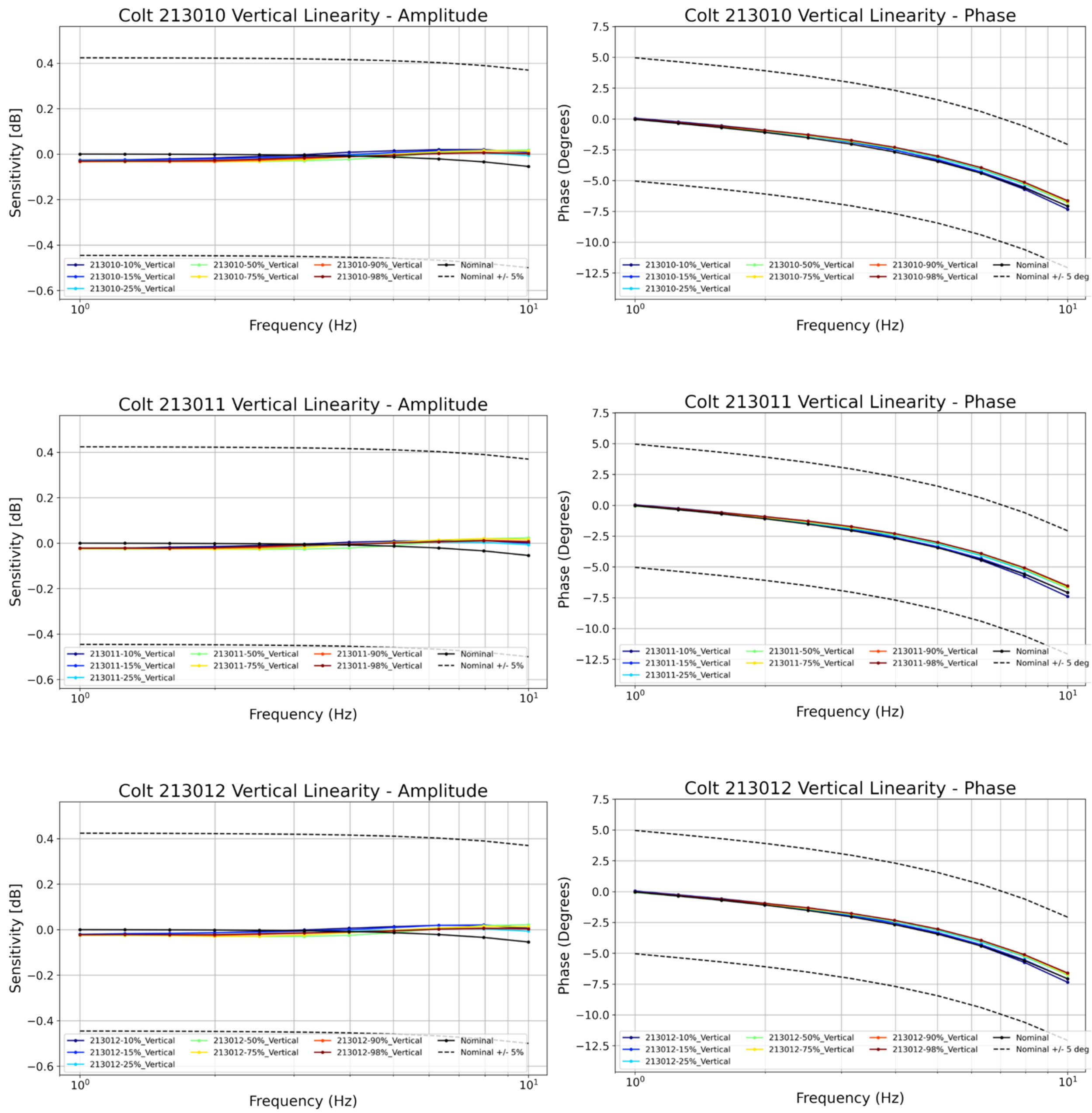


Figure 42 Change in Vertical Axis Response vs Input Signal Amplitude

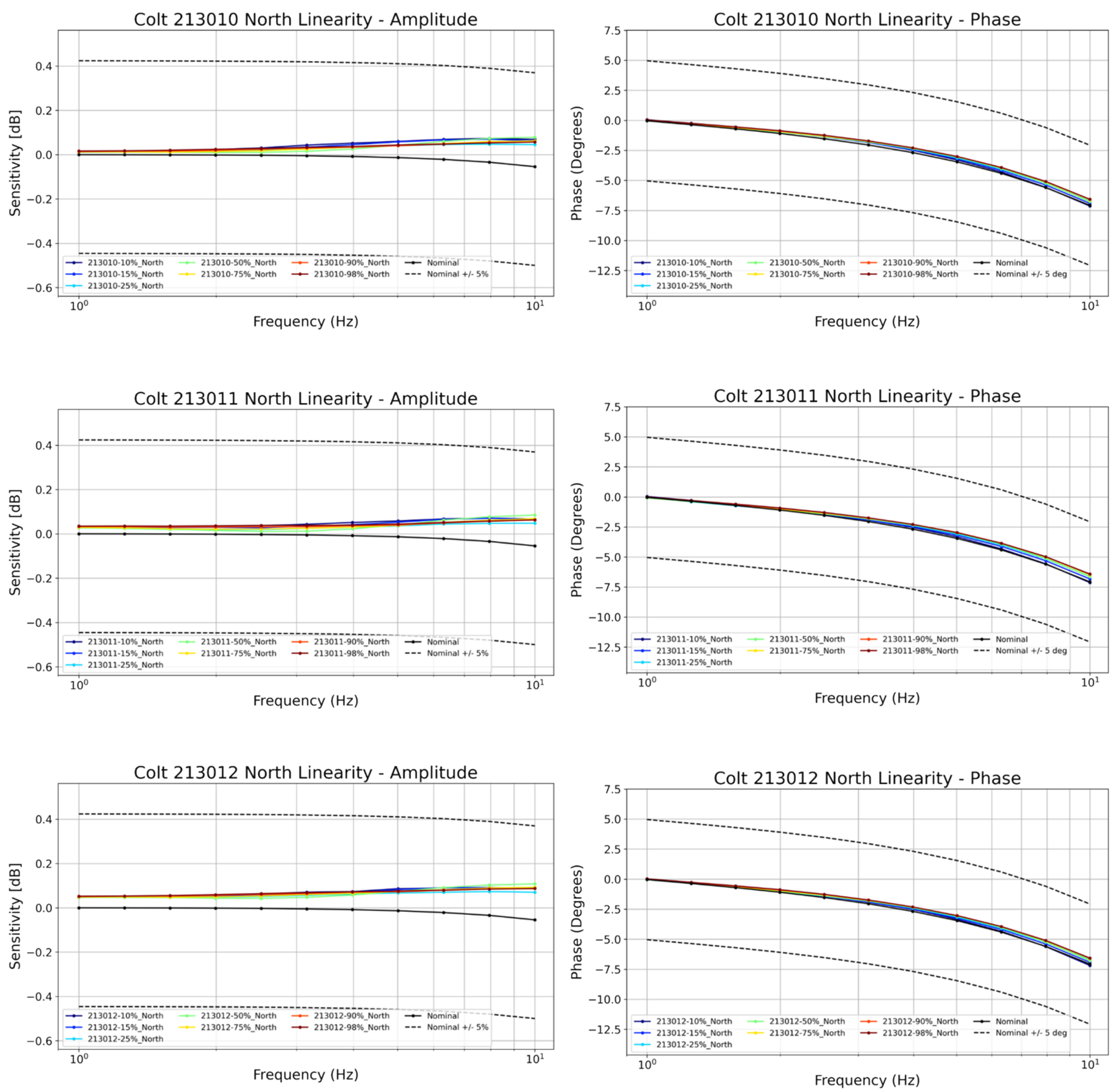


Figure 43 Change in North-South Axis Response vs Input Signal Amplitude

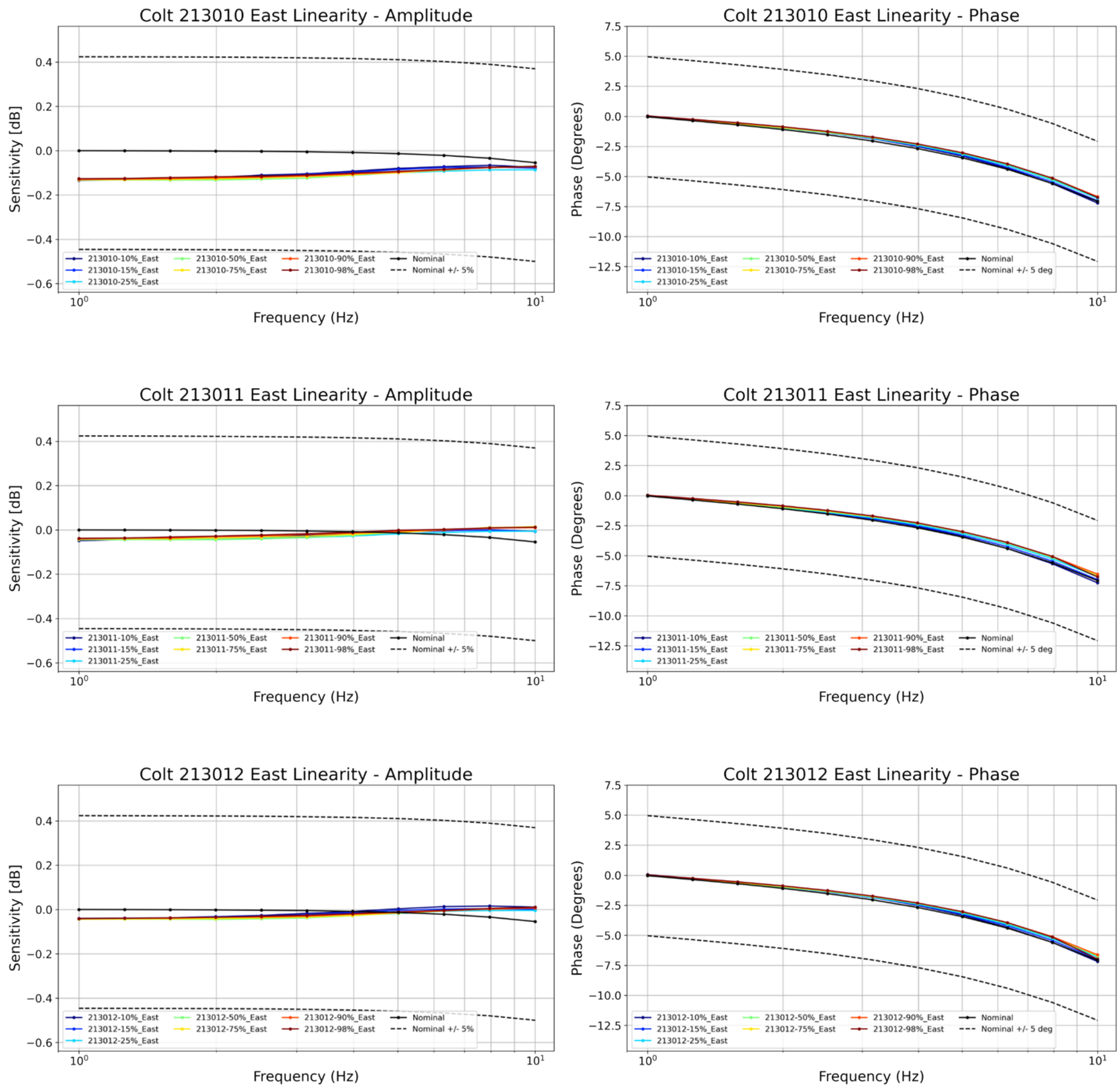


Figure 44 Change in East-West Axis Response vs Input Signal Amplitude

The above figures show that the Colt sensors had very little change in amplitude or phase response as the input amplitude signal level increased. The phase response of the sensors appeared to have a very small dependency on input signal amplitude at frequencies near 10Hz. Generally, the phase response was slightly smaller when the input signal was large. There was no discernable change in amplitude response with input signal level.

The following tables contain the values used to generate the above plots.

Table 30 Colt 213010 Response vs Input Amplitude

Colt 213010 - Response vs Input Amplitude														
Vertical Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	-0.03	0.06	-0.03	0.04	-0.03	0.02	-0.03	-0.04	-0.03	-0.01	-0.03	0.00	-0.03	0.01
1.26	-0.02	-0.23	-0.03	-0.27	-0.03	-0.31	-0.03	-0.34	-0.03	-0.30	-0.03	-0.29	-0.03	-0.28
1.59	-0.02	-0.55	-0.02	-0.59	-0.03	-0.65	-0.03	-0.63	-0.03	-0.61	-0.03	-0.60	-0.03	-0.59
2.00	-0.02	-0.91	-0.02	-0.96	-0.03	-1.01	-0.03	-0.96	-0.03	-0.96	-0.03	-0.93	-0.03	-0.92
2.51	-0.01	-1.34	-0.02	-1.40	-0.02	-1.41	-0.03	-1.35	-0.03	-1.33	-0.03	-1.30	-0.02	-1.28
3.16	0.00	-1.87	-0.01	-1.91	-0.02	-1.85	-0.03	-1.81	-0.02	-1.77	-0.02	-1.74	-0.02	-1.73
3.98	0.01	-2.52	0.00	-2.54	-0.01	-2.41	-0.02	-2.37	-0.01	-2.31	-0.01	-2.31	-0.01	-2.31
5.01	0.01	-3.35	0.01	-3.31	0.00	-3.15	-0.01	-3.08	0.00	-3.03	-0.01	-3.03	0.00	-3.03
6.31	0.02	-4.40	0.02	-4.29	0.01	-4.10	0.00	-4.01	0.01	-3.97	0.00	-3.96	0.00	-3.95
7.94	0.02	-5.71	0.02	-5.53	0.00	-5.30	0.02	-5.23	0.02	-5.18	0.01	-5.14	0.01	-5.13
10.00	0.01	-7.33	0.01	-7.09	-0.01	-6.80	0.02	-6.80	0.01	-6.71	0.00	-6.65	0.00	-6.63
12.59	-0.02	-9.34	-0.02	-9.02	-0.03	-8.64	0.01	-8.76	-	-	-	-	-	-
15.85	-0.06	-11.85	-0.06	-11.44	-0.07	-10.98	-0.03	-11.23	-	-	-	-	-	-
19.95	-0.13	-14.96	-0.12	-14.43	-0.13	-13.85	-0.09	-14.26	-	-	-	-	-	-
North-South Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	0.01	0.05	0.01	0.03	0.02	0.01	0.01	-0.02	0.01	0.01	0.01	0.02	0.02	0.04
1.26	0.02	-0.25	0.02	-0.27	0.01	-0.32	0.01	-0.32	0.01	-0.29	0.02	-0.27	0.02	-0.25
1.59	0.02	-0.56	0.02	-0.59	0.01	-0.65	0.01	-0.62	0.01	-0.60	0.02	-0.57	0.02	-0.55
2.00	0.02	-0.92	0.02	-0.96	0.02	-0.98	0.01	-0.97	0.01	-0.93	0.02	-0.89	0.02	-0.86
2.51	0.03	-1.33	0.03	-1.37	0.02	-1.34	0.01	-1.35	0.02	-1.30	0.02	-1.26	0.03	-1.25
3.16	0.04	-1.84	0.03	-1.85	0.03	-1.79	0.02	-1.80	0.02	-1.74	0.03	-1.72	0.03	-1.72
3.98	0.05	-2.49	0.04	-2.45	0.03	-2.38	0.03	-2.34	0.03	-2.30	0.03	-2.29	0.04	-2.29
5.01	0.06	-3.30	0.06	-3.19	0.04	-3.12	0.04	-3.05	0.04	-3.01	0.04	-3.01	0.04	-3.01
6.31	0.07	-4.30	0.07	-4.17	0.05	-4.05	0.06	-4.00	0.05	-3.94	0.05	-3.93	0.05	-3.93
7.94	0.07	-5.57	0.07	-5.38	0.05	-5.24	0.07	-5.22	0.06	-5.11	0.05	-5.09	0.05	-5.09
10.00	0.07	-7.14	0.06	-6.91	0.05	-6.73	0.08	-6.77	0.06	-6.61	0.06	-6.58	0.06	-6.57
12.59	0.05	-9.09	0.05	-8.81	0.03	-8.59	0.07	-8.71	-	-	-	-	-	-
15.85	0.02	-11.54	0.02	-11.16	0.01	-10.90	0.05	-11.12	-	-	-	-	-	-
19.95	-0.03	-14.55	-0.03	-14.08	-0.03	-13.79	0.00	-14.11	-	-	-	-	-	-
East-West Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	-0.13	0.04	-0.13	0.02	-0.13	0.00	-0.13	-0.03	-0.13	0.00	-0.13	0.01	-0.13	0.03
1.26	-0.13	-0.25	-0.13	-0.27	-0.13	-0.32	-0.13	-0.33	-0.13	-0.30	-0.13	-0.27	-0.13	-0.25
1.59	-0.12	-0.58	-0.12	-0.60	-0.13	-0.64	-0.13	-0.64	-0.13	-0.60	-0.13	-0.56	-0.12	-0.54
2.00	-0.12	-0.93	-0.12	-0.98	-0.13	-0.97	-0.13	-0.97	-0.13	-0.92	-0.12	-0.89	-0.12	-0.87
2.51	-0.11	-1.35	-0.12	-1.38	-0.12	-1.36	-0.13	-1.35	-0.12	-1.29	-0.12	-1.27	-0.12	-1.25
3.16	-0.10	-1.86	-0.11	-1.86	-0.12	-1.82	-0.12	-1.79	-0.12	-1.75	-0.11	-1.73	-0.11	-1.72
3.98	-0.09	-2.51	-0.10	-2.46	-0.11	-2.41	-0.11	-2.34	-0.11	-2.32	-0.11	-2.30	-0.10	-2.30
5.01	-0.08	-3.31	-0.09	-3.24	-0.10	-3.16	-0.10	-3.07	-0.10	-3.04	-0.10	-3.03	-0.09	-3.03
6.31	-0.07	-4.33	-0.08	-4.24	-0.09	-4.10	-0.09	-4.01	-0.09	-3.96	-0.09	-3.96	-0.08	-3.97
7.94	-0.07	-5.60	-0.07	-5.47	-0.09	-5.31	-0.07	-5.21	-0.08	-5.16	-0.08	-5.16	-0.07	-5.15
10.00	-0.07	-7.21	-0.08	-7.02	-0.09	-6.83	-0.07	-6.75	-0.07	-6.70	-0.07	-6.68	-0.07	-6.74
12.59	-0.09	-9.21	-0.09	-8.95	-0.10	-8.73	-0.08	-8.68	-	-	-	-	-	-
15.85	-0.12	-11.66	-0.12	-11.33	-0.12	-11.11	-0.10	-11.08	-	-	-	-	-	-
19.95	-0.17	-14.72	-0.17	-14.29	-0.16	-14.03	-0.14	-14.04	-	-	-	-	-	-

