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Laboratories

2023 T120 Horizon and Slim Posthole Seismometer Exploratory Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated a suite of four T120 broadband seismometers designed and manufactured by Nanometrics. Specifically, two T120 Horizon V2 sensors, one T120 Horizon V1 sensor and one T120 Slim Posthole (PH) sensor were evaluated. 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 T120 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).

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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
DUT	Device Under Test
DWR	Digital Waveform Recorder
GPS	Global Position System
GNSS	Global Navigation Satellite System
HNM	High Noise Model
IMS	International Monitoring System
LNМ	Low Noise Model
PH	Posthole
PSD	Power Spectral Density
SI	International System of Units
SNL	Sandia National Laboratories
SUT	Sensor Under Test

1 INTRODUCTION

The evaluation of the Trillium 120 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 T120 Slim Posthole 2024, T120 Horizon V2 2029, T120 Horizon V2 2028 and T120 Horizon V1 0769.



Figure 1 T120 Seismometers Included in the Evaluation

The T120 Slim Posthole and T120 Horizon V2 sensors were provided by Nanometrics. The T120 Horizon V1 sensor is owned by SNL and included in the evaluation.

The T120 Horizon, and T120 Slim PH specifications along with the IMS minimum requirements for primary and auxiliary seismological stations are shown in the figures below.

TECHNICAL SPECIFICATIONS TRILLIUM HORIZON

Specifications subject to change without notice

TECHNOLOGY

Topology: Symmetric triaxial

Feedback: Force balance with capacitive transducer

Mass centering: Automatic mechanical recentering, can be remotely initiated

PERFORMANCE

Self-noise: See self-noise graph

Sensitivity/model TH120-2-2000: (Nominal) 2000 V-s/m; (Actual) 1999.1 V-s/m $\pm 0.5\%$

Sensitivity/all other models: (Nominal) 1200 V-s/m; (Actual) 1202.5 V-s/m $\pm 0.5\%$

Accuracy: $\pm 0.5\%$ relative to User Guide specification

Bandwidth: -3 dB points at 120 s and 150 Hz

Clip level:

- 16.6 mm/s up to 10 Hz and 0.12 g above 10 Hz (Standard, Polar Certified & Magnetic Shield Models)
- 10.0 mm/s up to 20 Hz and 0.12 g above 20 Hz (2000 V/s/m Model)

Dynamic Range:

- 168 dB @ 1 Hz (Standard, Polar Certified & Magnetic Shield Models)
- 164 @ 1 Hz (2000 V/s/m Model)

Operating Tilt Range: $\pm 1.5^\circ$

Temperature: $\pm 45^\circ\text{C}$ without recentering

Magnetic Sensitivity: $< 0.03 \text{ (m/s}^2\text{)}/\text{T}$ (Polar Certified & Magnetic Shield Models)

AVAILABLE MODELS

TH120-2: Standard Model

TH120-2-XC: Polar Certified Model

TH120-2-M: Magnetic Shield

TH120-2-2000: 2000 V/s/m

INTERFACE

Connector: 19-pin UTS7-14D19P32

Velocity Output: 40 V peak-to-peak differential

- Selectable XYZ or UVW mode

Mass Position Output: Three independent $\pm 4 \text{ V}$ outputs

Calibration Input: Single voltage input with one active-high control signal for all channels; calibration with XYZ or UVW

Control Lines: Mass Center, Calibration Enable, XYZ/UVW mode

Serial Port:

- RS-232 compatible serial IP (SLIP) with onboard HTTP web server to select sensor operating modes, to mass center, and to access state-of-health, virtual level bubble, firmware updates and metadata
- Plug-and-Play automated workflow interface to select sensor operating modes, and to access state-of-health, virtual level bubble and metadata

LEVELING AND ALIGNMENT

Bubble level: Removable

Digital bubble level: Graphical bullseye level is available via Centaur digital recorder GUI

Alignment: Vertical scribe marks for (N and S); precision guide in cover for straight-edge, line, or laser level

Digital tiltmeter: Reports case tilt from vertical for easy installation and remote troubleshooting when using Centaur digital recorder

POWER

Supply Voltage: 9 to 36 V DC isolated input

Power Consumption: 230 mW typical quiescent

Protection:

- Reverse-voltage and over-voltage protected
- Self-resetting over-current protection

PHYSICAL

Diameter: 170 mm

Height: 174 mm, not including connector, feet

- 241 mm with handle and feet

Weight: 9.7 kg

Handling: Detachable lifting handle included

Optional: Internal magnetic shield

ENVIRONMENTAL

Operating Temperature:

- -20°C to 60°C (Standard & Magnetic Shield Models)
- -50°C to 60°C (Polar Certified Model)

Storage Temperature:

- -40°C to $+70^\circ\text{C}$ (Standard & Magnetic Shield Models)
- -60°C to $+70^\circ\text{C}$ (Polar Certified Model)

Optional: Insulating cover available for quick and convenient installation

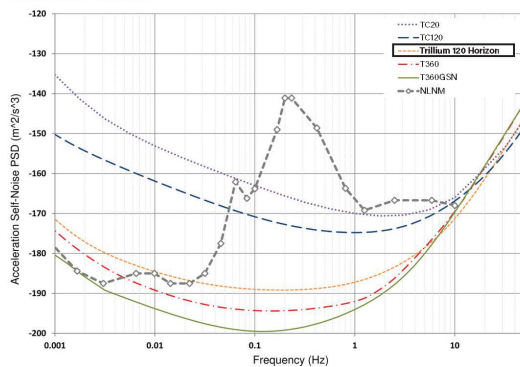
Humidity: 0% to 100% (submersible)

Shock:

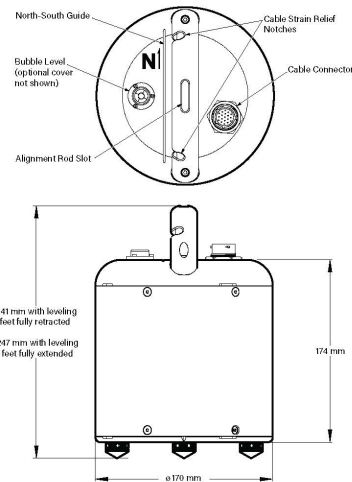
- 20 g half sine, 5 ms without damage, 6 axes
- no mass lock required for transport

Ingress Protection: (Standard Models) Rated to IP68 and NEMA 6P to 10m for prolonged immersion (Polar Certified Model) Rated to IP68 at 2 m for 72 hours when connector is mated

SELF-NOISE GRAPH



Seismometer self-noise plotted against NLNM (after Peterson, 1993) and MLNM (after McNamara and Buland, 2004)



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Figure 2 T120 Horizon Technical Specifications (from Nanometrics Datasheet)

TECHNICAL SPECIFICATIONS TRILLIUM 120 SLIM PH

Specifications subject to change without notice

SEISMOMETER

TECHNOLOGY

Topology: Symmetric triaxial

Feedback: Force balance with capacitive transducer

Mass Centering: Automatic motorized re-centering, can be remotely initiated

LEVELING & ALIGNMENT

Digital Bubble Level: Graphical bullseye level is available via Centaur digital recorder GUI

Alignment: Case-top north-south guide for straight-edge, line, or laser level; Vertical scribe marks for north and south on base

Digital Tiltmeter: Reports case tilt from vertical for easy installation and remote troubleshooting when using Centaur digital recorder

PERFORMANCE

Self-noise: See plot

Sensitivity: (Nominal) 1200 V-s/m; (Actual) 1202.5 V-s/m $\pm 0.5\%$

Accuracy: $\pm 0.5\%$ relative to User Guide specification

Bandwidth: -3 dB points at 120 s and 150 Hz

Clip Level: 16.6 mm/s up to 10 Hz and 0.12 g above 10 Hz

Dynamic Range: 168 dB @ 1 Hz

Oper. Tilt Range: 0° to 4° from vertical

Temperature: $\pm 45^\circ\text{C}$ without re-centering

Magnetic Sensitivity: $1 (\text{m/s}^2)/\text{T}$ (Standard Model) $< 0.03 (\text{m/s}^2)/\text{T}$ (Polar Certified & Magnetic Shield Models)