Table 31 Colt 213011 Response vs Input Amplitude

Colt 213011 - Response vs Input Amplitude														
Vertical Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	-0.03	0.04	-0.02	0.02	-0.02	0.01	-0.03	-0.07	-0.02	-0.02	-0.02	-0.01	-0.02	0.01
1.26	-0.02	-0.25	-0.02	-0.29	-0.02	-0.34	-0.03	-0.36	-0.02	-0.32	-0.02	-0.30	-0.02	-0.29
1.59	-0.02	-0.58	-0.02	-0.62	-0.02	-0.69	-0.03	-0.66	-0.03	-0.63	-0.02	-0.61	-0.02	-0.60
2.00	-0.01	-0.94	-0.02	-1.00	-0.03	-1.07	-0.03	-0.99	-0.03	-0.97	-0.02	-0.94	-0.02	-0.92
2.51	-0.01	-1.39	-0.02	-1.45	-0.02	-1.45	-0.03	-1.36	-0.03	-1.34	-0.02	-1.30	-0.01	-1.28
3.16	0.00	-1.92	-0.01	-1.98	-0.02	-1.89	-0.03	-1.82	-0.02	-1.77	-0.01	-1.74	-0.01	-1.73
3.98	0.00	-2.58	-0.01	-2.60	-0.01	-2.43	-0.02	-2.37	-0.01	-2.30	0.00	-2.29	0.00	-2.29
5.01	0.01	-3.41	0.00	-3.36	0.00	-3.16	-0.01	-3.06	0.00	-3.01	0.00	-3.00	0.00	-3.00
6.31	0.01	-4.47	0.01	-4.33	0.00	-4.08	0.01	-3.97	0.01	-3.93	0.01	-3.91	0.01	-3.91
7.94	0.01	-5.79	0.01	-5.55	0.00	-5.26	0.02	-5.17	0.02	-5.11	0.01	-5.08	0.01	-5.07
10.00	0.00	-7.40	0.00	-7.09	-0.01	-6.73	0.02	-6.72	0.02	-6.62	0.01	-6.56	0.01	-6.54
12.59	-0.03	-9.41	-0.02	-9.01	-0.03	-8.57	0.01	-8.68	-	-	-	-	-	-
15.85	-0.07	-11.91	-0.06	-11.41	-0.07	-10.86	-0.02	-11.11	-	-	-	-	-	-
19.95	-0.15	-15.04	-0.13	-14.39	-0.13	-13.71	-0.08	-14.11	-	-	-	-	-	-
North-South Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	0.03	0.04	0.03	-0.02	0.03	-0.04	0.03	-0.09	0.03	-0.04	0.03	-0.03	0.03	0.00
1.26	0.03	-0.29	0.03	-0.33	0.02	-0.41	0.02	-0.39	0.03	-0.36	0.03	-0.32	0.04	-0.30
1.59	0.03	-0.62	0.03	-0.66	0.02	-0.73	0.02	-0.70	0.02	-0.67	0.03	-0.63	0.03	-0.60
2.00	0.04	-0.98	0.03	-1.06	0.02	-1.06	0.02	-1.05	0.02	-1.00	0.03	-0.95	0.04	-0.92
2.51	0.04	-1.41	0.03	-1.46	0.02	-1.42	0.01	-1.41	0.02	-1.36	0.03	-1.32	0.04	-1.30
3.16	0.04	-1.94	0.03	-1.94	0.02	-1.82	0.01	-1.83	0.02	-1.77	0.03	-1.75	0.04	-1.75
3.98	0.05	-2.54	0.04	-2.48	0.03	-2.38	0.02	-2.33	0.03	-2.30	0.04	-2.29	0.04	-2.29
5.01	0.06	-3.32	0.05	-3.19	0.04	-3.08	0.04	-3.00	0.04	-2.96	0.04	-2.96	0.04	-2.97
6.31	0.07	-4.32	0.07	-4.12	0.04	-3.99	0.06	-3.92	0.05	-3.86	0.05	-3.85	0.05	-3.86
7.94	0.07	-5.57	0.07	-5.31	0.05	-5.15	0.08	-5.12	0.06	-5.00	0.06	-4.98	0.06	-4.98
10.00	0.07	-7.13	0.07	-6.83	0.05	-6.61	0.09	-6.64	0.07	-6.48	0.06	-6.44	0.06	-6.42
12.59	0.05	-9.08	0.05	-8.71	0.04	-8.47	0.08	-8.58	-	-	-	-	-	-
15.85	0.02	-11.49	0.02	-11.02	0.01	-10.77	0.06	-10.97	-	-	-	-	-	-
19.95	-0.04	-14.49	-0.03	-13.91	-0.03	-13.63	0.01	-13.94	-	-	-	-	-	-
East-West Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	-0.05	0.02	-0.04	0.02	-0.04	0.00	-0.04	-0.04	-0.04	0.00	-0.04	0.01	-0.04	0.03
1.26	-0.04	-0.27	-0.04	-0.29	-0.04	-0.35	-0.04	-0.33	-0.04	-0.30	-0.04	-0.26	-0.04	-0.24
1.59	-0.04	-0.60	-0.04	-0.63	-0.04	-0.68	-0.04	-0.65	-0.04	-0.59	-0.04	-0.55	-0.03	-0.53
2.00	-0.04	-0.96	-0.04	-1.03	-0.04	-1.02	-0.04	-0.98	-0.04	-0.91	-0.03	-0.88	-0.03	-0.85
2.51	-0.03	-1.41	-0.03	-1.45	-0.04	-1.40	-0.04	-1.34	-0.03	-1.28	-0.03	-1.25	-0.02	-1.23
3.16	-0.02	-1.94	-0.03	-1.95	-0.03	-1.85	-0.03	-1.78	-0.03	-1.73	-0.02	-1.71	-0.02	-1.69
3.98	-0.02	-2.58	-0.02	-2.52	-0.03	-2.43	-0.02	-2.33	-0.02	-2.29	-0.01	-2.28	-0.01	-2.28
5.01	-0.01	-3.40	-0.01	-3.29	-0.02	-3.16	-0.01	-3.04	-0.01	-3.01	-0.01	-3.00	0.00	-3.01
6.31	0.00	-4.41	0.00	-4.25	-0.01	-4.08	0.00	-3.96	0.00	-3.91	0.00	-3.91	0.00	-3.91
7.94	0.00	-5.67	0.00	-5.46	-0.01	-5.27	0.01	-5.14	0.01	-5.09	0.01	-5.07	0.01	-5.07
10.00	-0.01	-7.26	-0.01	-6.99	-0.01	-6.76	0.01	-6.65	0.01	-6.59	0.01	-6.53	0.01	-6.77
12.59	-0.02	-9.21	-0.02	-8.87	-0.01	-8.63	0.01	-8.55	-	-	-	-	-	-
15.85	-0.05	-11.68	-0.05	-11.24	-0.04	-10.96	-0.01	-10.91	-	-	-	-	-	-
19.95	-0.10	-14.70	-0.09	-14.16	-0.08	-13.85	-0.05	-13.83	-	-	-	-	-	-

Table 32 Colt 213012 Response vs Input Amplitude

Colt 213012 - Response vs Input Amplitude														
Vertical Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	-0.02	0.05	-0.02	0.02	-0.02	0.00	-0.03	-0.07	-0.02	-0.04	-0.02	-0.03	-0.02	-0.01
1.26	-0.02	-0.26	-0.02	-0.29	-0.02	-0.35	-0.03	-0.37	-0.02	-0.34	-0.02	-0.32	-0.02	-0.31
1.59	-0.02	-0.58	-0.02	-0.62	-0.02	-0.69	-0.03	-0.67	-0.03	-0.66	-0.02	-0.64	-0.02	-0.62
2.00	-0.01	-0.95	-0.01	-0.99	-0.02	-1.06	-0.03	-1.00	-0.03	-1.00	-0.03	-0.97	-0.02	-0.95
2.51	-0.01	-1.38	-0.01	-1.43	-0.02	-1.44	-0.03	-1.39	-0.03	-1.37	-0.02	-1.34	-0.02	-1.31
3.16	0.00	-1.90	-0.01	-1.95	-0.01	-1.88	-0.03	-1.84	-0.02	-1.80	-0.02	-1.77	-0.01	-1.77
3.98	0.01	-2.57	0.00	-2.57	-0.01	-2.43	-0.02	-2.39	-0.01	-2.33	-0.01	-2.33	-0.01	-2.33
5.01	0.01	-3.38	0.01	-3.33	0.00	-3.16	-0.01	-3.08	0.00	-3.04	-0.01	-3.04	0.00	-3.04
6.31	0.02	-4.42	0.02	-4.30	0.01	-4.09	0.00	-4.00	0.01	-3.97	0.00	-3.95	0.00	-3.95
7.94	0.02	-5.74	0.02	-5.53	0.00	-5.27	0.02	-5.21	0.02	-5.16	0.01	-5.13	0.01	-5.11
10.00	0.01	-7.36	0.01	-7.08	-0.01	-6.76	0.02	-6.78	0.01	-6.68	0.00	-6.62	0.00	-6.60
12.59	-0.02	-9.35	-0.01	-8.99	-0.03	-8.60	0.01	-8.75	-	-	-	-	-	-
15.85	-0.06	-11.87	-0.05	-11.40	-0.07	-10.91	-0.02	-11.20	-	-	-	-	-	-
19.95	-0.13	-14.99	-0.12	-14.38	-0.12	-13.76	-0.09	-14.24	-	-	-	-	-	-
North-South Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	0.05	0.02	0.05	0.01	0.05	-0.02	0.05	-0.05	0.05	0.00	0.05	0.00	0.05	0.02
1.26	0.05	-0.27	0.05	-0.31	0.05	-0.36	0.05	-0.34	0.05	-0.31	0.05	-0.29	0.05	-0.27
1.59	0.05	-0.59	0.05	-0.63	0.05	-0.68	0.05	-0.65	0.05	-0.63	0.05	-0.59	0.06	-0.56
2.00	0.06	-0.95	0.05	-1.00	0.05	-1.03	0.04	-1.00	0.05	-0.95	0.06	-0.91	0.06	-0.88
2.51	0.06	-1.42	0.06	-1.42	0.05	-1.40	0.04	-1.38	0.05	-1.32	0.06	-1.28	0.06	-1.27
3.16	0.07	-1.93	0.06	-1.91	0.06	-1.83	0.05	-1.82	0.06	-1.77	0.06	-1.75	0.07	-1.74
3.98	0.07	-2.53	0.07	-2.49	0.06	-2.41	0.06	-2.37	0.07	-2.33	0.07	-2.32	0.07	-2.32
5.01	0.09	-3.35	0.08	-3.24	0.07	-3.15	0.07	-3.08	0.07	-3.04	0.07	-3.04	0.08	-3.04
6.31	0.09	-4.35	0.09	-4.20	0.07	-4.09	0.09	-4.02	0.08	-3.96	0.08	-3.95	0.08	-3.95
7.94	0.09	-5.61	0.09	-5.40	0.07	-5.25	0.10	-5.23	0.09	-5.13	0.09	-5.11	0.08	-5.10
10.00	0.09	-7.19	0.09	-6.92	0.07	-6.73	0.11	-6.78	0.09	-6.63	0.09	-6.59	0.09	-6.58
12.59	0.07	-9.13	0.07	-8.79	0.06	-8.58	0.10	-8.71	-	-	-	-	-	-
15.85	0.04	-11.56	0.05	-11.14	0.04	-10.88	0.08	-11.12	-	-	-	-	-	-
19.95	-0.01	-14.55	0.00	-14.04	0.00	-13.75	0.04	-14.10	-	-	-	-	-	-
East-West Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)	Amp (dB)	Phase (deg)
1.00	-0.04	0.05	-0.04	0.02	-0.04	0.00	-0.04	-0.03	-0.04	0.00	-0.04	0.01	-0.04	0.03
1.26	-0.04	-0.26	-0.04	-0.29	-0.04	-0.33	-0.04	-0.33	-0.04	-0.30	-0.04	-0.27	-0.04	-0.26
1.59	-0.04	-0.60	-0.04	-0.61	-0.04	-0.65	-0.04	-0.65	-0.04	-0.60	-0.04	-0.58	-0.04	-0.55
2.00	-0.03	-0.93	-0.03	-0.98	-0.04	-0.99	-0.04	-0.98	-0.04	-0.93	-0.04	-0.90	-0.03	-0.89
2.51	-0.03	-1.37	-0.03	-1.40	-0.04	-1.38	-0.04	-1.35	-0.04	-1.31	-0.03	-1.29	-0.03	-1.27
3.16	-0.02	-1.86	-0.02	-1.88	-0.03	-1.85	-0.04	-1.80	-0.03	-1.77	-0.03	-1.75	-0.03	-1.74
3.98	-0.01	-2.52	-0.01	-2.47	-0.03	-2.42	-0.03	-2.35	-0.03	-2.33	-0.02	-2.32	-0.02	-2.31
5.01	0.00	-3.33	0.00	-3.25	-0.02	-3.16	-0.02	-3.08	-0.02	-3.04	-0.01	-3.04	-0.01	-3.04
6.31	0.01	-4.35	0.00	-4.21	-0.01	-4.10	-0.01	-4.00	-0.01	-3.96	-0.01	-3.95	0.00	-3.95
7.94	0.02	-5.60	0.00	-5.44	0.00	-5.29	0.00	-5.19	0.00	-5.14	0.00	-5.12	0.00	-5.16
10.00	0.01	-7.18	0.00	-6.98	0.00	-6.79	0.01	-6.71	0.01	-6.66	0.01	-6.62	0.01	-6.97
12.59	0.00	-9.16	-0.01	-8.87	-0.01	-8.68	0.00	-8.61	-	-	-	-	-	-
15.85	-0.03	-11.59	-0.04	-11.23	-0.03	-11.03	-0.02	-10.99	-	-	-	-	-	-
19.95	-0.08	-14.61	-0.08	-14.17	-0.08	-13.94	-0.05	-13.93	-	-	-	-	-	-

3.8 Full Scale

The full scale of a seismometer is defined as the maximum velocity amplitude that a sensor is capable of recording without clipping. To avoid possible damage to the sensors by apply a signal larger than their maximum rating, a velocity signal of 98% of the sensors' specified clip level was utilized for this test.

3.8.1 Measurand

The quantity being measured is the distortion present in the sensor's output signal expressed as a percentage. 0% distortion would be a perfect sinusoidal output signal with no distortion.

3.8.2 Configuration

The sensors are placed one at a time on a seismic calibration table and subjected to sinusoidal velocity signals with an amplitude varied from 10% to 98% of their full-scale velocity rating. The sensors are calibrated from 1Hz to 10Hz. The SPEKTRA CS-18P system records the output of the seismometer and the reference laser vibrometer and calculates the amplitude response and phase response of the sensor for each amplitude step. It also calculates the amount of distortion, as a percentage, present in the output waveform of both the SUT and the reference laser vibrometer. Figure 45 shows a block diagram of a sensor installed on the shake tables system.

The maximum input velocity signal rating of the Colt is specified as 10.0 mm/s up to 20Hz and then 125.6gal above 20Hz.

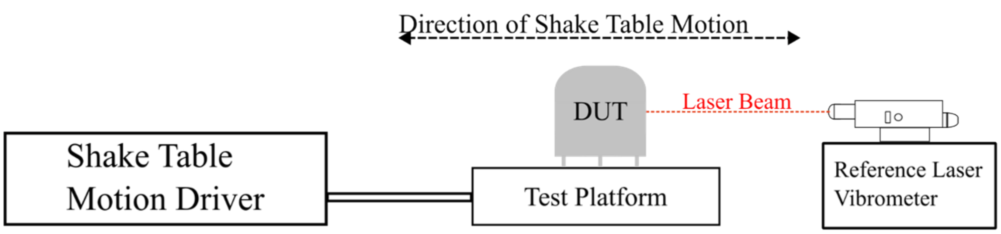


Figure 45 Full Scale Test Configuration

Table 33 Full Scale Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.00 to 9.84 mm/s Input Voltage = 12V Frequency = 1Hz to >=10Hz Pressure = 823.1 ± 5.9hPa Temperature = 21.7 ± 3.7C Humidity = 18.3 ± 8.9%

3.8.3 Analysis

The Spektra seismometer calibrator performs the analysis of data internally by fitting a sine function to both the sensor output and a primary measurement of the sensor displacement, which is converted to velocity.

After a sinusoidal equation is fit to the output of the seismometer and the reference laser vibrometer, The CS-18P system calculates the amount of distortion present in the output of both devices. The distortion is expressed as a percent and indicates the quality of the sinusoidal output signal. If a given sensor was no longer operating as a linear system due to it being exposed to too large of an input signal, one would expect the distortion in its output to increase while the distortion in the output of the laser vibrometer should remain stable.

3.8.4 Result

The figures below show the amount of distortion present in the output of the seismometers as well as the reference laser vibrometer for the 10% to 98% of full-scale tests.

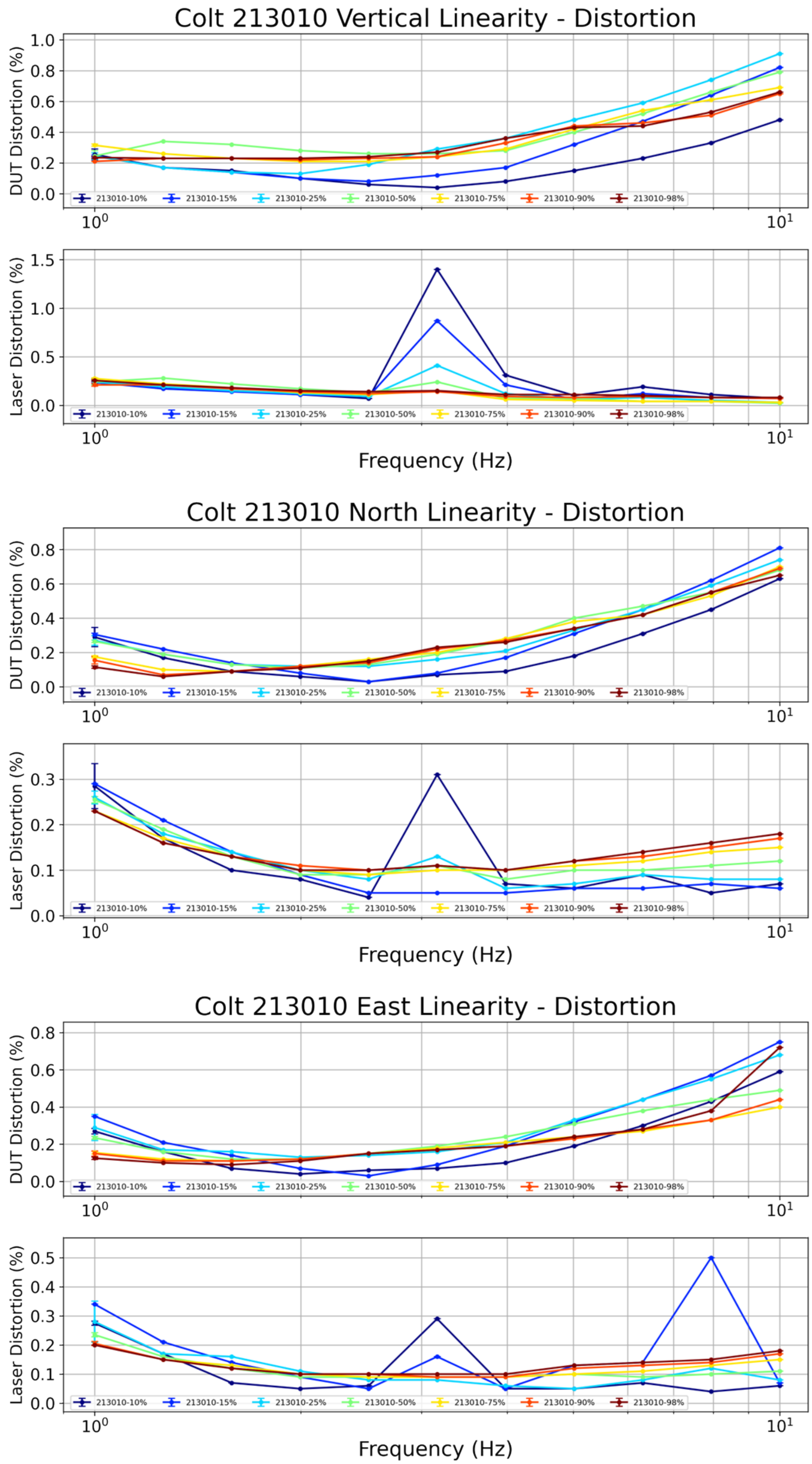


Figure 46 DUT and Laser Distortion Levels for Colt 213010

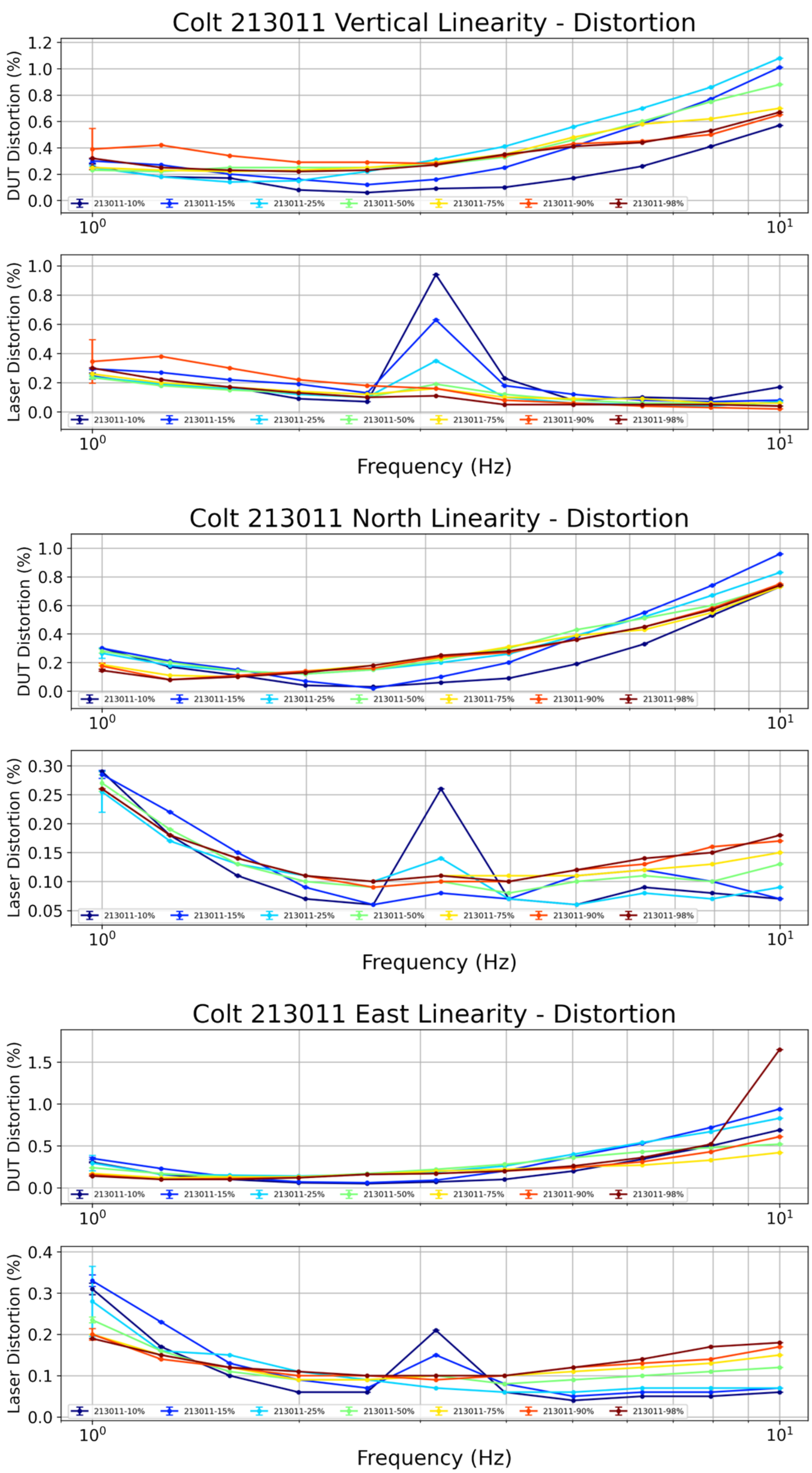


Figure 47 DUT and Laser Distortion Levels for Colt 213011

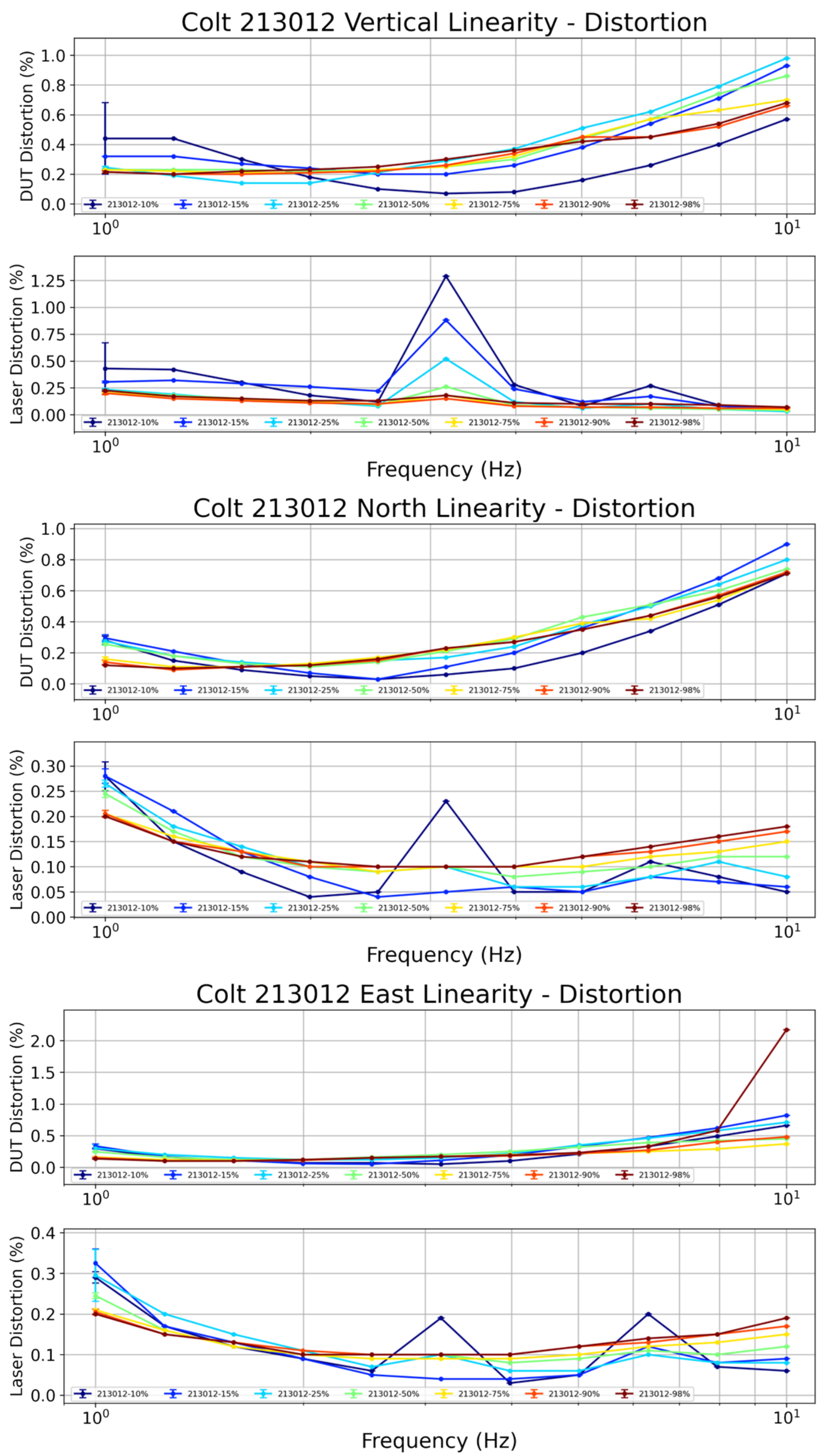


Figure 48 DUT and Laser Distortion Levels for Colt 213012

The above figures show that the Laser Distortion levels were well below 1% at all frequencies and for all tests except for the vertical axis testing. The laser distortion has a peak at about 3.1Hz for all vertical axis tests. The distortion peak is not large and never exceeds 1.5%. It is inversely proportional to signal amplitude. That is, the distortion peak is larger when the input signal is small. It is likely due to a resonance caused by the mounting and installation of the laser.

The low distortion in the laser signal for all tests indicates that the output from the laser was a high-quality sinusoid and that the shake table system was correctly generating low distortion sinusoidal ground motion for all frequencies included in the full-scale test.

The DUT distortion for the vertical axis tests was generally at or below 1.0%, meaning that all three Colt sensors had low distortion levels for all test amplitudes. This is an indication that the sensors were outputting high quality sinusoidal signals and that they were correctly operating as linear systems even when excited with a signal at 98% of their rated input velocity.

Figure 47 and Figure 48 indicate that sensors 213011 and 213012 had increased distortion at 10Hz for their East axis when operating at 98% of full scale. The distortion level was around 2% for both sensors which, while still low, is about twice the amount of distortion present when the sensors were operating with input signals at or below 90% of their clip level. This likely indicates that the sensors are operating near their clipping level and that the sensors' east axis may have a slightly lower clip level than the north and vertical axes which do not show a similar increase in distortion at 10Hz.

All sensors operated correctly at 98% of their full-scale input when tested from 1Hz to 10Hz and distortion levels never exceeded 2.25% and were generally below 1.0%.

The following tables contains the distortion data displayed in the above figures.

Table 34 Waveform Distortion vs Input Amplitude for Colt 213010

Colt 213010 - Distortion vs Input Amplitude														
Vertical Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.25	0.26	0.24	0.25	0.24	0.25	0.24	0.25	0.28	0.32	0.21	0.21	0.26	0.24
1.26	0.17	0.17	0.17	0.17	0.19	0.17	0.28	0.34	0.22	0.26	0.21	0.23	0.21	0.23
1.59	0.15	0.15	0.14	0.14	0.15	0.14	0.22	0.32	0.18	0.23	0.17	0.23	0.18	0.23
2.00	0.11	0.10	0.11	0.10	0.12	0.13	0.17	0.28	0.13	0.21	0.14	0.22	0.15	0.23
2.51	0.07	0.06	0.09	0.08	0.09	0.19	0.13	0.26	0.11	0.21	0.12	0.23	0.14	0.24
3.16	1.40	0.04	0.87	0.12	0.41	0.29	0.24	0.26	0.15	0.24	0.14	0.24	0.15	0.27
3.98	0.31	0.08	0.21	0.17	0.12	0.36	0.07	0.28	0.06	0.29	0.09	0.33	0.11	0.36
5.01	0.10	0.15	0.06	0.32	0.06	0.48	0.07	0.40	0.05	0.42	0.08	0.44	0.11	0.43
6.31	0.19	0.23	0.12	0.47	0.08	0.59	0.04	0.52	0.04	0.54	0.09	0.46	0.10	0.44
7.94	0.11	0.33	0.08	0.64	0.05	0.74	0.04	0.66	0.04	0.61	0.08	0.51	0.08	0.53
10.00	0.07	0.48	0.07	0.82	0.03	0.91	0.02	0.79	0.03	0.69	0.07	0.65	0.08	0.66
12.59	0.08	0.64	0.05	1.04	0.06	1.11	0.04	0.90	-	-	-	-	-	-
15.85	0.05	0.81	0.08	1.27	0.03	1.33	0.02	1.01	-	-	-	-	-	-
19.95	0.09	0.99	0.04	1.50	0.03	1.56	0.04	1.13	-	-	-	-	-	-
North-South Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.29	0.29	0.29	0.31	0.26	0.27	0.26	0.27	0.23	0.18	0.23	0.16	0.23	0.12
1.26	0.17	0.17	0.21	0.22	0.18	0.19	0.19	0.19	0.17	0.10	0.16	0.07	0.16	0.06
1.59	0.10	0.09	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.09	0.13	0.09	0.13	0.09
2.00	0.08	0.06	0.09	0.08	0.10	0.12	0.09	0.11	0.10	0.12	0.11	0.12	0.10	0.11
2.51	0.04	0.03	0.05	0.03	0.08	0.12	0.09	0.13	0.09	0.16	0.10	0.14	0.10	0.15
3.16	0.31	0.07	0.05	0.08	0.13	0.16	0.11	0.19	0.10	0.20	0.11	0.22	0.11	0.23
3.98	0.07	0.09	0.05	0.17	0.06	0.21	0.08	0.27	0.10	0.28	0.10	0.27	0.10	0.26
5.01	0.06	0.18	0.06	0.31	0.07	0.33	0.10	0.40	0.11	0.38	0.12	0.34	0.12	0.34
6.31	0.09	0.31	0.06	0.45	0.09	0.45	0.10	0.47	0.12	0.42	0.13	0.42	0.14	0.42
7.94	0.05	0.45	0.07	0.62	0.08	0.59	0.11	0.55	0.14	0.53	0.15	0.55	0.16	0.55
10.00	0.07	0.63	0.06	0.81	0.08	0.74	0.12	0.68	0.15	0.70	0.17	0.69	0.18	0.65
12.59	0.10	0.83	0.08	1.03	0.10	0.87	0.15	0.80	-	-	-	-	-	-
15.85	0.06	1.04	0.08	1.25	0.10	1.03	0.16	0.97	-	-	-	-	-	-
19.95	0.06	1.26	0.09	1.49	0.12	1.17	0.18	1.15	-	-	-	-	-	-
East-West Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.28	0.27	0.34	0.35	0.28	0.29	0.24	0.24	0.21	0.16	0.21	0.15	0.20	0.13
1.26	0.17	0.16	0.21	0.21	0.17	0.17	0.16	0.16	0.15	0.12	0.15	0.11	0.15	0.10
1.59	0.07	0.07	0.14	0.14	0.16	0.16	0.12	0.12	0.13	0.11	0.12	0.11	0.12	0.09
2.00	0.05	0.04	0.09	0.07	0.11	0.13	0.09	0.12	0.10	0.12	0.10	0.12	0.10	0.11
2.51	0.06	0.06	0.05	0.03	0.08	0.14	0.09	0.15	0.09	0.15	0.10	0.15	0.10	0.15
3.16	0.29	0.07	0.16	0.09	0.08	0.16	0.09	0.19	0.09	0.18	0.09	0.17	0.10	0.17
3.98	0.05	0.10	0.05	0.19	0.06	0.21	0.09	0.24	0.09	0.21	0.09	0.19	0.10	0.19
5.01	0.05	0.19	0.13	0.32	0.05	0.33	0.10	0.31	0.10	0.24	0.12	0.23	0.13	0.24
6.31	0.07	0.30	0.14	0.44	0.08	0.44	0.09	0.38	0.11	0.27	0.13	0.28	0.14	0.28
7.94	0.04	0.43	0.50	0.57	0.12	0.55	0.10	0.44	0.13	0.33	0.14	0.33	0.15	0.38
10.00	0.06	0.59	0.07	0.75	0.08	0.68	0.11	0.49	0.15	0.40	0.17	0.44	0.18	0.72
12.59	0.07	0.76	0.12	0.94	0.09	0.82	0.14	0.57	-	-	-	-	-	-
15.85	0.10	0.95	0.09	1.15	0.10	0.94	0.15	0.69	-	-	-	-	-	-
19.95	0.07	1.13	0.08	1.36	0.11	1.06	0.18	0.80	-	-	-	-	-	-