AVAILABLE MODELS

T120-SPH2: Standard Model

T120-SPH2-XC: Polar Certified Model, Magnetic Shield

T120-SPH2-M: Standard Model, Magnetic Shield

INTERFACE

Connector: 20-pin marine

Velocity Output: 40 V peak-to-peak

• Selectable XYZ or UVW mode

Mass Position Output: Three independent $\pm 4\text{V}$ outputs for UVW

Calibration Input: Single voltage input for all channels, single calibration enable pin for all channels

• Calibration in XYZ or UVW

• Independent channel selection by serial port

Control Lines: Mass Center, Calibration Enable, XYZ/UVW mode

Serial Port:

• RS-232 compatible serial IP (SLIP) with onboard HTTP web server to select sensor operating modes, to mass center, and to access state-of-health, virtual level bubble, firmware updates and metadata

• Plug-and-Play automated workflow interface to select sensor operating modes, and to access state-of-health, virtual level bubble and metadata

POWER

Supply Voltage: 9 to 36 Volts DC isolated input

Power Consumption: 230 mW typical quiescent

Protection:

• Reverse-voltage and over-voltage protected

• Self-resetting over-current protection

PHYSICAL

Case Design: Stainless steel pressure vessel

Diameter: 104 mm (Standard Model)

106 mm (Polar Certified & Magnetic Shield Models)

Height: 444 mm (Standard Model)*

455 mm (Polar Certified & Magnetic Shield Models)*

*Not including handle

Weight: 10 kg (Standard Model)

~11.5 kg (Polar Certified & Magnetic Shield Models)

Hoisting Attachment Point: Handle on lid for lifting cable 1500 lb rated

ENVIRONMENTAL

Operating Temperature:

-20°C to 60°C (Standard & Magnetic Shield Models)

-50°C to 60°C (Polar Certified Model)

Storage Temperature:

-40°C to +70°C (Standard & Magnetic Shield Models)

-60°C to +70°C (Polar Certified Model)

Shock: 20 g half sine, 5 ms without damage, 6 axis

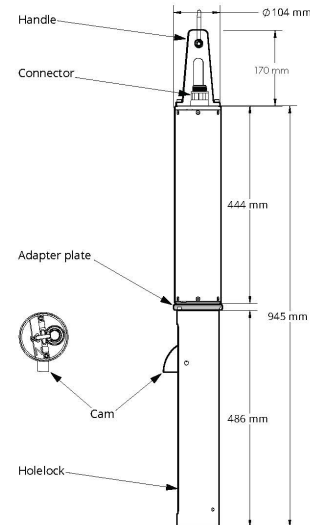
• No mass lock required for transport

Humidity: 0% to 100% (submersible)

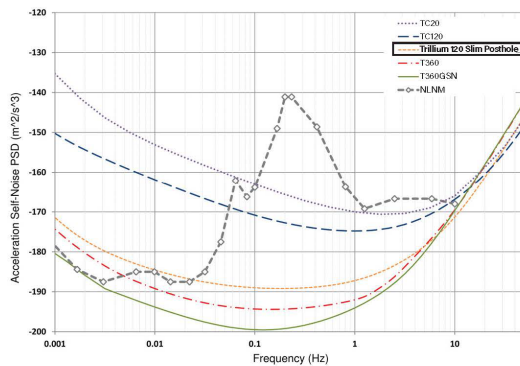
Pressure: Enclosure optimized to be insensitive to atmospheric variations

Ingress Protection: Seismometer is rated to IP68 and NEMA6P to 300 m for prolonged immersion

SLIM PH WITH OPTIONAL HOLE-LOCK FOR BOREHOLE APPLICATIONS (Standard Model shown)



SELF-NOISE GRAPH



Seismometer self-noise plotted against NLNM (after Peterson, 1993) and MLNM (after McNamara and Buland, 2004)

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Figure 3 T120 Slim PH Technical Specifications (from Nanometrics 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 4 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 to evaluate 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 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 analyses based on these standards were 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 5, and in the subterranean bunker shown in Figure 6 and Figure 7.



Figure 5 FACT Site Seismic Calibration System



Figure 6 FACT Site Subterranean Bunker



Figure 7 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 8 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)
Comparison Sensitivity at 1Hz
Comparison 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 13 to December 5, 2023.

Table 2 Timeline of Testing

Day	Time (Local)	Description
October 13, 2023	Morning	Start Electrical Calibration Tests: • Long and short duration Pseudo Random Binary Signal Calibrations • Verification of UVW and Calibration Enable control lines
October 17, 2023	Afternoon	Complete Electrical Calibration Tests
November 3, 2023	Morning	Start shake table tests: • Primary Sensitivity • Primary Frequency Response • Sensitivity vs power supply voltage • Sensitivity vs input amplitude • Full Scale
November 21, 2023	Afternoon	Complete shake table testing
November 27, 2023	Morning	Install sensors in FACT bunker for: • Comparison Sensitivity • Comparison Frequency Response • Self-Noise
December 5, 2023	Morning	Complete Comparison Sensitivity, Comparison Frequency Response and Self Noise
December 5, 2023	Afternoon	Power Testing Mass recenter control line verification

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 $n = -17, -16, \dots, 12, 13$. 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 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.

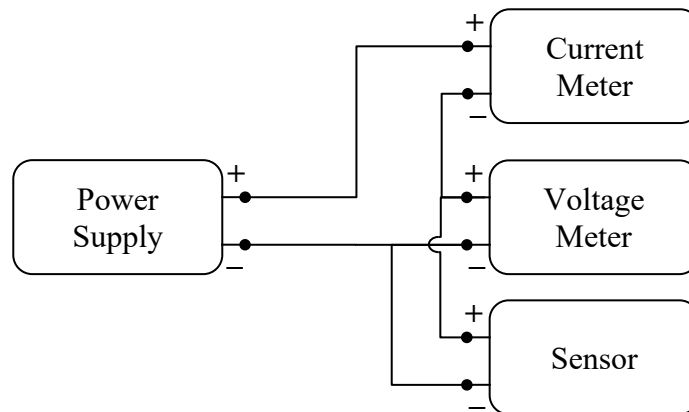


Figure 9 Power Consumption Configuration Diagram



Figure 10 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.

The first figure shows T120 Horizon V2 2029's steady state voltage and current waveforms. The next figure shows its voltage and current waveforms during start up. The third figure shows the voltage and current waveforms during a re-center operation.

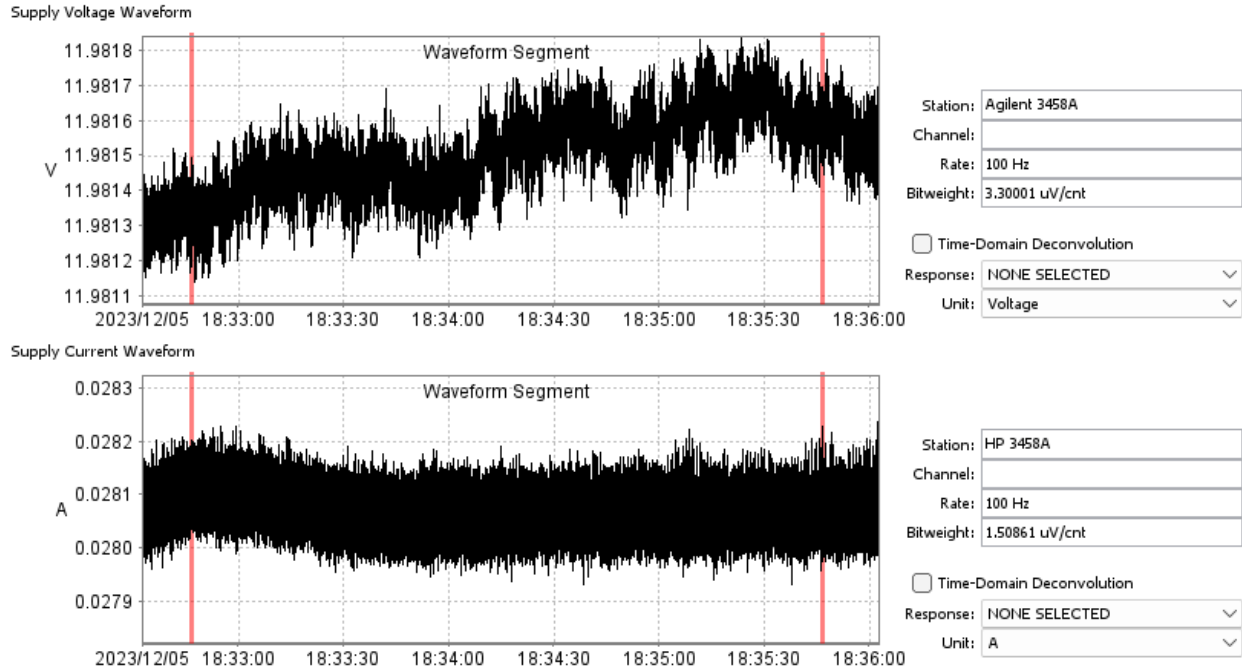


Figure 11 T120 Horizon V2 2029 Voltage and Current Waveforms in Steady State Operation

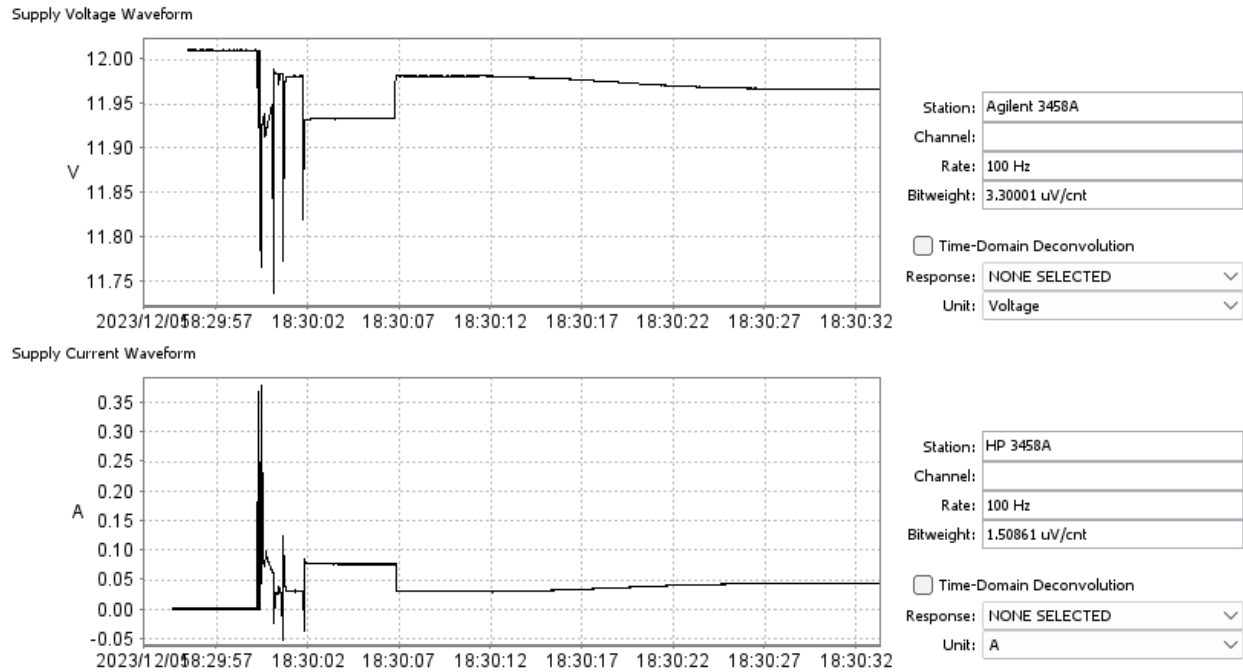


Figure 12 T120 Horizon V2 2029 Voltage and Current Waveforms During Start Up

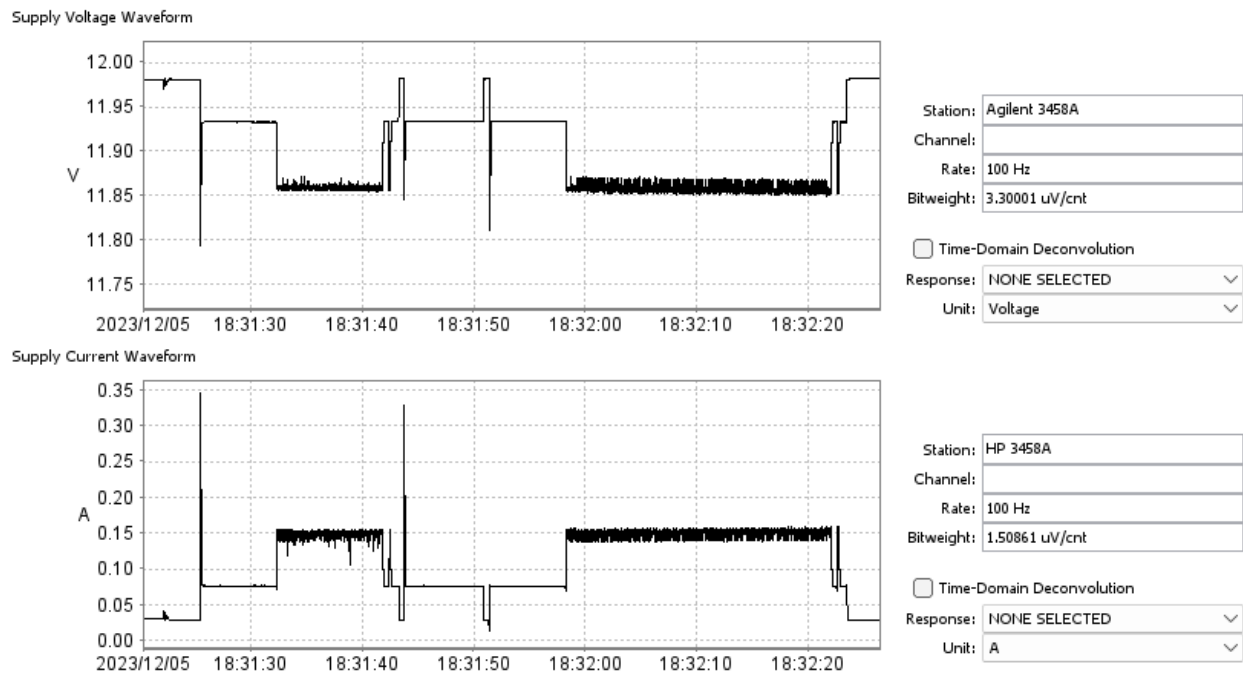


Figure 13 T120 Horizon V2 2029 Voltage and Current Waveforms During Recenter Operation

The resulting voltage, current, and power consumption levels are shown in Table 4, below. In addition, the peak current use of the sensor for each test is listed in Table 5. Table 5 also lists the operation the sensor was undertaking 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
T120 Horizon V2 2029	9.50 V	0.12 mV	23.85 mA	0.04 mA	0.23 W	0.40 mW
	12.19 V	0.23 mV	18.48 mA	0.04 mA	0.23 W	0.52 mW
	30 V	0.09 mV	7.61 mA	0.03 mA	0.23 W	0.94 mW
T120 Horizon V2 2028	9.49 V	0.06 mV	22.90 mA	0.044 mA	0.22 W	0.41 mW
	12 V	0.10 mV	18.09 mA	0.05 mA	0.22 W	0.55 mW
	30 V	0.21 mV	7.66 mA	0.03 mA	0.23 W	0.94 mW
T120 Horizon V1 0769	9.46 V	0.07mV	51.24 mA	0.03 mA	0.48 W	0.32 mW
	11.97 V	0.10 mV	40.68 mA	0.03 mA	0.49 W	0.35 mW
	30 V	0.13 mV	19.41 mA	0.05 mA	0.58 W	1.38 mW
T120 Slim PH 2024	9.49 V	0.17 mV	22.74 mA	0.17 mA	0.22 W	1.64 mW
	12 V	0.07 mV	17.69 mA	0.05 mA	0.21 W	0.58 mW
	30 V	0.11 mV	7.49 mA	0.029 mA	0.22 W	0.86 mW