Table 35 Waveform Distortion vs Input Amplitude for Colt 213011

Colt 213011 - Distortion vs Input Amplitude														
Vertical Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.25	0.26	0.30	0.30	0.24	0.25	0.24	0.23	0.26	0.25	0.35	0.39	0.30	0.32
1.26	0.18	0.18	0.27	0.27	0.19	0.18	0.18	0.22	0.20	0.23	0.38	0.42	0.22	0.25
1.59	0.17	0.17	0.22	0.20	0.16	0.14	0.15	0.25	0.17	0.22	0.30	0.34	0.17	0.23
2.00	0.09	0.08	0.19	0.16	0.12	0.15	0.13	0.25	0.14	0.23	0.22	0.29	0.13	0.22
2.51	0.07	0.06	0.13	0.12	0.10	0.22	0.10	0.25	0.12	0.25	0.18	0.29	0.10	0.23
3.16	0.94	0.09	0.63	0.16	0.35	0.31	0.19	0.27	0.16	0.29	0.16	0.28	0.11	0.27
3.98	0.23	0.10	0.18	0.25	0.10	0.41	0.12	0.33	0.10	0.35	0.08	0.34	0.05	0.35
5.01	0.08	0.17	0.12	0.41	0.06	0.56	0.08	0.46	0.09	0.48	0.06	0.43	0.05	0.41
6.31	0.10	0.26	0.08	0.58	0.05	0.70	0.06	0.60	0.09	0.58	0.04	0.45	0.05	0.44
7.94	0.09	0.41	0.07	0.77	0.04	0.86	0.06	0.75	0.06	0.62	0.03	0.50	0.05	0.53
10.00	0.17	0.57	0.08	1.01	0.07	1.08	0.04	0.88	0.06	0.70	0.02	0.65	0.04	0.67
12.59	0.04	0.75	0.05	1.27	0.06	1.32	0.04	0.98	-	-	-	-	-	-
15.85	0.05	0.97	0.03	1.58	0.04	1.58	0.04	1.09	-	-	-	-	-	-
19.95	0.07	1.20	0.06	1.87	0.04	1.85	0.04	1.21	-	-	-	-	-	-
North-South Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.29	0.30	0.29	0.30	0.26	0.27	0.27	0.28	0.26	0.19	0.26	0.18	0.26	0.15
1.26	0.18	0.17	0.22	0.21	0.17	0.18	0.19	0.20	0.18	0.11	0.18	0.08	0.18	0.08
1.59	0.11	0.11	0.15	0.15	0.13	0.14	0.13	0.14	0.14	0.10	0.14	0.11	0.14	0.10
2.00	0.07	0.04	0.09	0.07	0.11	0.12	0.10	0.12	0.11	0.14	0.11	0.14	0.11	0.13
2.51	0.06	0.03	0.06	0.02	0.10	0.15	0.09	0.15	0.10	0.18	0.09	0.16	0.10	0.18
3.16	0.26	0.06	0.08	0.10	0.14	0.20	0.10	0.22	0.11	0.23	0.10	0.24	0.11	0.25
3.98	0.07	0.09	0.07	0.20	0.07	0.26	0.08	0.30	0.11	0.31	0.10	0.27	0.10	0.28
5.01	0.06	0.19	0.11	0.38	0.06	0.39	0.10	0.43	0.11	0.39	0.12	0.36	0.12	0.36
6.31	0.09	0.33	0.12	0.55	0.08	0.52	0.11	0.51	0.12	0.43	0.13	0.45	0.14	0.45
7.94	0.08	0.53	0.10	0.74	0.07	0.67	0.10	0.60	0.13	0.55	0.16	0.58	0.15	0.57
10.00	0.07	0.73	0.07	0.96	0.09	0.83	0.13	0.74	0.15	0.73	0.17	0.75	0.18	0.74
12.59	0.15	0.98	0.09	1.20	0.09	0.97	0.14	0.86	-	-	-	-	-	-
15.85	0.07	1.22	0.08	1.48	0.10	1.13	0.16	1.03	-	-	-	-	-	-
19.95	0.08	1.49	0.09	1.75	0.13	1.28	0.19	1.21	-	-	-	-	-	-
East-West Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.31	0.31	0.33	0.35	0.28	0.30	0.24	0.24	0.20	0.17	0.20	0.16	0.19	0.14
1.26	0.17	0.16	0.23	0.23	0.16	0.16	0.16	0.17	0.15	0.12	0.14	0.10	0.15	0.10
1.59	0.10	0.10	0.13	0.13	0.15	0.15	0.11	0.13	0.12	0.13	0.12	0.11	0.12	0.10
2.00	0.06	0.06	0.09	0.07	0.11	0.14	0.09	0.13	0.09	0.13	0.10	0.12	0.11	0.12
2.51	0.06	0.05	0.07	0.06	0.09	0.16	0.09	0.17	0.09	0.16	0.10	0.16	0.10	0.16
3.16	0.21	0.07	0.15	0.09	0.07	0.19	0.10	0.22	0.10	0.20	0.09	0.17	0.10	0.17
3.98	0.06	0.10	0.08	0.20	0.06	0.26	0.08	0.28	0.10	0.22	0.10	0.20	0.10	0.20
5.01	0.04	0.20	0.05	0.37	0.06	0.40	0.09	0.36	0.11	0.25	0.12	0.24	0.12	0.26
6.31	0.05	0.34	0.06	0.53	0.07	0.54	0.10	0.43	0.12	0.27	0.13	0.31	0.14	0.36
7.94	0.05	0.50	0.06	0.72	0.07	0.67	0.11	0.48	0.13	0.33	0.14	0.43	0.17	0.52
10.00	0.06	0.69	0.07	0.94	0.07	0.83	0.12	0.52	0.15	0.42	0.17	0.61	0.18	1.65
12.59	0.06	0.91	0.08	1.18	0.09	0.98	0.14	0.58	-	-	-	-	-	-
15.85	0.09	1.15	0.08	1.44	0.10	1.13	0.15	0.68	-	-	-	-	-	-
19.95	0.08	1.39	0.09	1.71	0.11	1.27	0.18	0.79	-	-	-	-	-	-

Table 36 **Waveform Distortion vs Input Amplitude for Colt 213012**

Colt 213012 - Distortion vs Input Amplitude														
Vertical Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.43	0.44	0.31	0.32	0.24	0.25	0.23	0.23	0.21	0.23	0.20	0.22	0.23	0.22
1.26	0.42	0.44	0.32	0.32	0.19	0.19	0.18	0.23	0.17	0.22	0.15	0.20	0.17	0.20
1.59	0.30	0.30	0.29	0.27	0.14	0.14	0.15	0.23	0.14	0.21	0.13	0.20	0.15	0.22
2.00	0.18	0.18	0.26	0.24	0.12	0.14	0.13	0.22	0.12	0.21	0.11	0.21	0.13	0.23
2.51	0.12	0.10	0.22	0.20	0.08	0.21	0.09	0.23	0.10	0.23	0.10	0.22	0.13	0.25
3.16	1.29	0.07	0.88	0.20	0.52	0.29	0.26	0.25	0.18	0.25	0.15	0.26	0.18	0.30
3.98	0.28	0.08	0.24	0.26	0.12	0.37	0.09	0.30	0.08	0.32	0.08	0.34	0.11	0.36
5.01	0.08	0.16	0.12	0.38	0.06	0.51	0.07	0.44	0.07	0.45	0.07	0.45	0.10	0.42
6.31	0.27	0.26	0.17	0.54	0.10	0.62	0.06	0.57	0.07	0.57	0.07	0.45	0.10	0.45
7.94	0.09	0.40	0.08	0.71	0.05	0.79	0.05	0.74	0.06	0.63	0.06	0.52	0.09	0.54
10.00	0.05	0.57	0.05	0.93	0.03	0.98	0.04	0.86	0.05	0.70	0.06	0.66	0.07	0.68
12.59	0.06	0.75	0.04	1.17	0.04	1.19	0.05	0.98	-	-	-	-	-	-
15.85	0.06	0.96	0.03	1.46	0.03	1.43	0.04	1.10	-	-	-	-	-	-
19.95	0.05	1.16	0.06	1.73	0.03	1.68	0.04	1.23	-	-	-	-	-	-
North-South Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.28	0.28	0.28	0.30	0.27	0.28	0.25	0.26	0.21	0.16	0.21	0.14	0.20	0.12
1.26	0.15	0.15	0.21	0.21	0.18	0.18	0.17	0.18	0.16	0.11	0.15	0.09	0.15	0.10
1.59	0.09	0.09	0.13	0.13	0.14	0.14	0.12	0.13	0.13	0.11	0.13	0.11	0.12	0.11
2.00	0.04	0.05	0.08	0.07	0.10	0.11	0.10	0.11	0.11	0.13	0.10	0.12	0.11	0.12
2.51	0.05	0.03	0.04	0.03	0.09	0.15	0.09	0.14	0.09	0.17	0.10	0.15	0.10	0.16
3.16	0.23	0.06	0.05	0.11	0.10	0.17	0.10	0.21	0.10	0.22	0.10	0.23	0.10	0.23
3.98	0.05	0.10	0.06	0.20	0.06	0.24	0.08	0.29	0.10	0.30	0.10	0.27	0.10	0.27
5.01	0.05	0.20	0.05	0.36	0.06	0.38	0.09	0.43	0.10	0.39	0.12	0.35	0.12	0.35
6.31	0.11	0.34	0.08	0.51	0.08	0.50	0.10	0.51	0.12	0.42	0.13	0.44	0.14	0.44
7.94	0.08	0.51	0.07	0.68	0.11	0.64	0.12	0.60	0.13	0.54	0.15	0.57	0.16	0.56
10.00	0.05	0.71	0.06	0.90	0.08	0.80	0.12	0.74	0.15	0.72	0.17	0.72	0.18	0.71
12.59	0.07	0.93	0.07	1.13	0.09	0.94	0.14	0.86	-	-	-	-	-	-
15.85	0.07	1.18	0.08	1.39	0.10	1.10	0.16	1.01	-	-	-	-	-	-
19.95	0.07	1.43	0.08	1.66	0.12	1.24	0.18	1.21	-	-	-	-	-	-
East-West Axis														
	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
Freq (Hz)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)	Laser Dist (%)	DUT Dist (%)
1.00	0.29	0.30	0.33	0.34	0.30	0.30	0.25	0.25	0.21	0.16	0.21	0.15	0.20	0.14
1.26	0.17	0.16	0.17	0.17	0.20	0.20	0.16	0.16	0.16	0.12	0.15	0.10	0.15	0.10
1.59	0.12	0.11	0.13	0.11	0.15	0.15	0.12	0.12	0.12	0.11	0.13	0.10	0.13	0.10
2.00	0.09	0.07	0.09	0.06	0.11	0.12	0.10	0.12	0.10	0.12	0.11	0.11	0.10	0.12
2.51	0.06	0.07	0.05	0.05	0.07	0.12	0.10	0.16	0.09	0.15	0.10	0.15	0.10	0.15
3.16	0.19	0.05	0.04	0.11	0.10	0.15	0.10	0.20	0.09	0.17	0.10	0.17	0.10	0.17
3.98	0.03	0.10	0.04	0.19	0.06	0.22	0.08	0.25	0.09	0.20	0.10	0.18	0.10	0.19
5.01	0.05	0.21	0.05	0.33	0.06	0.35	0.09	0.32	0.10	0.22	0.12	0.22	0.12	0.23
6.31	0.20	0.33	0.12	0.47	0.10	0.46	0.11	0.39	0.12	0.25	0.13	0.27	0.14	0.33
7.94	0.07	0.49	0.08	0.62	0.08	0.58	0.10	0.42	0.13	0.29	0.15	0.40	0.15	0.58
10.00	0.06	0.66	0.09	0.82	0.08	0.71	0.12	0.45	0.15	0.37	0.17	0.48	0.19	2.17
12.59	0.08	0.87	0.08	1.03	0.10	0.84	0.13	0.51	-	-	-	-	-	-
15.85	0.10	1.08	0.09	1.25	0.10	0.95	0.15	0.62	-	-	-	-	-	-
19.95	0.08	1.29	0.11	1.49	0.12	1.05	0.17	0.72	-	-	-	-	-	-

3.9 Self-Noise

Sensor self-noise is defined to be any deviation between the sensor output signal and the input signal that is unrelated to the linear time invariant (LTI) amplitude and phase response, DC offset, and harmonic distortion of the sensor. This definition of self-noise is consistent with established definitions of total noise used for digitizers (IEEE Std 1241-2010 section 9.1). The measurement unit is the decibel (dB) relative to 1 $(m/s^2)^2/Hz$.

3.9.1 Measurand

Static self-noise expressed in power spectral density in units of dB relative to 1 $(m/s^2)^2/Hz$ over the defined frequencies.

3.9.2 Configuration

Three or more seismometers are placed on a seismic pier. They are insulated from thermal changes and placed physically close to each other to ensure they are exposed to the same ground motion signals. They are connected to seismic dataloggers and then allowed to operate undisturbed for at least one week. Their time series data is inspected to identify a quiet period in which there are no large signals present (i.e., a period in which no earthquake signals are present and minimal anthropogenic signals are present). This quiet period is then used to determine the self-noise of the sensors. Figure 49 provides a block diagram showing how the equipment is installed and connected during a self-noise test and Figure 50 shows a picture of how the equipment was installed for the test.

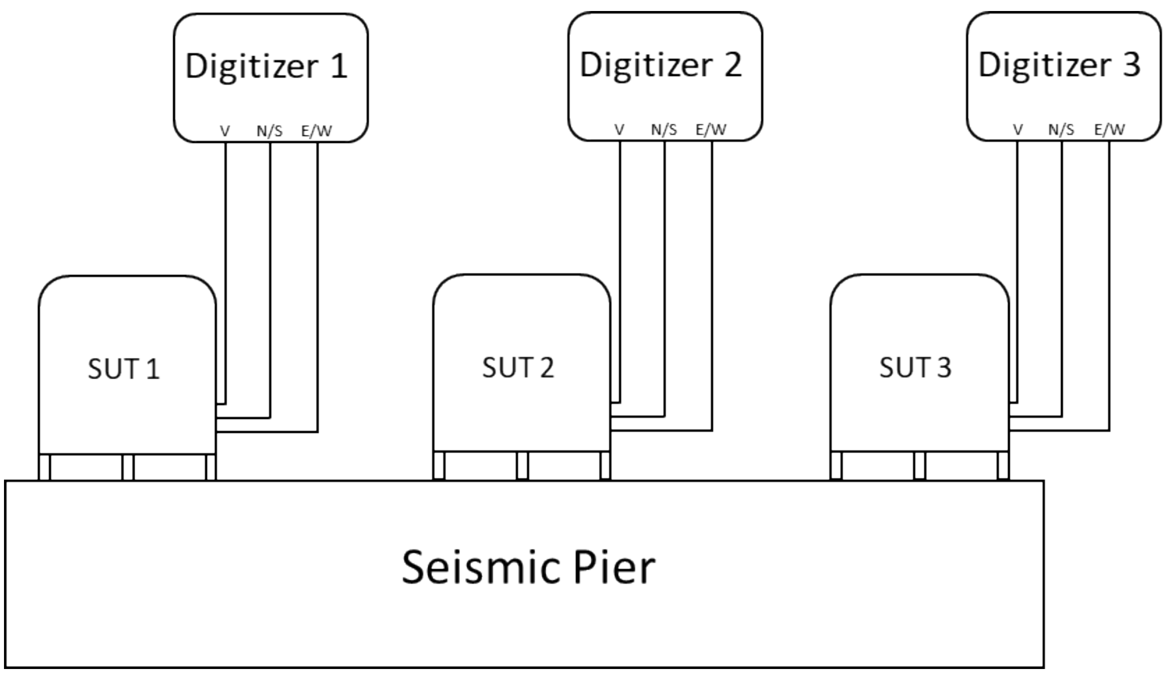


Figure 49 Self-Noise Configuration Diagram

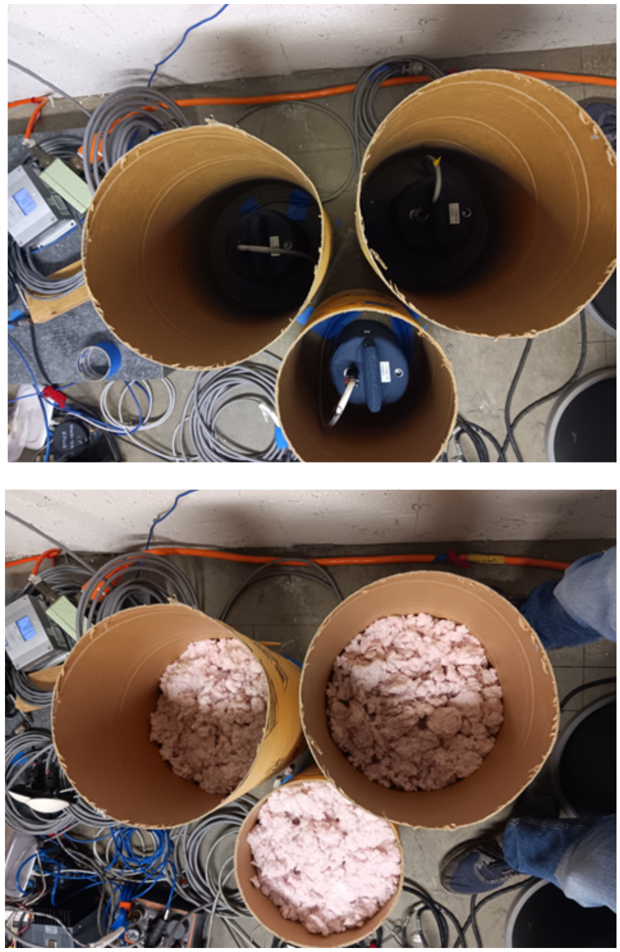


Figure 50 Sensors installed on seismic pier for self-noise test

Table 37 Self-Noise Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Seismic Pier	SNL	Bunker	23C
SUT Digitizer 1	Reftek / Wrangler	3052D	200Hz, 64x gain Port A: Colt 213011 Port B: Colt 213012
SUT Digitizer 2	Reftek / Wrangler	3052C	200Hz, 64x gain Port A: Colt 213010 Port B: None

The self-noise measurement was taken on October 6, 2024, from the period of 01:30 to 13:30 UTC

3.9.3 Analysis

The measured sensitivities are applied to the collected data:

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 32k-sample Hann window. The measured frequency response for each sensor is used to shape the response.

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

Over frequencies (in Hertz):

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

The window length and data duration were chosen such that there were several points below the lower limit of the evaluation passband of 0.02 Hz. The resulting 95% confidence interval was determined to be 0.55 dB.

A multi-channel coherence technique (Sleeman, 2006; Merchant, 2011) is applied to remove any coherent portion of the PSD.

In addition, the total RMS noise over the application passband of 0.02Hz-16Hz is computed:

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

where $f[n]$ and $f[m]$ are the passband limits

3.9.4 Result

The figure below shows the vertical waveform time series for the three Colt sensors that was utilized for the determination of vertical axis self-noise. The same period of time was utilized for determination of the north-south and east-west axis self-noise levels.

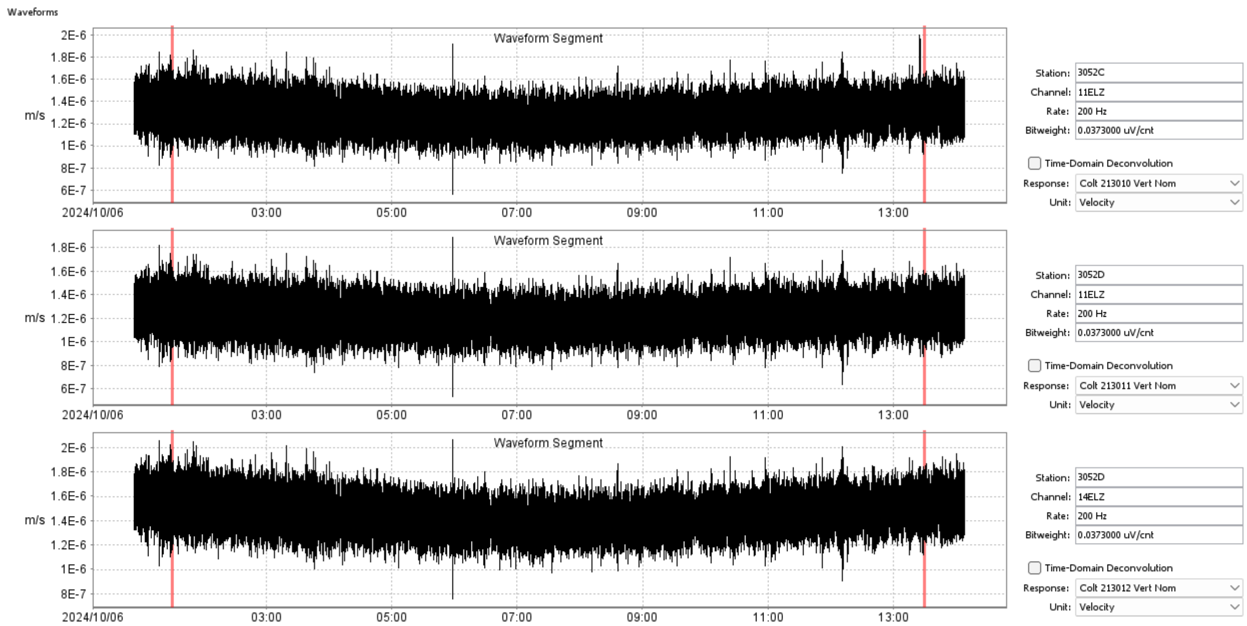


Figure 51 Self-Noise Time Series

The time series data above was used to calculate PSDs which are shown for all three axes in Figure 52.

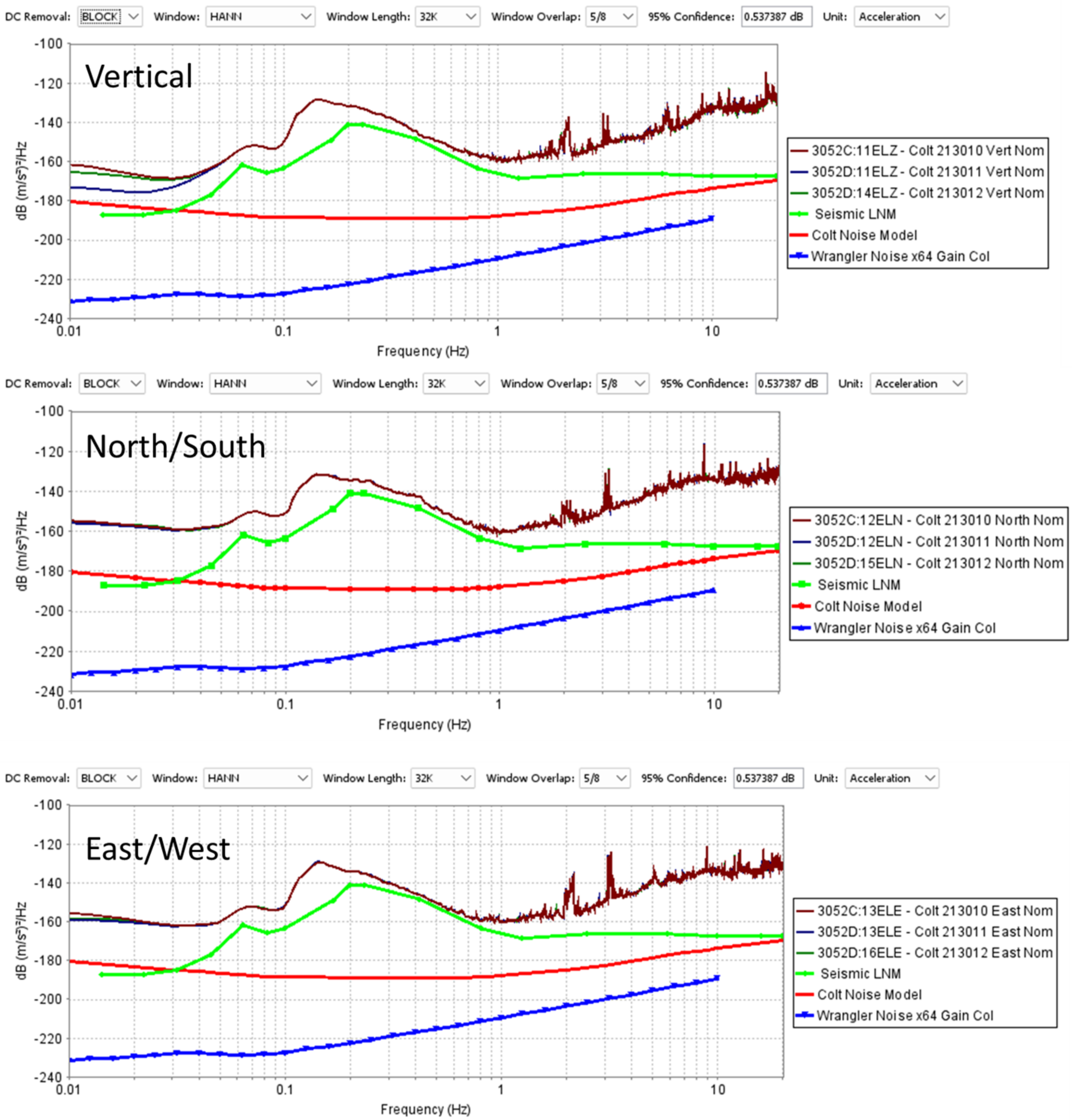


Figure 52 PSD of Self Noise time series data

Figure 53, Figure 54, and Figure 55, below, show the measured self-noise levels for the Colt sensors' vertical, north-south and east-west axes respectively after application of the coherent signal removal technique (Sleeman, 2006; Merchant, 2011). Note the noise data is shown with units of acceleration. Also included in the figures is the New Low Noise Model (Peterson, 1993) in green, and the Colt self-noise model in red. In blue is the Wrangler noise level when it's configured to operate at x64 gain. The Wrangler noise model is obtained from the Sandia evaluation of the digitizer (Bloomquist, 2024) and indicates that the self-noise of the digitizer is well below that of the Colt seismometer across the bandwidth of interest and, as a result, is not a significant contributor to the measured noise levels.

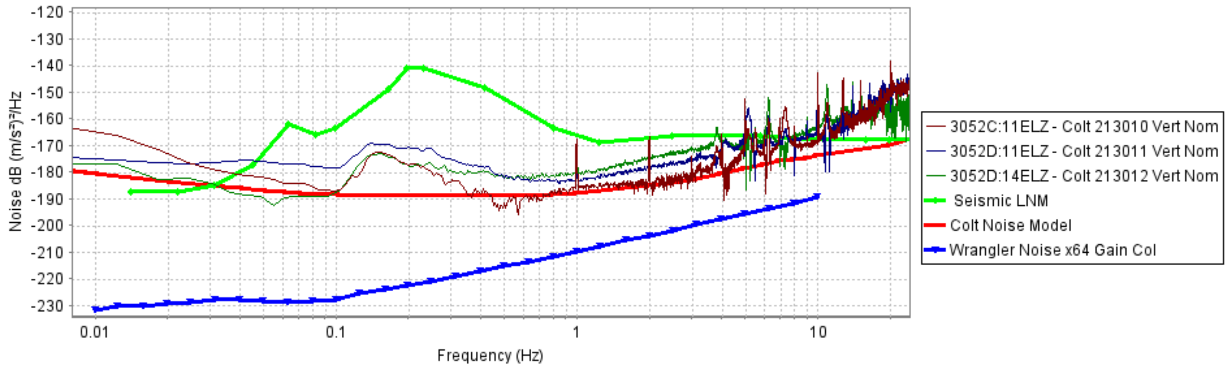


Figure 53 Self-Noise of Vertical Axis

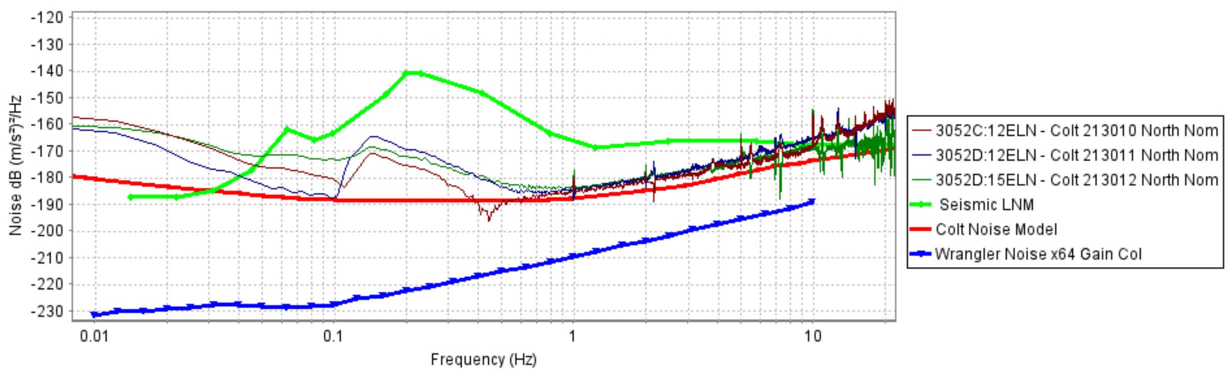


Figure 54 Self-Noise of North-South Axis

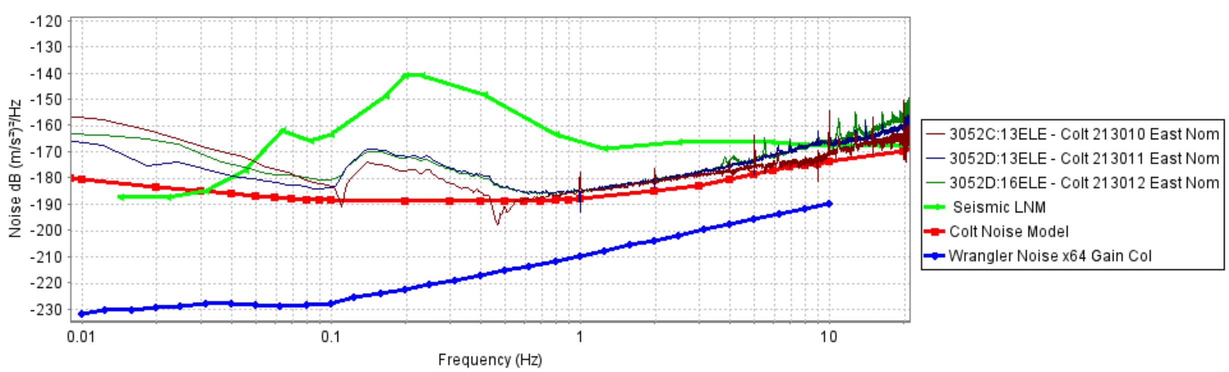


Figure 55 Self-Noise of East-West Axis

Figure 53, showing the self-noise for the vertical axis, indicates from 0.01Hz-20Hz the measured self-noise levels of the three Colt seismometers generally match the manufacture's self-noise model. All sensors show an increase in noise within the microseism which, as expected, indicates a non-perfect removal of coherent signals. At higher frequencies the measured self-noise is higher than the sensor noise model. This is likely due to the significant amount of higher frequency noise sources at the FACT site (HVAC equipment, nearby vehicle traffic, etc.…) and the incoherent nature of these signals which makes the coherency removal technique less effective. At lower frequencies the measured self-noise of all three Colt instruments shows some deviation with sensor 213012 tracking the noise model very closely while 213011 and 213010 are slightly higher than the noise model. Like at high frequencies, much of the deviation can be explained by non-idealities of the testing location. The FACT bunker is not located on bedrock and does not have particularly strong thermal stability. Both issues can lead to elevated long period noise.

Figure 54 and Figure 55, showing the measured self-noise levels for the horizontal axes, indicate good agreement between the measured noise levels and the manufactures specifications from 0.1Hz to 20Hz. At lower frequencies the measured self-noise is higher than the manufactures specifications and higher than the measured vertical axis noise. This is not unexpected given the limitations of the test location and the higher amount of noise in long period horizontal seismic data (Bormann, 2013).

The following tables contains the integrated RMS self-noise levels over the 0.02 – 16 Hz application passband, first in acceleration and then in velocity, for each of the three axes of the Colt sensors.

Table 38 Acceleration Self Noise RMS

Sensor	Vertical 0.02Hz - 16Hz	North-South 0.02Hz - 16Hz	East-West 0.02Hz - 16Hz
Colt 213010	32.07 nm/s² rms	19.09 nm/s² rms	12.03 nm/s² rms
Colt 213011	28.50 nm/s² rms	21.29 nm/s² rms	16.38 nm/s² rms
Colt 213012	39.87 nm/s² rms	12.37 nm/s² rms	20.91 nm/s² rms

Table 39 Velocity Self Noise RMS

Sensor	Vertical 0.02Hz - 16Hz	North-South 0.02Hz - 16Hz	East-West 0.02Hz - 16Hz
Colt 213010	1.31 nm/s rms	3.29 nm/s rms	3.72 nm/s rms
Colt 213011	1.87 nm/s rms	2.05 nm/s rms	1.75 nm/s rms
Colt 213012	1.06 nm/s rms	3.76 nm/s rms	2.92 nm/s rms

The following table contains incoherent self-noise levels in acceleration with units of dB relative to 1 $(m/s^2)^2/Hz$ that was used to make the plots shown above. The total combined uncertainty estimate for the PSD is included as well.

Table 40 Vertical Axis Self-Noise Power Spectra

Vertical Noise (dB relative to 1 $(m/s^2)^2/Hz$)				
Frequency (Hz)	Colt 213010	Colt 213011	Colt 213012	Uncertainty (k=2)
0.02	-172.73	-176.46	-182.46	0.55
0.025	-176.62	-176.91	-182.31	0.55
0.0315	-179.10	-176.27	-184.67	0.55
0.04	-180.87	-175.54	-188.29	0.55
0.05	-181.93	-175.86	-188.86	0.55
0.063	-184.00	-176.79	-189.66	0.55
0.08	-185.41	-177.76	-188.91	0.55
0.1	-186.78	-178.38	-187.90	0.55
0.125	-181.51	-173.30	-177.81	0.55
0.16	-173.36	-169.52	-173.57	0.55
0.2	-176.90	-170.88	-177.08	0.54
0.25	-179.60	-171.85	-177.72	0.54
0.315	-183.82	-175.93	-179.98	0.54
0.4	-187.76	-177.89	-180.06	0.54
0.5	-191.77	-181.51	-181.76	0.54
0.63	-189.87	-182.96	-181.61	0.54
0.8	-187.97	-183.30	-181.15	0.54
1	-185.83	-182.92	-180.52	0.54
1.25	-184.99	-181.58	-179.12	0.54
1.6	-184.52	-179.95	-176.96	0.54
2	-183.95	-178.02	-174.64	0.54
2.5	-182.58	-176.75	-172.97	0.54
3.15	-180.02	-174.97	-171.38	0.54
4	-177.02	-171.00	-168.73	0.54
5	-171.22	-168.17	-170.34	0.54
6.3	-171.86	-169.52	-167.38	0.54
8	-169.41	-167.48	-166.58	0.54
10	-167.82	-166.17	-163.29	0.54
12.5	-162.39	-162.45	-158.97	0.55
16	-158.68	-156.97	-158.05	0.55
20	-150.31	-149.68	-155.51	0.55

Table 41 North-South Axis Self-Noise Power Spectra

N/S Noise (dB relative to 1 $(m/s^2)^2/Hz$)				
Frequency (Hz)	Colt 213010	Colt 213011	Colt 213012	Uncertainty (k=2)
0.02	-163.72	-169.62	-163.85	0.55
0.025	-166.27	-174.17	-166.04	0.55
0.0315	-169.46	-177.03	-168.70	0.55
0.04	-173.45	-179.18	-170.99	0.55
0.05	-176.04	-182.29	-171.77	0.55
0.063	-176.55	-184.16	-171.59	0.55
0.08	-178.93	-186.00	-172.88	0.55
0.1	-180.48	-186.12	-173.23	0.55
0.125	-178.57	-171.15	-172.03	0.55
0.16	-172.36	-165.83	-169.59	0.55
0.2	-175.66	-169.38	-172.17	0.54
0.25	-177.99	-171.40	-174.38	0.54
0.315	-183.19	-175.72	-177.15	0.54
0.4	-191.57	-180.48	-179.31	0.54
0.5	-190.11	-183.69	-182.13	0.54
0.63	-187.85	-185.15	-183.33	0.54
0.8	-186.29	-185.21	-183.83	0.54
1	-185.45	-184.58	-183.68	0.54
1.25	-184.26	-183.29	-182.85	0.54
1.6	-182.89	-181.87	-181.35	0.54
2	-181.80	-180.48	-179.76	0.54
2.5	-180.10	-179.08	-178.67	0.54
3.15	-178.82	-176.70	-176.87	0.54
4	-175.44	-174.32	-176.36	0.54
5	-175.46	-173.01	-173.82	0.54
6.3	-173.44	-170.23	-172.28	0.54
8	-171.12	-167.60	-170.33	0.54
10	-167.99	-165.28	-169.01	0.54
12.5	-163.84	-163.21	-168.68	0.55
16	-160.72	-161.18	-167.45	0.55
20	-156.27	-157.06	-166.21	0.55