Table 5 Peak Current Use

Sensor	Supply Voltage	Peak Current Use	Operation
T120 Horizon V2 2029	9.50 V	0.47 A	Start Up
	12 V	0.43 A	Start Up
	30 V	0.24 A	Start Up
T120 Horizon V2 2028	9.49 V	0.40 A	Recenter
	12 V	0.78 A	Start Up
	30 V	0.76 A	Recenter
T120 Horizon V1 0769	9.46 V	0.48 A	Start Up
	11.97 V	0.21 A	Start Up
	30 V	0.08 A	Start Up
T120 Slim PH 2024	9.49 V	0.42 A	Recenter
	12 V	0.77 A	Start Up
	30 V	0.80 A	Start Up

The specification sheets for the T120 Horizon V2 and the T120 Slim PH state that the units consume 230mW of power in typical operation. The specification sheet for the T120 Horizon V1 states that the sensor consumes 490mW of power under normal operating conditions. The four sensors evaluated here were found to have power consumption levels that matched these specifications. Additionally, all four sensors operated successfully when tested at 9.5V, 12V and 30V.

The peak current use by any of the four sensors was 0.8A which occurred during the startup period of T120 Slim BH 2024 when it was operating at 30V. This value is an average of the current usage during a 0.01s 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 first powers up.

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 T120 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 T120 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 shows photos of the T120 sensors installed on the horizontal and vertical calibration tables.

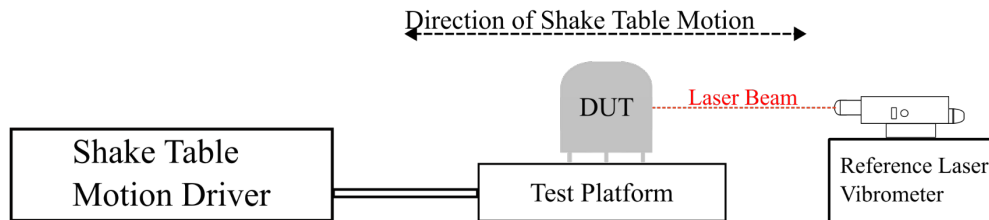


Figure 14 Horizontal Sensitivity Testbed

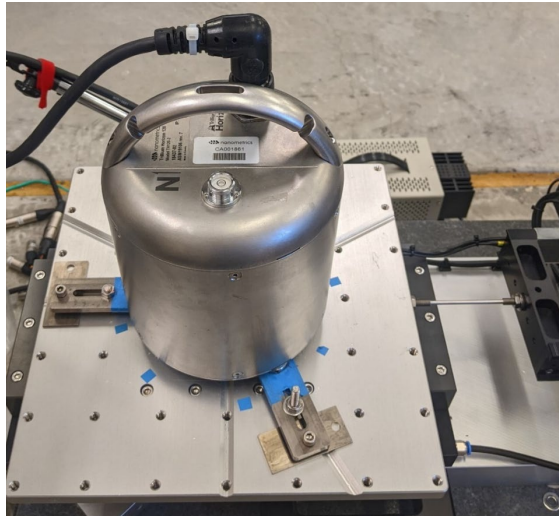


Figure 15 T120 Slim PH installed on vertical shake table (left) and T120 Horizon installed on horizontal shake table (right)

Table 6 Sensitivity Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.64 mm/s Frequency = 1Hz Pressure = 820.8 ± 5.1hPa Temperature = 22.7 ± 0.7C Humidity = 20.7 ± 6.7%

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 provides 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 illustrated in the Figure below.

**Figure 16 T120 Horizon Sensor Clamped to the Horizontal Shake Table**

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 terms of the fitted sinusoidal equations:

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

The sensor phase sensitivity in degrees is computed using the phase terms 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 (V/m/s)	Uncertainty (k=2, %)	Phase (Degrees)	Uncertainty (k=2, degrees)
T120 Horizon 2029	1.64	1201.50	0.7	0.30	1.0
T120 Horizon 2028	1.64	1200.55	0.7	0.31	1.0
T120 Horizon 0769	1.64	1206.70	0.7	0.41	1.0
T120 Slim BH 2024	1.64	1203.85	0.7	0.27	1.0
Nominal		1202.5		0.5	

North-South Axis					
Sensor	Test Velocity (mm/s)	Amplitude (V/m/s)	Uncertainty (k=2, %)	Phase (Degrees)	Uncertainty (k=2, degrees)
T120 Horizon 2029	1.64	1207.60	0.7	0.34	1.0
T120 Horizon 2028	1.64	1205.30	0.7	0.34	1.0
T120 Horizon 0769	1.64	1203.00	0.7	0.48	1.0
T120 Slim BH 2024	1.64	1202.85	0.7	0.28	1.0
Nominal		1202.5		0.5	

East-West Axis					
Sensor	Test Velocity (mm/s)	Amplitude (V/m/s)	Uncertainty (k=2, %)	Phase (Degrees)	Uncertainty (k=2, degrees)
T120 Horizon 2029	1.64	1206.15	0.7	0.32	1.0
T120 Horizon 2028	1.65	1204.65	0.7	0.31	1.0
T120 Horizon 0769	1.65	1202.85	0.7	0.47	1.0
T120 Slim BH 2024	1.63	1207.30	0.7	0.25	1.0
Nominal		1202.5		0.5	

The measured amplitude response values are all within 0.4% of the nominal value. The measured phase values are all within 0.25 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.

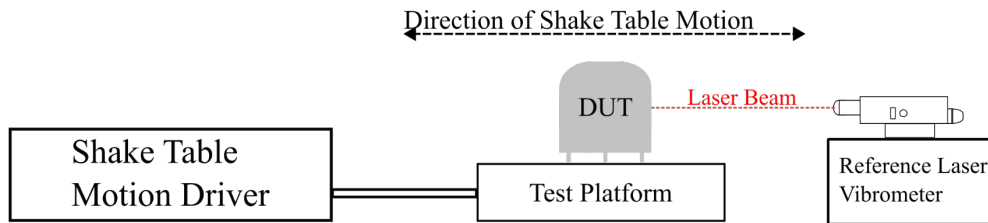


Figure 17 Primary Frequency Response Configuration Diagram

Table 8 Primary Frequency Response Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.64 mm/s Frequency = 0.1-20Hz Pressure = 820.8 ± 5.1hPa Temperature = 22.7 ± 0.7C Humidity = 20.7 ± 6.7%

The SUT is clamped to the surface of the shake table for both horizontal and vertical testing as shown in Figure 16.

3.3.3 Analysis

The Spektra CS18P system 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). Despite having different model numbers and form factors all the T120 sensors included in this evaluation have the same nominal frequency response. This nominal response 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 1Hz sensitivity. Hence the nominal response curve in the following plots will have an amplitude response of 0dB at 1Hz.

The specified k=2 uncertainties for the CS-18P system are shown as shaded regions around the response trace for each sensor. The vertical shake table generates a large 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. Additionally, the T120 Slim Posthole sensor exhibited a mechanical resonance when its North/South and East/West axes were evaluated on the horizontal shake table. This resonance is likely due to the tall and narrow form factor of the sensor and the fact that it is coupled to the shake table surface at its base only. The sensor is designed to be installed in a posthole or borehole and coupled to the earth or casing along its entire length. When installed in the intended manner we expect that the mechanical resonance will be eliminated. To avoid presenting misleading data, the horizontal

response plots below do not show data above 7Hz for the T120 Slim Posthole. For the three Horizon T120 sensors, horizontal response data is shown from 0.1Hz to 20Hz.

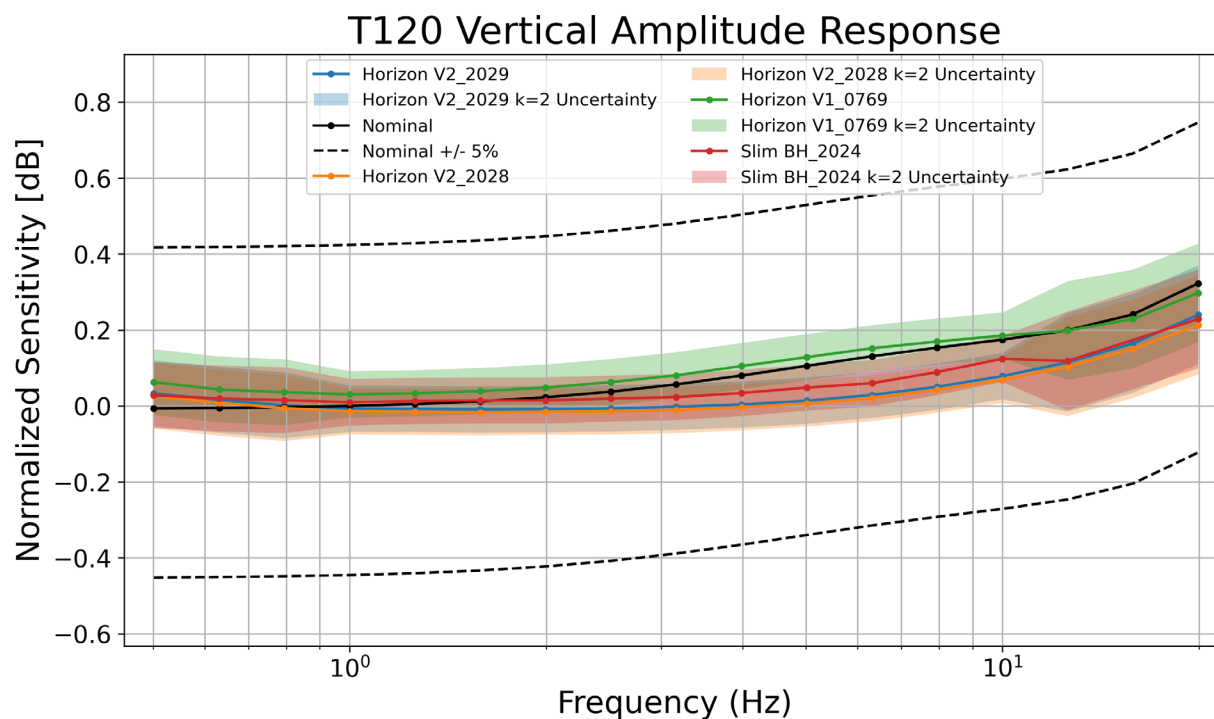


Figure 18 Vertical Amplitude Response

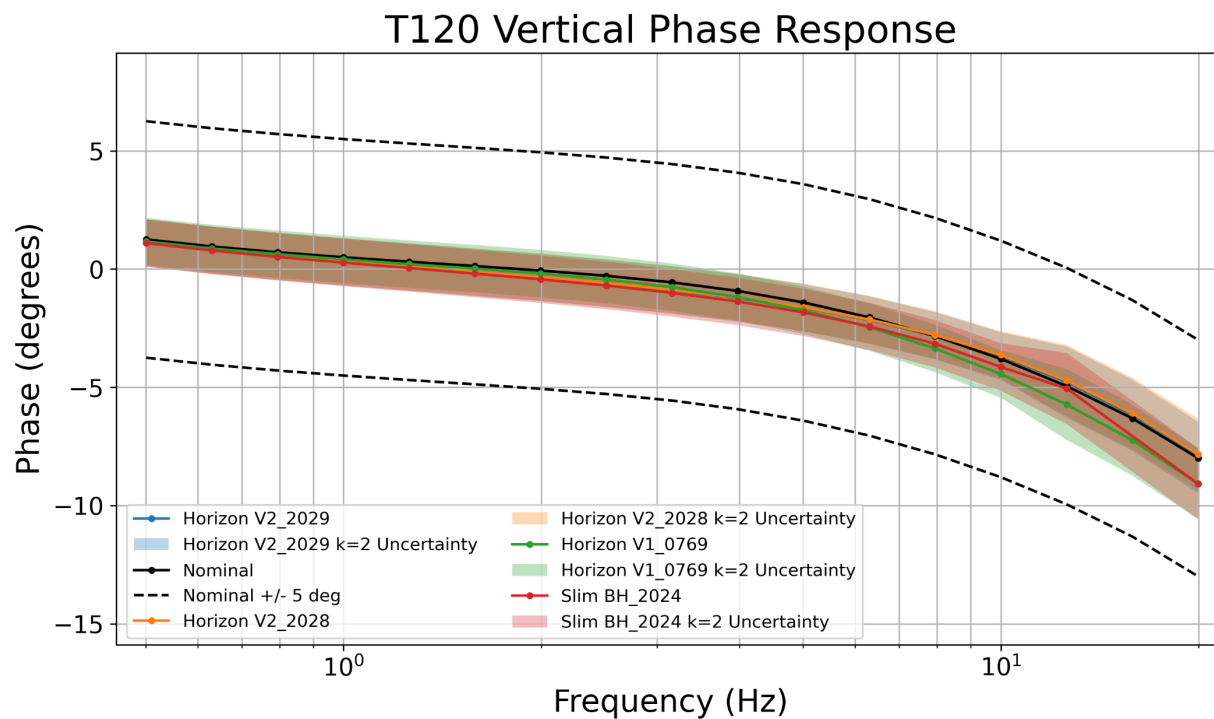


Figure 19 Vertical Phase Response

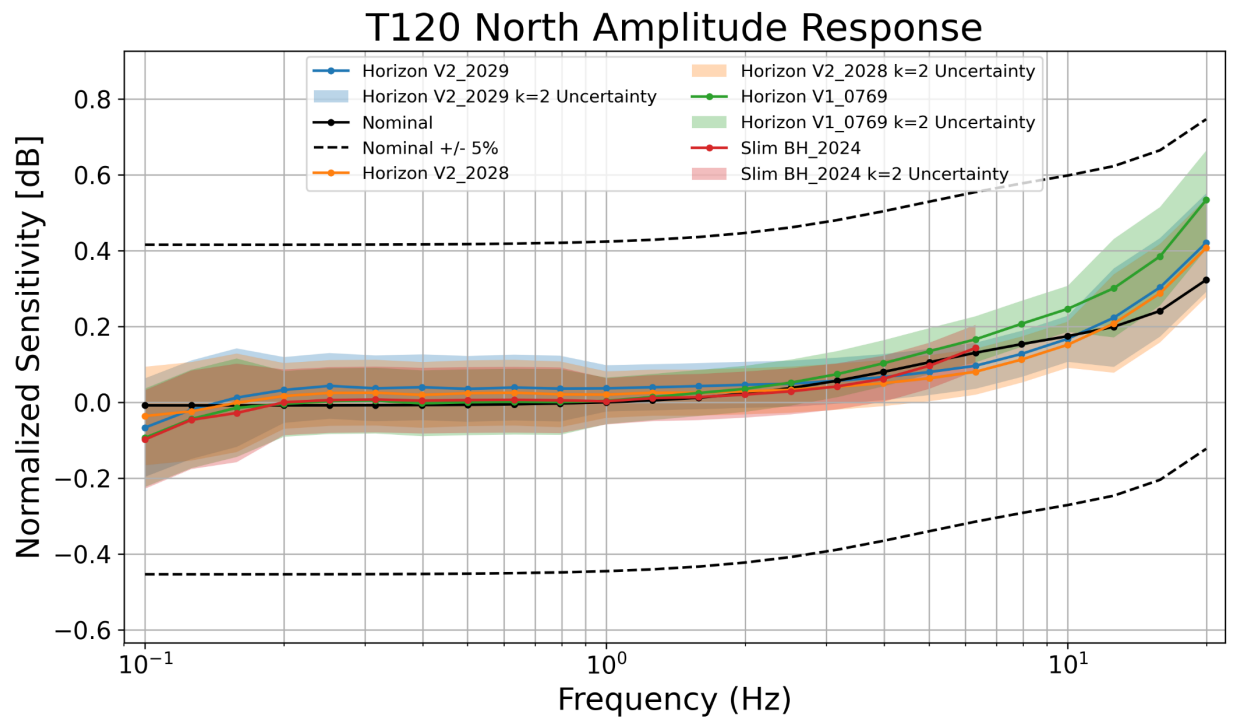


Figure 20 North-South Amplitude Response

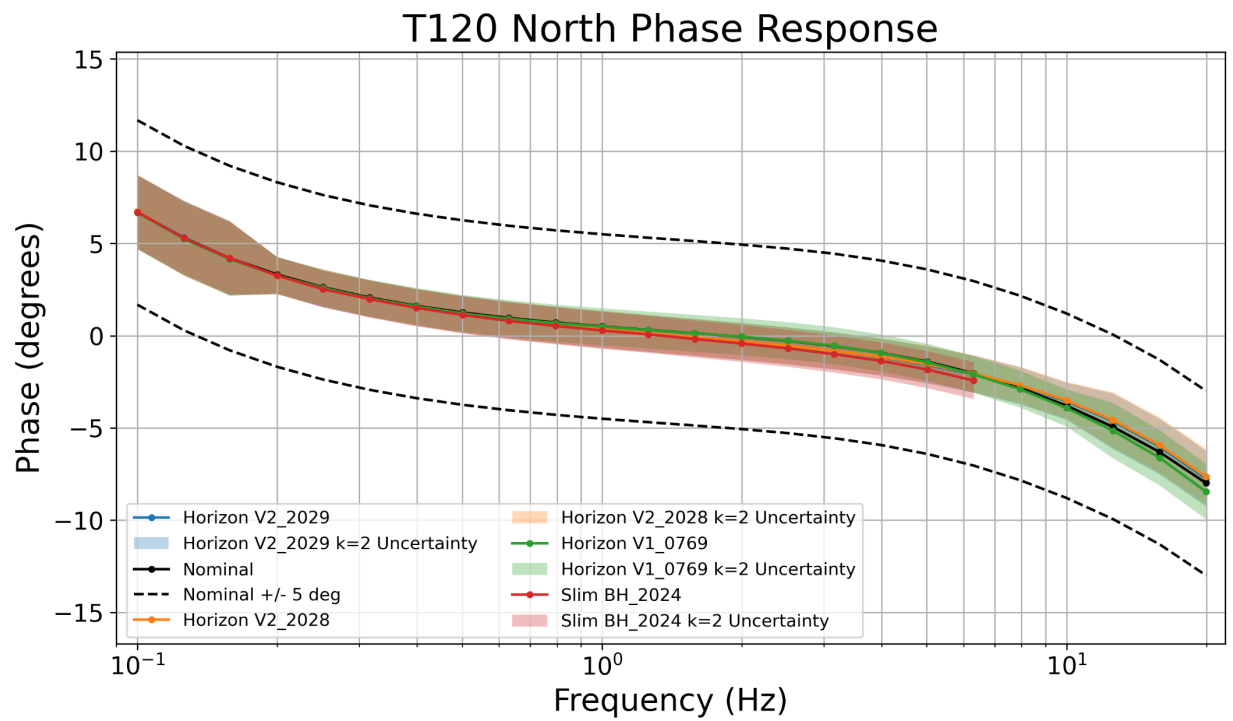


Figure 21 North-South Phase Response

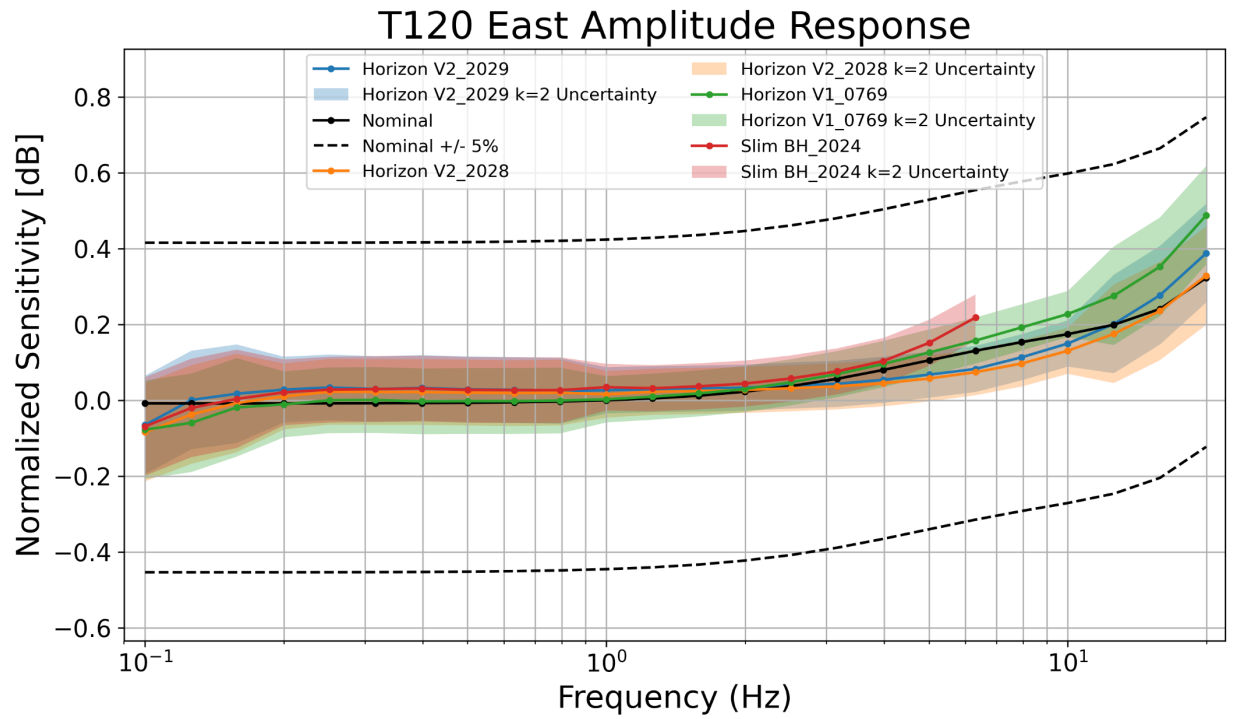


Figure 22 East-West Amplitude Response

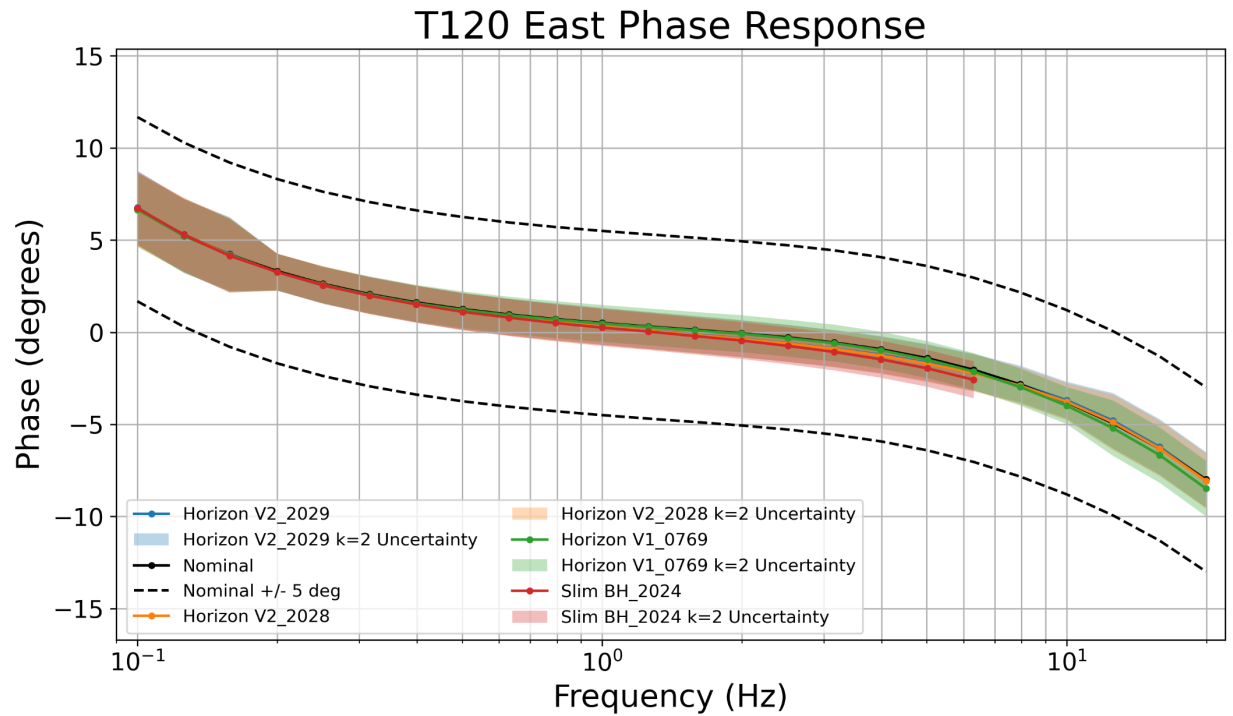


Figure 23 East-West Phase Response

The measured phase responses for all axes of the four sensors are consistent and closely match the nominal response model. Additionally, the measured vertical amplitude responses of the four sensors are generally consistent and closely match the nominal model.

The measured horizontal amplitude response of the four T120 sensors closely matches the nominal response from 0.1Hz to 7Hz. Above 7Hz the measured response of the T120 Slim Posthole had a mechanical resonance due to its installation on the shake table and, as a result, the data are not presented. The three T120 Horizon sensors' horizontal amplitude response closely matched nominal up to 20Hz with all three sensors being well within $\pm 5\%$ of the nominal amplitude response.

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

Table 9 Primary Amplitude Response

Vertical Amplitude Response						
Frequency (Hz)	T120 Horizon V2 2029 [dB]	T120 Horizon V2 2028 [dB]	T120 Horizon V1 769 [dB]	T120 Slim PH2024 [dB]	Nominal [dB]	Uncertainty k=2 [dB]
0.50	0.033	0.027	0.063	0.028	-0.007	0.087