Table 42 East-West Axis Self-Noise Power Spectra

E/W Noise (dB relative to 1 $(m/s^2)^2/Hz$)				
Frequency (Hz)	Colt 213010	Colt 213011	Colt 213012	Uncertainty (k=2)
0.02	-162.56	-174.96	-165.43	0.55
0.025	-165.21	-174.33	-167.52	0.55
0.0315	-168.18	-176.56	-171.37	0.55
0.04	-170.89	-179.21	-174.63	0.55
0.05	-173.57	-180.47	-177.05	0.55
0.063	-177.03	-181.76	-178.84	0.55
0.08	-180.94	-183.09	-179.79	0.55
0.1	-182.80	-183.80	-180.33	0.55
0.125	-179.64	-173.78	-174.17	0.55
0.16	-175.07	-169.42	-170.18	0.55
0.2	-177.03	-171.57	-172.37	0.54
0.25	-178.23	-172.54	-173.52	0.54
0.315	-182.60	-176.80	-177.16	0.54
0.4	-185.64	-178.79	-179.57	0.54
0.5	-192.74	-183.28	-183.73	0.54
0.63	-187.96	-185.32	-185.46	0.54
0.8	-186.43	-185.39	-185.65	0.54
1	-185.19	-184.74	-184.93	0.54
1.25	-184.37	-183.37	-183.78	0.54
1.6	-182.67	-182.18	-182.23	0.54
2	-181.46	-180.64	-180.84	0.54
2.5	-179.99	-179.36	-179.31	0.54
3.15	-178.60	-177.28	-177.43	0.54
4	-177.32	-175.25	-173.20	0.54
5	-175.62	-173.41	-173.06	0.54
6.3	-174.51	-170.36	-171.30	0.54
8	-173.74	-168.11	-168.26	0.54
10	-170.94	-166.74	-165.97	0.54
12.5	-168.22	-165.37	-163.11	0.55
16	-165.93	-163.10	-160.54	0.55
20	-164.57	-160.00	-156.22	0.55

3.10 Dynamic Range

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

3.10.1 Measurand

The Dynamic Range is measured in decibels as 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 output of the sensor. The smallest signal is defined to have power equal to the self-noise of the sensor. 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).

3.10.2 Configuration

There is no test configuration for the dynamic range test. The value for the smallest signal comes from the evaluated sensor self-noise determined in section 3.9 Self-Noise. The largest signal value is obtained from the manufacture's specifications. The sensors' ability to operate at 98% of this largest signal was verified in the Full Scale section.

3.10.3 Analysis

The dynamic range over a given passband is:

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

Where

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

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

The frequency passband over which the noise is integrated should be selected to be consistent with the application passband.

3.10.4 Result

The following table contains the full scale, rms noise, and dynamic range values.

Table 43 Dynamic Range of the Colt Sensors

Sensor	Full Scale (Peak)	Vertical RMS Noise (0.02-16Hz)	N/S RMS Noise (0.02-16Hz)	E/W RMS Noise (0.02-16Hz)	Vertical Dynamic Range (0.02-16Hz)	N/S Dynamic Range (0.02-16Hz)	E/W Dynamic Range (0.02-16Hz)
Colt 213010	10 mm/s	1.31 nm/s rms	3.29 nm/s rms	3.72 nm/s rms	137.65 dB	129.66 dB	128.59 dB
Colt 213011	10 mm/s	1.87 nm/s rms	2.05 nm/s rms	1.75 nm/s rms	134.56 dB	133.76 dB	135.14 dB
Colt 213012	10 mm/s	1.06 nm/s rms	3.76 nm/s rms	2.92 nm/s rms	139.49 dB	128.50 dB	130.69 dB

The dynamic range values were between 134.56 dB –139.49 dB for the vertical axis and 128.50 dB – 135.14 dB for the horizontal axis. All measured dynamic range values exceeded the IMS specification of greater than or equal to 120dB. Note that these dynamic range values may be smaller than what is in the manufacturer datasheet due to the higher estimates of sensor noise that were made in the evaluation.

3.11 Calibrator Frequency Response

The calibrator frequency response is defined as being the linear time-invariant (LTI) change in the simulated ground motion to an input volage signal.

3.11.1 Measurand

Response, including the amplitude expressed in units of ground motion per volt (typically acceleration per volt but for some sensors it's velocity per volt) and the phase expressed in degrees, over the defined frequencies.

3.11.2 Configuration

The seismometer under test is placed on a concrete seismic pier and allowed to reach stable operation. Its velocity output signals are connected to a seismic datalogger capable of generating calibration electrical signals. The calibration signal output from the datalogger is connected to the seismometer's calibration input. The datalogger is configured to internally record the calibration signal it generates. This configuration is illustrated in Figure 56, below.

A pseudo random binary signal type is generated by the datalogger. This is a broadband signal that allows for the full passband of the sensor to be simultaneously evaluated. The seismometer is configured to output ground motion data in its native UVW orientation instead of the XYZ orientation. This ensures a high signal to noise ratio on all three output signals so that their frequency response can be individually determined and compared to the nominal frequency response specifications.

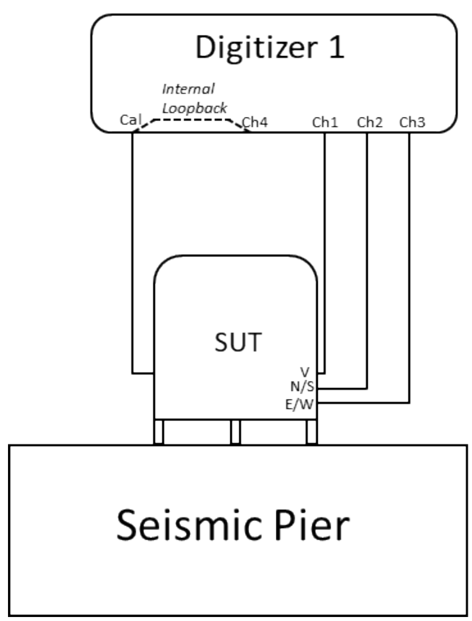


Figure 56 Calibrator Frequency Response Configuration Diagram

Table 44 Calibrator Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Seismic Pier	SNL	Bunker	23C
SUT Digitizer 1	Reftek / Wrangler	3052D	500Hz, 1x gain Port A: Colt 213011 Port B: Colt 213012
SUT Digitizer 2	Reftek / Wrangler	3052C	500Hz, 1x gain Port A: Colt 213010 Port B: None

3.11.3 Analysis

There are four recorded time series data channels. Three are output voltage signals from the seismometer that are proportional to velocity and are in the UVW orientation. The fourth is the electrical signal applied to the calibration input of the seismometer and is proportional to acceleration. The correct bitweight for the datalogger is applied to the data channels:

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

The relative transfer function, both amplitude and phase, is computed between each output signal from the seismometer and the common input calibration signal from the power spectral density (Merchant, 2011), which is calculated with units of acceleration:

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

The sensor's response to ground motion is then removed from the relative transfer functions. The U, W, and V response information from the sensor's calibration sheet is used. These corrected transfer functions can then be directly compared to the manufacturer's specification for the response of the electrical calibration system.

3.11.4 Result

The figure below shows a representative waveform time series for Colt 213011 when the pseudo random binary signal was applied to the sensor's calibration input. The top waveform is the calibration input signal, generated by the datalogger, with units of acceleration, and the next three waveforms are the sensors U, W, and V output signals respectively, with units of velocity.

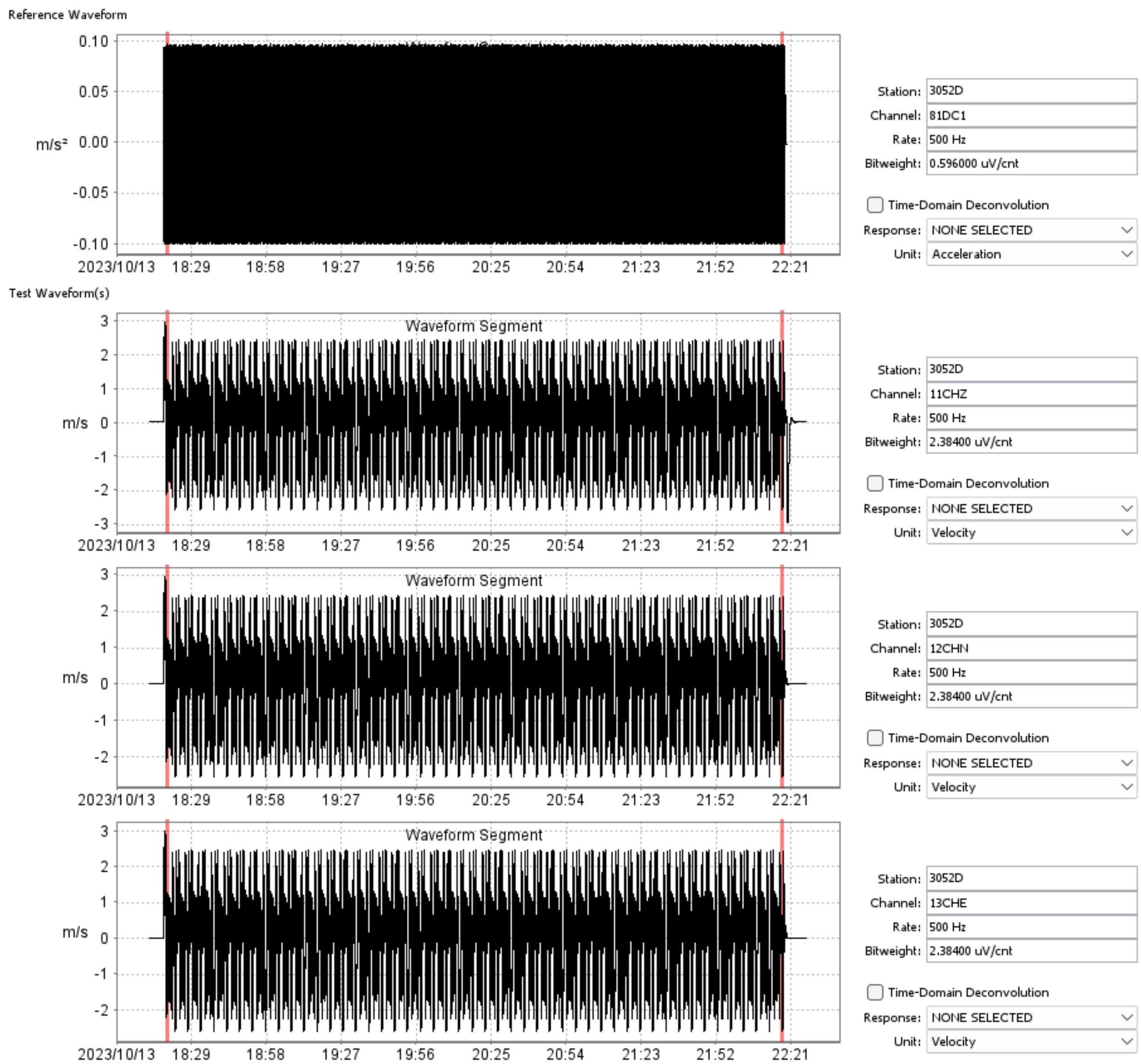


Figure 57 Colt 213011 Calibrator Frequency Response Time Series

The following plots show the calculated amplitude and phase response of the electrical calibration system for each of the three Colt sensors. Note that the manufacturer provides a unique calibration response value for each component of each sensor. The response is a single value, with units of (m/s^2)/Amp, which indicates that the response of the calibration system should not depend on frequency. In the figures below, the measured amplitude and phase response of the calibration system are compared to the specified response provided by the manufacturer. For the amplitude response plots, the amplitude data is shown with units of dB and has been normalized to the specified calibration system response. Hence if the measured response has a value of 0dB this would indicate it perfectly matches the specified response.