0.63	0.016	0.008	0.043	0.019	-0.005	0.087
0.79	0.001	-0.006	0.036	0.015	-0.003	0.087
1.00	-0.007	-0.014	0.030	0.010	0.000	0.061
1.26	-0.008	-0.016	0.033	0.013	0.005	0.061
1.59	-0.009	-0.017	0.039	0.014	0.012	0.061
2.00	-0.009	-0.015	0.048	0.014	0.023	0.061
2.51	-0.006	-0.014	0.063	0.019	0.037	0.061
3.16	-0.002	-0.011	0.081	0.023	0.057	0.061
3.98	0.004	-0.004	0.105	0.034	0.080	0.061
5.01	0.014	0.007	0.128	0.048	0.105	0.061
6.31	0.029	0.020	0.152	0.060	0.131	0.061
7.94	0.050	0.043	0.170	0.089	0.153	0.061
10.00	0.078	0.068	0.185	0.124	0.174	0.061
12.59	0.115	0.103	0.199	0.118	0.199	0.130
15.85	0.165	0.150	0.229	---	0.241	0.130
19.95	0.240	0.213	0.298	0.229	0.323	0.130

North/South Amplitude Response						
Frequency (Hz)	T120 Horizon V2 2029 [dB]	T120 Horizon V2 2028 [dB]	T120 Horizon V1 769 [dB]	T120 Slim PH2024 [dB]	Nominal [dB]	Uncertainty k=2 [dB]
0.10	-0.067	-0.036	-0.094	-0.098	-0.008	0.130
0.13	-0.020	-0.024	-0.044	-0.046	-0.008	0.130
0.16	0.012	-0.001	-0.014	-0.028	-0.008	0.130
0.20	0.032	0.017	-0.004	0.000	-0.008	0.087
0.25	0.043	0.025	0.003	0.006	-0.008	0.087
0.32	0.037	0.025	0.004	0.007	-0.008	0.087
0.40	0.040	0.019	-0.003	0.004	-0.007	0.087
0.50	0.035	0.024	0.000	0.006	-0.007	0.087
0.63	0.039	0.025	0.001	0.007	-0.005	0.087
0.79	0.036	0.021	0.001	0.005	-0.003	0.087
1.00	0.037	0.020	0.004	0.003	0.000	0.061
1.26	0.040	0.025	0.014	0.011	0.005	0.061
1.59	0.043	0.025	0.025	0.014	0.012	0.061
2.00	0.046	0.029	0.035	0.020	0.023	0.061
2.51	0.049	0.033	0.052	0.029	0.037	0.061