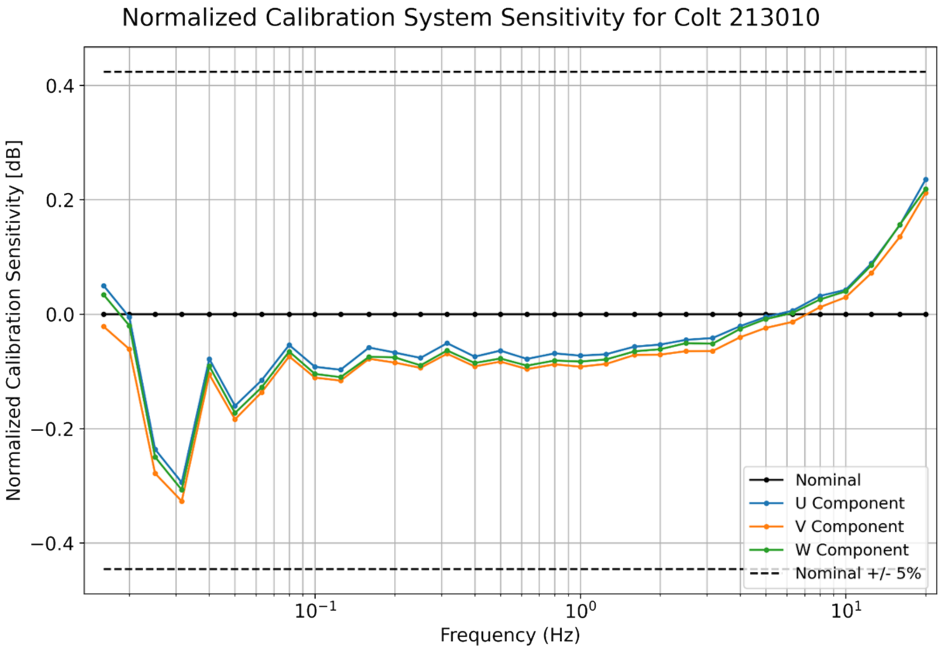


Figure 58 Colt 213010 Calibrator Amplitude Response

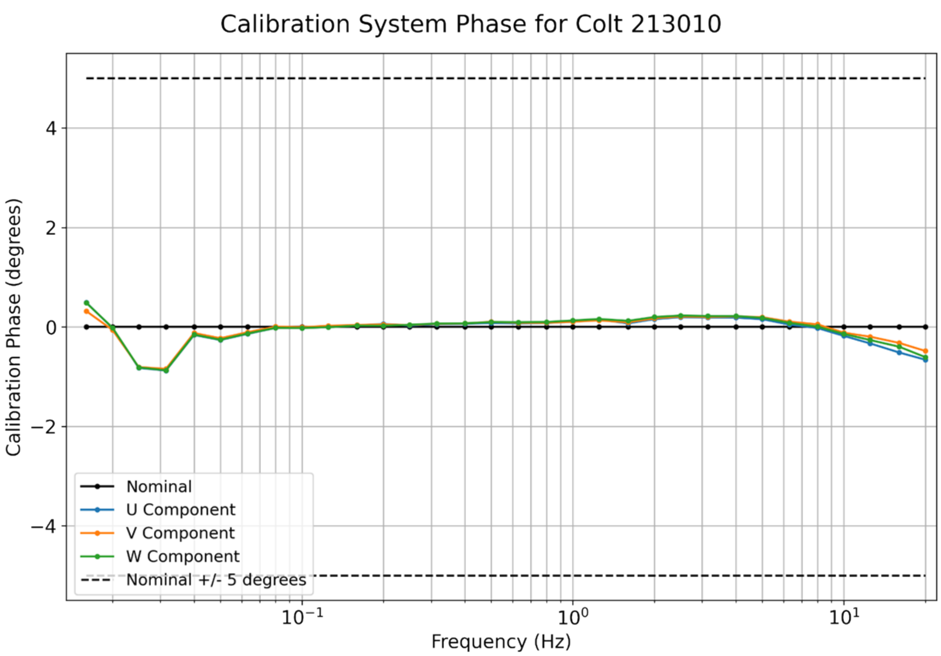


Figure 59 Colt 213010 Calibrator Phase Response

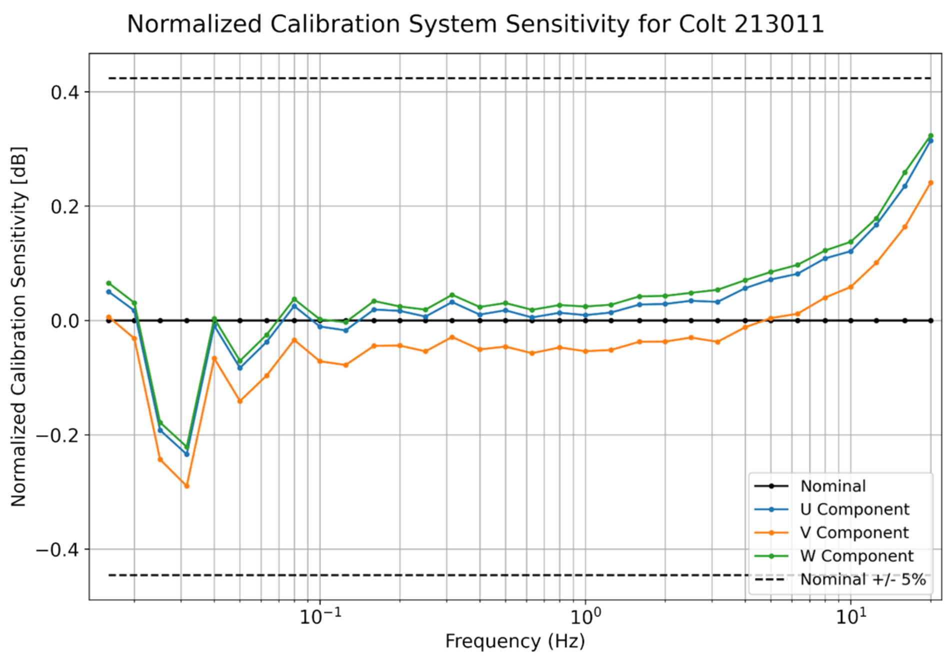


Figure 60 Colt 213011 Calibrator Amplitude Response

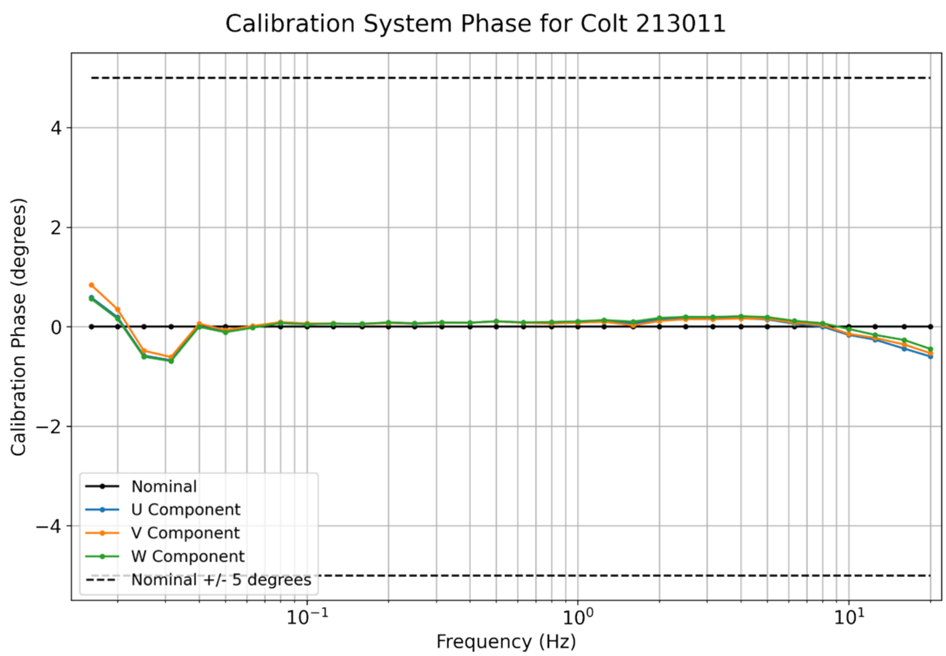


Figure 61 Colt 213011 Calibrator Phase Response

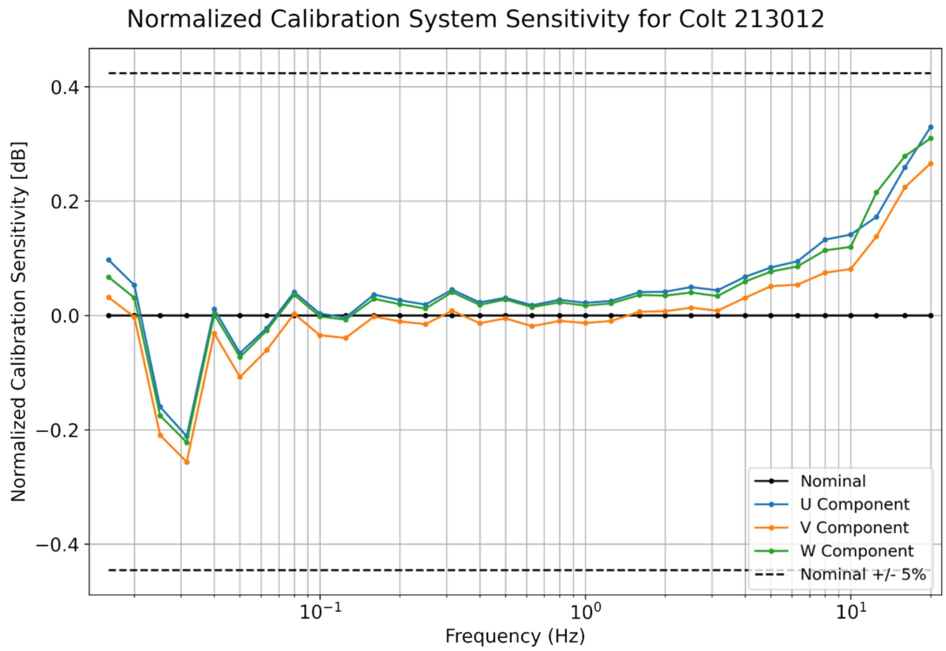


Figure 62 Colt 213012 Calibrator Amplitude Response

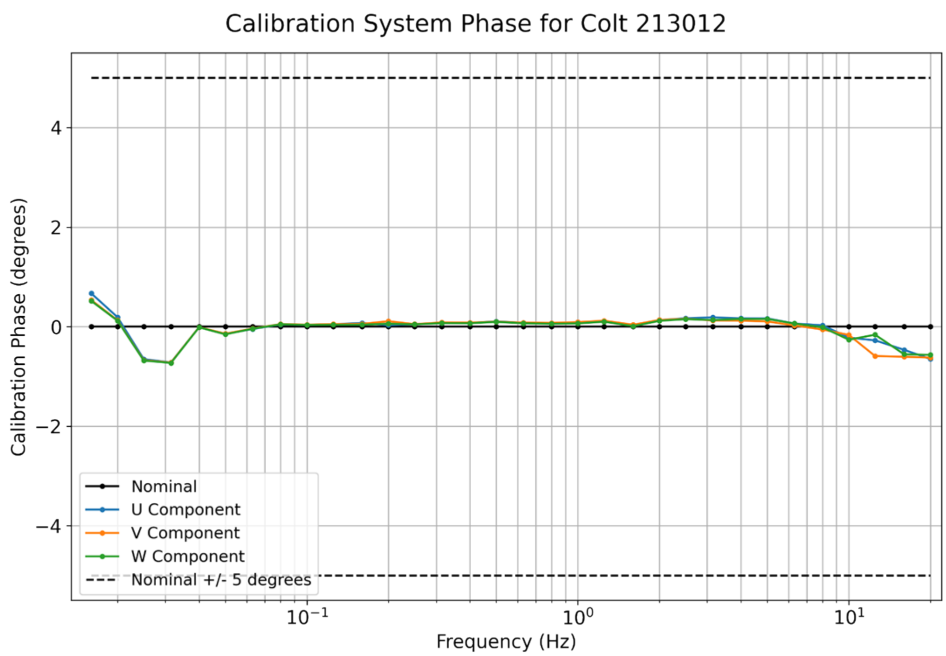


Figure 63 Colt 213012 Calibrator Phase Response

The measured calibration system responses of the three Colt sensors are all within ±5% and ±5 degrees of their specified amplitude and phase response across the entire evaluated frequency range of 0.02Hz-20Hz. The amplitude and phase response of the calibration system is generally flat from 0.02Hz-20Hz.

The following tables contains the values used to generate the above plots.

Table 45 Colt 213010 Calibrator Amplitude Response

Colt 213010 Calibrator Response						
	U component		W component		V component	
	Amplitude (m/s2/V)	Phase (Degrees)	Amplitude (m/s2/V)	Phase (Degrees)	Amplitude (m/s2/V)	Phase (Degrees)
Nominal	**0.0513**	**0.0000**	**0.0527**	**0.0000**	**0.0511**	**0.0000**
Frequency (Hz)	Amplitude (dB)	Phase (Degrees)	Amplitude (dB)	Phase (Degrees)	Amplitude (dB)	Phase (Degrees)
0.016	0.0498	0.4899	0.0339	0.4852	-0.0216	0.3180
0.02	-0.0054	-0.0219	-0.0201	-0.0161	-0.0611	-0.0610
0.025	-0.2362	-0.8249	-0.2496	-0.8163	-0.2783	-0.8079
0.0315	-0.2942	-0.8791	-0.3071	-0.8732	-0.3269	-0.8447
0.04	-0.0783	-0.1628	-0.0907	-0.1557	-0.1054	-0.1231
0.05	-0.1603	-0.2646	-0.1727	-0.2587	-0.1838	-0.2293
0.063	-0.1156	-0.1410	-0.1279	-0.1345	-0.1365	-0.1077
0.08	-0.0539	-0.0212	-0.0654	-0.0194	-0.0739	0.0055
0.1	-0.0920	-0.0221	-0.1044	-0.0229	-0.1110	-0.0063
0.125	-0.0971	-0.0066	-0.1101	-0.0065	-0.1161	0.0208
0.16	-0.0583	0.0291	-0.0745	0.0246	-0.0780	0.0390
0.2	-0.0672	0.0584	-0.0756	0.0231	-0.0847	0.0473
0.25	-0.0765	0.0262	-0.0895	0.0426	-0.0939	0.0382
0.315	-0.0507	0.0548	-0.0635	0.0677	-0.0692	0.0628
0.4	-0.0743	0.0619	-0.0853	0.0714	-0.0914	0.0697
0.5	-0.0638	0.0786	-0.0775	0.0971	-0.0829	0.1015
0.63	-0.0783	0.0688	-0.0901	0.0935	-0.0960	0.0815
0.8	-0.0685	0.0774	-0.0810	0.0992	-0.0878	0.0818
1	-0.0725	0.1048	-0.0828	0.1291	-0.0918	0.1040
1.25	-0.0701	0.1460	-0.0792	0.1582	-0.0871	0.1308
1.6	-0.0567	0.0708	-0.0650	0.1217	-0.0714	0.0914
2	-0.0533	0.1562	-0.0613	0.1979	-0.0707	0.1728
2.5	-0.0449	0.1950	-0.0508	0.2281	-0.0648	0.2096
3.15	-0.0418	0.1872	-0.0516	0.2182	-0.0645	0.1993
4	-0.0211	0.1859	-0.0258	0.2178	-0.0404	0.2128
5	-0.0048	0.1548	-0.0086	0.1814	-0.0240	0.1942
6.3	0.0060	0.0459	0.0020	0.0806	-0.0136	0.1047
8	0.0318	-0.0233	0.0257	0.0043	0.0122	0.0500
10	0.0426	-0.1812	0.0399	-0.1428	0.0296	-0.1176
12.5	0.0886	-0.3322	0.0856	-0.2645	0.0719	-0.1974
16	0.1559	-0.5150	0.1566	-0.3988	0.1352	-0.3226
20	0.2353	-0.6606	0.2189	-0.6092	0.2119	-0.4845

Table 46 Colt 213011 Calibrator Amplitude Response

Colt 213011 Calibrator Response						
	U component		W component		V component	
	Amplitude (m/s2/V)	Phase (Degrees)	Amplitude (m/s2/V)	Phase (Degrees)	Amplitude (m/s2/V)	Phase (Degrees)
Nominal	**0.0519**	**0.0000**	**0.0518**	**0.0000**	**0.0526**	**0.0000**
Frequency (Hz)	Amplitude (dB)	Phase (Degrees)	Amplitude (dB)	Phase (Degrees)	Amplitude (dB)	Phase (Degrees)
0.016	0.0502	0.5876	0.0655	0.5593	0.0061	0.8366
0.02	0.0172	0.1906	0.0309	0.1605	-0.0316	0.3499
0.025	-0.1919	-0.5818	-0.1785	-0.6037	-0.2432	-0.4841
0.0315	-0.2342	-0.6755	-0.2212	-0.6931	-0.2898	-0.6105
0.04	-0.0091	0.0098	0.0035	-0.0041	-0.0665	0.0587
0.05	-0.0832	-0.1023	-0.0707	-0.1126	-0.1410	-0.0666
0.063	-0.0375	-0.0139	-0.0251	-0.0214	-0.0965	0.0118
0.08	0.0252	0.0728	0.0374	0.0696	-0.0341	0.0903
0.1	-0.0107	0.0482	0.0019	0.0478	-0.0714	0.0626
0.125	-0.0173	0.0609	-0.0030	0.0595	-0.0780	0.0631
0.16	0.0191	0.0525	0.0339	0.0568	-0.0444	0.0510
0.2	0.0167	0.0779	0.0244	0.0831	-0.0440	0.0717
0.25	0.0068	0.0563	0.0188	0.0682	-0.0541	0.0622
0.315	0.0321	0.0782	0.0448	0.0826	-0.0290	0.0762
0.4	0.0102	0.0779	0.0235	0.0798	-0.0507	0.0780
0.5	0.0177	0.1039	0.0304	0.1089	-0.0458	0.1060
0.63	0.0052	0.0795	0.0186	0.0861	-0.0573	0.0766
0.8	0.0134	0.0765	0.0269	0.0917	-0.0473	0.0627
1	0.0093	0.0906	0.0243	0.1061	-0.0539	0.0788
1.25	0.0138	0.1086	0.0274	0.1317	-0.0517	0.0977
1.6	0.0277	0.0608	0.0421	0.1006	-0.0373	0.0250
2	0.0288	0.1424	0.0429	0.1737	-0.0370	0.1132
2.5	0.0344	0.1680	0.0483	0.1960	-0.0300	0.1495
3.15	0.0324	0.1680	0.0536	0.1932	-0.0374	0.1481
4	0.0563	0.1681	0.0703	0.2098	-0.0120	0.1649
5	0.0716	0.1443	0.0847	0.1904	0.0040	0.1585
6.3	0.0815	0.0589	0.0971	0.1162	0.0116	0.0786
8	0.1085	-0.0007	0.1222	0.0678	0.0398	0.0327
10	0.1210	-0.1663	0.1375	-0.0473	0.0586	-0.1471
12.5	0.1675	-0.2622	0.1787	-0.1665	0.1009	-0.2264
16	0.2351	-0.4412	0.2592	-0.2683	0.1637	-0.3595
20	0.3146	-0.5998	0.3233	-0.4472	0.2408	-0.5343

Table 47 Colt 213012 Calibrator Amplitude Response

Colt 213012 Calibrator Response						
	U component		W component		V component	
	Amplitude (m/s2/V)	Phase (Degrees)	Amplitude (m/s2/V)	Phase (Degrees)	Amplitude (m/s2/V)	Phase (Degrees)
Nominal	**0.0507**	**0.0000**	**0.0507**	**0.0000**	**0.0527**	**0.0000**
Frequency (Hz)	Amplitude (dB)	Phase (Degrees)	Amplitude (dB)	Phase (Degrees)	Amplitude (dB)	Phase (Degrees)
0.016	0.0970	0.6688	0.0670	0.5163	0.0315	0.5344
0.02	0.0528	0.1895	0.0308	0.1200	-0.0028	0.1276
0.025	-0.1599	-0.6526	-0.1752	-0.6819	-0.2095	-0.6746
0.0315	-0.2113	-0.7198	-0.2221	-0.7301	-0.2563	-0.7220
0.04	0.0108	-0.0125	0.0020	-0.0143	-0.0315	-0.0111
0.05	-0.0660	-0.1458	-0.0731	-0.1547	-0.1078	-0.1418
0.063	-0.0223	-0.0487	-0.0267	-0.0432	-0.0608	-0.0393
0.08	0.0409	0.0429	0.0360	0.0466	0.0028	0.0515
0.1	0.0033	0.0356	-0.0019	0.0348	-0.0346	0.0391
0.125	-0.0036	0.0478	-0.0074	0.0379	-0.0394	0.0504
0.16	0.0365	0.0739	0.0291	0.0387	-0.0020	0.0555
0.2	0.0265	0.0303	0.0196	0.0601	-0.0105	0.1084
0.25	0.0190	0.0512	0.0120	0.0459	-0.0152	0.0500
0.315	0.0449	0.0734	0.0406	0.0698	0.0082	0.0843
0.4	0.0227	0.0756	0.0184	0.0681	-0.0136	0.0813
0.5	0.0308	0.1051	0.0279	0.0951	-0.0052	0.0979
0.63	0.0178	0.0773	0.0145	0.0664	-0.0189	0.0806
0.8	0.0273	0.0676	0.0229	0.0579	-0.0096	0.0748
1	0.0220	0.0885	0.0171	0.0643	-0.0132	0.0902
1.25	0.0253	0.1095	0.0210	0.0993	-0.0098	0.1187
1.6	0.0406	0.0318	0.0357	0.0105	0.0064	0.0387
2	0.0414	0.1312	0.0347	0.1162	0.0073	0.1335
2.5	0.0495	0.1681	0.0400	0.1497	0.0136	0.1576
3.15	0.0439	0.1865	0.0339	0.1331	0.0082	0.1238
4	0.0674	0.1671	0.0592	0.1533	0.0309	0.1193
5	0.0838	0.1648	0.0766	0.1541	0.0510	0.1049
6.3	0.0947	0.0624	0.0858	0.0626	0.0538	0.0233
8	0.1325	0.0269	0.1138	-0.0139	0.0746	-0.0583
10	0.1414	-0.2207	0.1198	-0.2625	0.0812	-0.1664
12.5	0.1723	-0.2754	0.2151	-0.1626	0.1380	-0.5908
16	0.2590	-0.4666	0.2784	-0.5552	0.2240	-0.6059
20	0.3296	-0.6494	0.3099	-0.5675	0.2660	-0.6222

3.12 Sensor Control Line Functionality

The Colt seismometer has several control lines that were exercised throughout the testing. These include the unlock and lock control lines, mass recenter control line, the UVW output control line and the calibration enable control line. The calibration enable and the UVW output control lines were exercised in the Calibrator Frequency Response section, and the lock, unlock and mass re-center control lines were exercised throughout the testing but special attention was paid to their functionality during the Power Consumption section. Here, the functionality of these control lines is summarized.

3.12.1 Measurand

The sensors' ability to correctly execute the requested command after exercising of the appropriate control line.

3.12.2 Configuration

This functionality test is performed throughout the evaluation and the specific configuration of the instrument depends on the test being conducted.

3.12.3 Analysis

A qualitative assessment is performed to check if the sensor correctly performed the command after exercising of the control line.

3.12.4 Result

Table 48 summarizes the control line observations made during the evaluation.

Table 48 Summary of Control Line Functionality Verification

	9.5V Operation			12V Operation					18V Operation		
Sensor	Mass recenter	Lock	Unlock	Mass recenter	Lock	Unlock	UVW Mode	Cal Enable	Mass recenter	Lock	Unlock
Colt 213010	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colt 213011	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colt 213012	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The command and control of the three Colt sensors was correct and no issues were encountered during the evaluation.