3.16	0.057	0.041	0.074	0.042	0.057	0.061
3.98	0.066	0.050	0.103	0.062	0.080	0.061
5.01	0.080	0.063	0.135	0.096	0.105	0.061
6.31	0.096	0.081	0.166	0.143	0.131	0.061
7.94	0.128	0.113	0.207	---	0.153	0.061
10.00	0.167	0.152	0.246	---	0.174	0.061
12.59	0.223	0.208	0.301	---	0.199	0.130
15.85	0.303	0.288	0.385	---	0.241	0.130
19.95	0.421	0.407	0.534	---	0.323	0.130

East/West Amplitude Response						
Frequency (Hz)	T120 Horizon V2 2029 [dB]	T120 Horizon V2 2028 [dB]	T120 Horizon V1 769 [dB]	T120 Slim PH2024 [dB]	Nominal [dB]	Uncertainty k=2 [dB]
0.10	-0.065	-0.084	-0.078	-0.069	-0.008	0.130
0.13	0.001	-0.038	-0.059	-0.020	-0.008	0.130
0.16	0.017	-0.007	-0.019	0.004	-0.008	0.130
0.20	0.028	0.010	-0.011	0.021	-0.008	0.087
0.25	0.034	0.022	0.000	0.028	-0.008	0.087
0.32	0.030	0.022	0.001	0.030	-0.008	0.087
0.40	0.032	0.022	-0.003	0.031	-0.007	0.087
0.50	0.029	0.020	-0.002	0.027	-0.007	0.087
0.63	0.027	0.019	-0.002	0.027	-0.005	0.087
0.79	0.025	0.020	-0.001	0.027	-0.003	0.087
1.00	0.026	0.016	0.003	0.035	0.000	0.061
1.26	0.030	0.022	0.009	0.032	0.005	0.061
1.59	0.031	0.025	0.018	0.037	0.012	0.061
2.00	0.033	0.027	0.030	0.044	0.023	0.061
2.51	0.039	0.032	0.048	0.058	0.037	0.061
3.16	0.043	0.037	0.069	0.076	0.057	0.061
3.98	0.054	0.045	0.096	0.103	0.080	0.061
5.01	0.068	0.058	0.126	0.152	0.105	0.061
6.31	0.083	0.074	0.157	0.218	0.131	0.061
7.94	0.113	0.097	0.192	---	0.153	0.061
10.00	0.150	0.130	0.227	---	0.174	0.061
12.59	0.201	0.175	0.276	---	0.199	0.130
15.85	0.277	0.236	0.352	---	0.241	0.130
19.95	0.388	0.329	0.488	---	0.323	0.130