4 SUMMARY

Power Consumption
The Colt sensors consumed between 0.78W to 0.79W at 12V. These values were slightly above the manufacturer specification of less than 0.7W. The sensors were fully functional when operated at input voltages of 9.5V, 12V and 18V.

Primary Sensitivity
The Colt sensors were found to have sensitivity values that were consistent with the manufacturer's specifications at 1 Hz. All measured 1Hz amplitude response values were within 1.5% of the nominal values and all measured phase response values were within 0.10 degrees of the nominal value.

Primary Frequency Response
The frequency response of the Colt sensors was evaluated with mechanical shake tables from 0.5Hz-20Hz for the vertical axis and 0.1Hz-20Hz for the North/South and East/West axes. The measured response for all sensors was within ±5% and ±5 degrees of the nominal amplitude and phase response for all three axes.

Reference Sensitivity
The Colt sensors were found to have reference sensitivity values that were consistent with the manufacturer's specifications at 1 Hz. The measured amplitude response values were all within 1.4% of the nominal values and the measured phase response values were all within 0.78 degrees of the nominal value.

Reference Frequency Response
The reference frequency response of the Colt sensors was evaluated from 0.01Hz to 20Hz. The measured amplitude and phase response of the three Colt sensors were within ±5% and ±5 degrees of the nominal amplitude and phase response for all three axes except for the vertical amplitude response of Colt 213010 at 20Hz. At this frequency, the measured response of the 213010 sensor was slightly more than 5% higher than the nominal response.

Passband
The Colt sensors all had a passband that exceeded the range of frequencies evaluated. That is, the lower corner of the passband was below 0.02Hz and the higher corner of the passband was above 20Hz.

Sensitivity vs Power Supply Voltage
The response of the vertical axis of the Colt sensors at 1Hz and 10Hz did not change as the power supply voltage changed from 9.0V to 18.0V.

Sensitivity vs Input Amplitude
The response of the Colt sensors from 1Hz to 10Hz did not appreciably change as the amplitude of the velocity signal increased from 10% to 98% of the full-scale value.

Full Scale
When the Colt sensors were exposed to a velocity signal with an amplitude equal to 98% of their clip level from 1Hz to 10Hz, all maintained a low distortion output signal from 1Hz to 10Hz.

The east axis of Colts 213011 and 213012 did have increased distortion at 10Hz when operated at 98% of full scale. The increase was modest but noticeable and likely indicates that the sensors are near their clipping level which is expected given the large test amplitude. The three Colt sensors correctly operated at 98% of their rated full-scale input and their amplitude and phase responses closely matched the nominal response model.

Self-Noise
The measured self-noise level of the vertical axis of the Colt sensors was generally below the New Low Noise Model (NLNM) from 0.04Hz to 8Hz. For the horizontal axes, the self-noise of the sensors was at or below the NLNM from 0.05Hz to 10Hz.

It is likely that the test location and non-idealities in the installation of the sensors resulted in higher noise levels. None the less, the measured noise levels of the Colts were consistent with the manufacturer's specifications across the range of frequencies that were free from significant levels of site and installation noise.

Dynamic Range
The measured dynamic ranges of the vertical axis of the Colt sensors were all greater than 134.56dB. The measured dynamic ranges of the horizontal axes were all greater than 128.50dB. All measured dynamic range values exceed the IMS requirements of greater than 120dB. Note that the actual seismometer dynamic range is expected to be higher than evaluated, due to the over-estimation of self-noise.

Calibrator Frequency Response
The calibrator frequency response of the Colt sensors closely matched the manufacturer's specifications. The amplitude and phase response of the calibration system is generally flat with frequency.

Sensor Control Line Functionality
The lock, unlock, recenter, calibration enable, and UVW mode control lines of all sensors functioned correctly.

References

1. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, Guide to the Expression of Uncertainty in Measurement, JCGM 100:2008 (GUM 1995 with minor corrections), 2008

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

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

4. IEEE Standard for Analog to Digital Converters, IEEE Std. 1241-2001.

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

6. 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.

7. Peterson, Jon. (1993). Observations and Modeling of Seismic Background Noise. Tech. rep., U.S. Geol. Surv. Open File Rep.. 93-322.

8. Bloomquist, Doug and Merchant, B. John (2023), 2023 Reftek Wrangler Digitizer Type Approval Evaluation, SAND2024-11238.

9. Bormann, Peter and Erhard Wielandt. “Seismic Signals and Noise.” (2013).

APPENDEX A: TEST REFERENCES

CS18 Shake Table Specifications

CS18P Seismic

Calibration System for Seismic Sensors

SPEKTRA

Components

- Vibration control system **SRS-35**
- Software CS18P with primary operation modes: Sensor Calibration, Measurement, Vibration Generation
- Vertical Excitation
  - ⇒ Air bearing vibration exciter **SE-13**
  - ⇒ Power amplifier **APS 125**
- Horizontal Excitation
  - ⇒ Air bearing vibration exciter **APS 129**
  - ⇒ Power amplifier **APS 125**
  - ⇒ Electronic zero position controller **APS 0109**
- Reference standard accelerometer **BN-07** or **BN-13** for secondary calibration according to ISO 16063-21
- Digital laser vibrometer **PLV-01** as **primary reference standard according to ISO 16063-11**
- **Prism** for the calibration of laser vibrometers
- Vibration isolation **VI-02** for vibrometer PLV-02

Specification of CS18P Seismic with **vertical** air bearing vibration exciter **SE-13** in the frequency range **0.1 Hz … 400 Hz** for sensor mass up to 50 kg (DUT) for environmental conditions: temperature 23°C (± 2°C) and relative humidity 30 % ... 75 %:

Frequency Range		Sensor Mass DUT	Expanded Measurement Uncertainty [2]	Working Range (peak value)		
from	to	vertical	Amount [3] / Phase [1]	Minimum	Maximum [4] (Displacement, Velocity, Acceleration)	Maximum [5] (Displacement, Velocity, Acceleration)
0.1 Hz	< 0.2 Hz	50 kg	1.5 % / 2.0°	0.1 Hz .. 400 Hz: **2.0 mm/s**	0.1 Hz .. 4 Hz: **10 mm**	0.2 Hz .. 4 Hz: **10 mm**
0.2 Hz	< 1 Hz		1.0 % / 1.0°		4 Hz .. 6.5 Hz: **250 mm/s**	4 Hz .. 25 Hz: **250 mm/s**
1 Hz	10 Hz		0.7 % / 1.0°		6.5 Hz .. 400 Hz: **10 m/s²**	25 Hz .. 120 Hz: **40 m/s²**
> 10 Hz	160 Hz	20 kg	1.5 % / 1.5°			120 Hz .. 400 Hz: **40 m/s².. 25 m/s²**
> 160 Hz	400 Hz	10 kg	2.0 % / 2.0°			
Ref. Freq.: 8 Hz			0.7 % / 1.0°			

Specification of CS18P Seismic with **horizontal** air bearing vibration exciter **APS 129** in the frequency range **0.1 Hz … 160 Hz** for sensor mass up to 30 kg (DUT) for environmental conditions: temperature 23°C (± 2°C) and relative humidity 30 % ... 75 %:

0.1 Hz	< 0.2 Hz	30 kg	1.5 % / 2.0°	0.2 Hz .. 400 Hz: **0.01 m/s²**	0.2 Hz .. 4 Hz: **10 mm**	0.2 Hz .. 4 Hz: **10 mm**
0.2 Hz	< 1 Hz		1.0 % / 1.0°		4 Hz .. 6.5 Hz: **250 mm/s**	4 Hz .. 25 Hz: **250 mm/s**
1 Hz	10 Hz		0.7 % / 1.0°		6.5 Hz .. 400 Hz: **10 m/s²**	25 Hz .. 120 Hz: **40 m/s²**
> 10 Hz	160 Hz	20 kg	1.5 % / 1.5°			120 Hz .. 400 Hz: **40 m/s².. 25 m/s²**
Ref. Freq.: 8 Hz			0.7 % / 0.7°			

1) Only in combination with optional extra PHASE
2) Determined according to GUM (ISO Guide to the expression of uncertainty in measurement) with k = 2 (coverage factor) for the best possible DUT (other devices that are not as ideal have to be evaluated with individual additions)
3) Values only valid for electrical sensor signals ≥ (1 mV or 1 pC)
4) Maximum acceleration for maximum payload (DUT)
5) Maximum acceleration without any payload (DUT)

Options for calibration systems CS18P Seismic:

- **EF**: Extended frequency range from 0.05 Hz
- **TABLE**: granite plate on block of sandstone or concrete to mount and use the system properly

All data are subject to change without notice

November 2016

SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany

www.spektra-dresden.com

Figure 64 SPEKTRA CS18P Specifications

Nominal Response Model for Colt Sensors

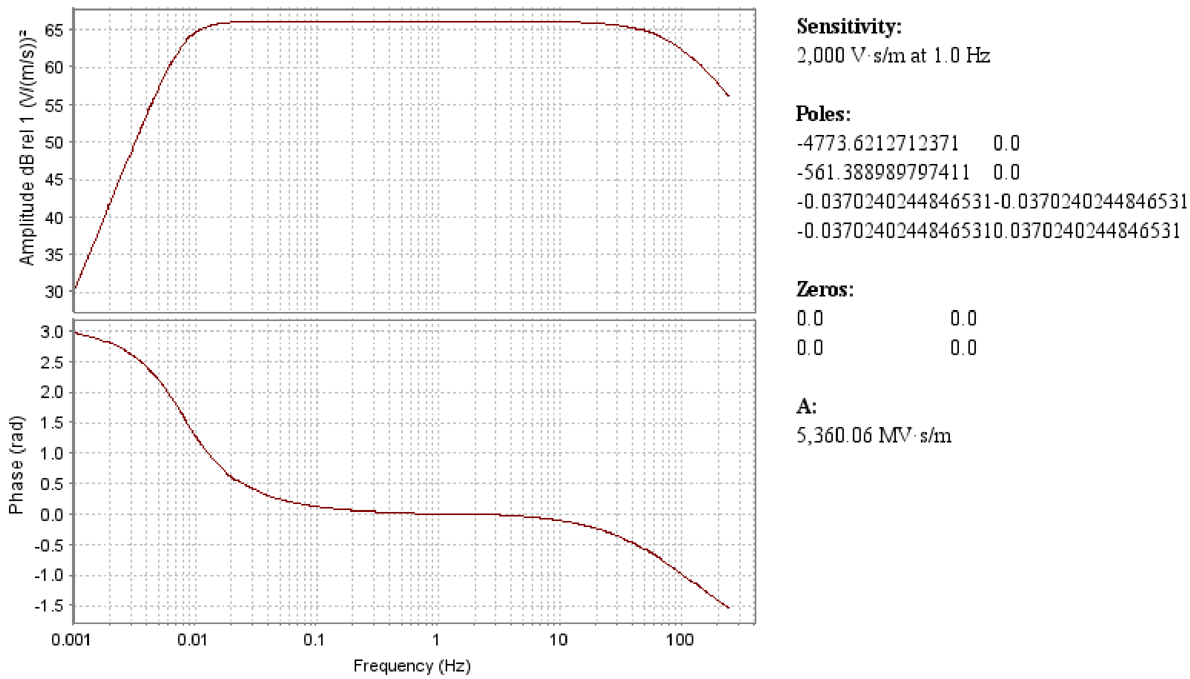


Figure 65 Nominal Response Model for Colt Sensors

Calibration Sheet for Colt 213010

REF TEK
SYSTEMS INC.

Colt_120 **Broadband Seismometer** **Date:** 2024-11-29

P/N: R-117400-120 **120 Second** **S/N:** 213010

Component	Period (sec)	Damping Coefficient	Output Voltage Sensitivity (V/(m/s))	Calibration Sensitivity (m/s^2/A)	Component	Output Voltage Sensitivity (V/(m/s))
U	119.58	0.694	2009.41	9.61	Z	2011.81
W	119.41	0.710	2009.50	9.89	N	2015.26
V	120.63	0.697	2010.19	9.58	E	2008.57

Zeros: 2 radians

z1 = 0
z2 = 0

Poles: 4 radians

U	p1 =	-0.036465 +0.037830 i	p2 =	-0.036465	-0.037830 i
	p3 =	-561.389	p4 =	-4773.621	
W	p1 =	-0.037359 +0.037054 i	p2 =	-0.037359	-0.037054 i
	p3 =	-561.389	p4 =	-4773.621	
V	p1 =	-0.036304 +0.037350 i	p2 =	-0.036304	-0.037350 i
	p3 =	-561.389	p4 =	-4773.621	

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REF TEK SYSTEMS INC. reftek.com HIGH RESOLUTION SEISMIC RECORDERS, SENSORS & SOFTWARE

Figure 66 Calibration Sheet for Colt 213010

Calibration Sheet for Colt 213011

REFTEK SYSTEMS INC.

Colt_120 **Broadband Seismometer** **Date:** 2024-11-29

P/N: R-117400-120 **120 Second** **S/N:** 213011

Component	Period (sec)	Damping Coefficient	Output Voltage Sensitivity (V/(m/s))	Calibration Sensitivity (m/s^2/A)	Component	Output Voltage Sensitivity (V/(m/s))
U	120.93	0.715	2000.11	9.74	Z	2000.97
W	120.80	0.715	1999.90	9.72	N	1998.85
V	120.51	0.702	2002.72	9.86	E	1999.64

Zeros: 2 radians

z1 = 0

z2 = 0

Poles: 4 radians

U	p1 =	-0.037149	+0.036325 i	p2 =	-0.037149	-0.036325 i
	p3 =	-561.389		p4 =	-4773.621	
W	p1 =	-0.037189	+0.036364 i	p2 =	-0.037189	-0.036364 i
	p3 =	-561.389		p4 =	-4773.621	
V	p1 =	-0.036601	+0.037132 i	p2 =	-0.036601	-0.037132 i
	p3 =	-561.389		p4 =	-4773.621	

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Figure 67 Calibration sheet for Colt 213011

Calibration Sheet for Colt 213012

Colt_120 **Broadband Seismometer** **Date: 2024-11-29**

P/N: R-117400-120 **120 Second** **S/N: 213012**

Component	Period (sec)	Damping Coefficient	Output Voltage Sensitivity (V/(m/s))	Calibration Sensitivity (m/s^2/A)	Component	Output Voltage Sensitivity (V/(m/s))
U	119.75	0.703	1991.25	9.51	Z	1999.81
W	120.99	0.708	1990.90	9.50	N	1992.05
V	120.63	0.716	2011.92	9.89	E	2003.36

Zeros: 2 radians

z1 = 0

z2 = 0

Poles: 4 radians

U	p1 =	-0.036886 +0.037316 i	p2 =	-0.036886 -0.037316 i
	p3 =	-561.389	p4 =	-4773.621
W	p1 =	-0.036767 +0.036675 i	p2 =	-0.036767 -0.036675 i
	p3 =	-561.389	p4 =	-4773.621
V	p1 =	-0.037294 +0.036362 i	p2 =	-0.037294 -0.036362 i
	p3 =	-561.389	p4 =	-4773.621

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Figure 68 Calibration sheet for Colt 213012

Nominal Response Model for STS-2 Generation 3 Serial Number: 120651 and 1Hz Sensitivity Values Measured with the CS18P.

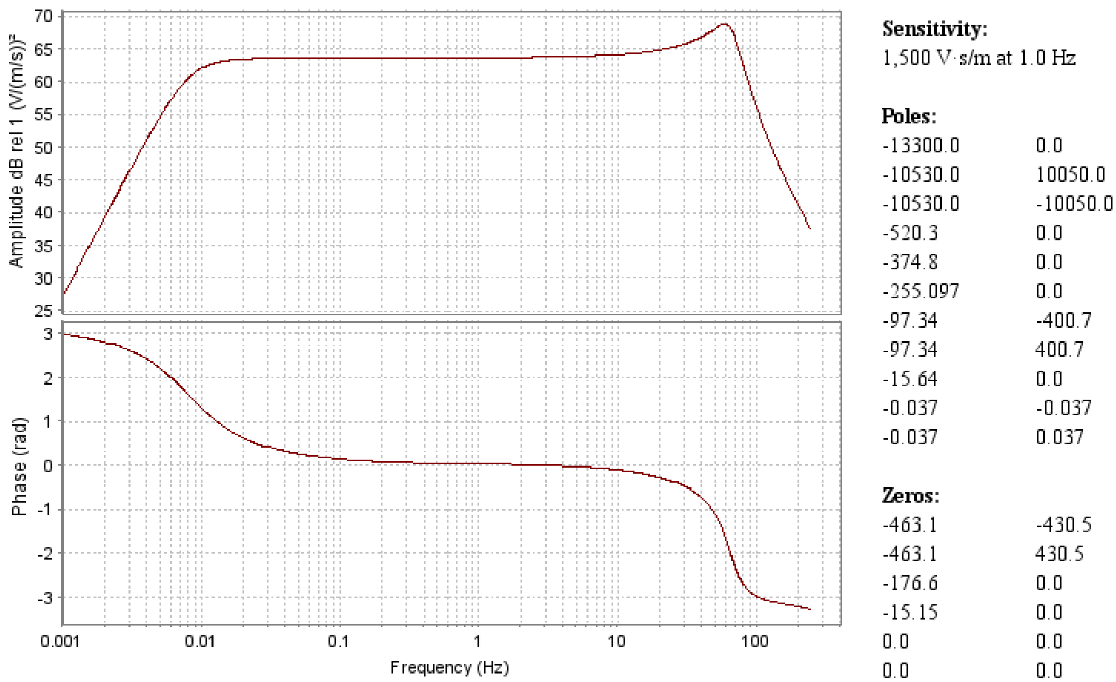

Figure 69 Nominal Response Model for STS-2 Generation 3

Table 49 1Hz Sensitivity Values for STS-2 120651

STS-2 120651 1Hz Sensitivity	
Axis	Gain (V/(m/s))
Vertical	1497.13
North-South	1492.31
East-West	1490.76
Nominal	1500.00

Distribution

Email—External

Name	Company Email Address	Company Name

Email—Internal

Name	Org.	Sandia Email Address
Technical Library	9536	libref@sandia.gov

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