Table 10 Primary Phase Response

Vertical Phase Response						
Frequency (Hz)	T120 Horizon 2029 (deg)	T120 Horizon 2028 (deg)	T120 Horizon 769 (deg)	T120 Slim PH2024 (deg)	Nominal (deg)	Uncertainty k=2 (deg)
0.50	1.11	1.11	1.17	1.10	1.25	1.00
0.63	0.80	0.80	0.87	0.78	0.96	1.00
0.79	0.54	0.54	0.63	0.51	0.71	1.00
1.00	0.30	0.31	0.41	0.27	0.50	1.00
1.26	0.09	0.09	0.21	0.05	0.31	1.00
1.59	-0.14	-0.13	0.02	-0.19	0.13	1.00
2.00	-0.36	-0.34	-0.19	-0.43	-0.06	1.00
2.51	-0.61	-0.59	-0.45	-0.70	-0.28	1.00
3.16	-0.89	-0.87	-0.77	-1.01	-0.56	1.00
3.98	-1.23	-1.21	-1.19	-1.37	-0.93	1.00
5.01	-1.64	-1.62	-1.74	-1.83	-1.41	1.00
6.31	-2.16	-2.13	-2.46	-2.43	-2.04	1.00
7.94	-2.82	-2.79	-3.36	-3.16	-2.84	1.00
10.00	-3.68	-3.63	-4.44	-4.14	-3.80	1.00
12.59	-4.78	-4.71	-5.72	-5.05	-4.95	1.50
15.85	-6.18	-6.09	-7.24	---	-6.31	1.50
19.95	-7.96	-7.83	-9.08	-9.08	-7.99	1.50

North/South Phase Response						
Frequency (Hz)	T120 Horizon 2029 (deg)	T120 Horizon 2028 (deg)	T120 Horizon 769 (deg)	T120 Slim PH2024 (deg)	Nominal (deg)	Uncertainty k=2 (deg)
0.10	6.70	6.73	6.68	6.70	6.68	2.00
0.13	5.32	5.26	5.24	5.29	5.29	2.00
0.16	4.21	4.21	4.16	4.20	4.21	2.00
0.20	3.26	3.24	3.26	3.26	3.31	1.00
0.25	2.53	2.58	2.59	2.52	2.62	1.00
0.32	2.01	2.00	2.03	1.98	2.06	1.00
0.40	1.54	1.53	1.59	1.51	1.61	1.00
0.50	1.15	1.15	1.20	1.12	1.25	1.00
0.63	0.83	0.84	0.92	0.80	0.96	1.00
0.79	0.57	0.58	0.68	0.53	0.71	1.00
1.00	0.34	0.34	0.48	0.28	0.50	1.00
1.26	0.11	0.12	0.30	0.07	0.31	1.00
1.59	-0.10	-0.09	0.12	-0.18	0.13	1.00
2.00	-0.32	-0.32	-0.06	-0.42	-0.06	1.00
2.51	-0.56	-0.56	-0.28	-0.69	-0.28	1.00
3.16	-0.83	-0.83	-0.55	-1.01	-0.56	1.00
3.98	-1.17	-1.15	-0.94	-1.37	-0.93	1.00
5.01	-1.59	-1.55	-1.44	-1.84	-1.41	1.00
6.31	-2.09	-2.06	-2.11	-2.44	-2.04	1.00
7.94	-2.72	-2.69	-2.91	---	-2.84	1.00
10.00	-3.56	-3.51	-3.92	---	-3.80	1.00
12.59	-4.64	-4.58	-5.15	---	-4.95	1.50
15.85	-6.01	-5.93	-6.62	---	-6.31	1.50
19.95	-7.75	-7.65	-8.46	---	-7.99	1.50

East/West Phase Response						
Frequency (Hz)	T120 Horizon 2029 (deg)	T120 Horizon 2028 (deg)	T120 Horizon 769 (deg)	T120 Slim PH2024 (deg)	Nominal (deg)	Uncertainty k=2 (deg)
0.10	6.76	6.63	6.65	6.73	6.68	2.00
0.13	5.21	5.28	5.22	5.28	5.29	2.00
0.16	4.25	4.20	4.18	4.14	4.21	2.00
0.20	3.26	3.25	3.25	3.27	3.31	1.00
0.25	2.54	2.59	2.56	2.55	2.62	1.00
0.32	2.00	1.99	2.03	1.98	2.06	1.00
0.40	1.53	1.53	1.57	1.51	1.61	1.00
0.50	1.13	1.13	1.21	1.10	1.25	1.00
0.63	0.81	0.81	0.92	0.79	0.96	1.00
0.79	0.56	0.55	0.68	0.50	0.71	1.00
1.00	0.32	0.31	0.47	0.25	0.50	1.00
1.26	0.09	0.08	0.29	0.03	0.31	1.00
1.59	-0.12	-0.15	0.09	-0.21	0.13	1.00
2.00	-0.35	-0.37	-0.08	-0.45	-0.06	1.00
2.51	-0.61	-0.62	-0.32	-0.74	-0.28	1.00
3.16	-0.89	-0.90	-0.59	-1.07	-0.56	1.00
3.98	-1.22	-1.26	-0.98	-1.47	-0.93	1.00
5.01	-1.65	-1.71	-1.49	-1.96	-1.41	1.00
6.31	-2.18	-2.22	-2.14	-2.58	-2.04	1.00
7.94	-2.82	-2.90	-2.98	---	-2.84	1.00
10.00	-3.69	-3.77	-3.99	---	-3.80	1.00
12.59	-4.81	-4.90	-5.21	---	-4.95	1.50
15.85	-6.22	-6.31	-6.67	---	-6.31	1.50
19.95	-8.02	-8.07	-8.49	---	-7.99	1.50

3.4 Comparison Sensitivity

The sensitivity of a sensor is defined as the ratio between the change in sensor's output voltage and the corresponding change in the quantity being measured. For comparison 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 comparison 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 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 T120 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.

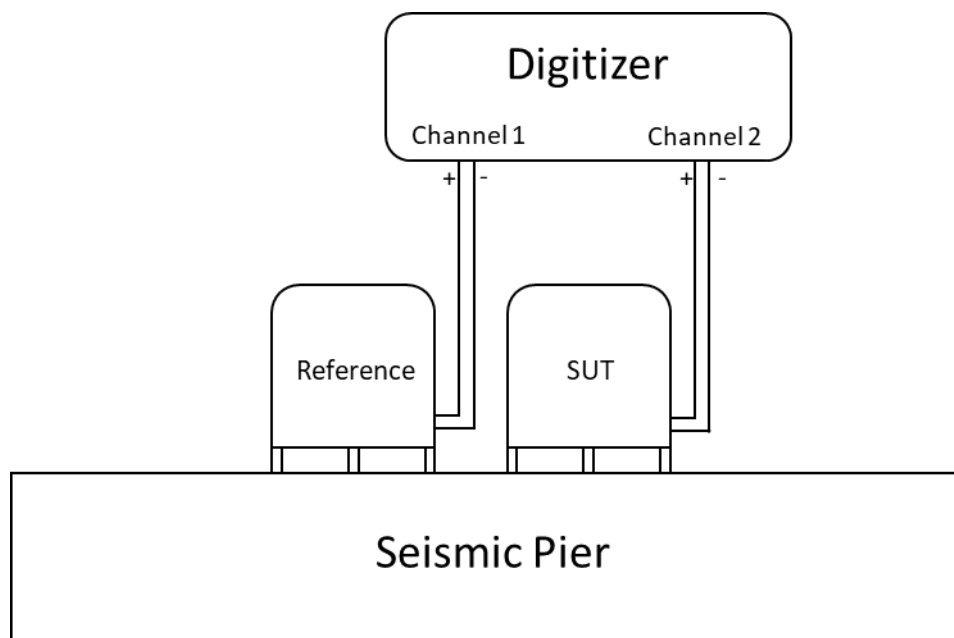


Figure 24 Comparison Sensitivity Configuration Diagram



Figure 25 Sensors installed for Comparison Sensitivity Test

Table 11 Comparison 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	Nanometrics / Centaur	9403	200Hz, 40x gain Port A: Horizon V2 2029 Port B: Horizon V2 2028
SUT Digitizer 2	Nanometrics / Centaur	9404	200Hz, 40x gain Port A: Horizon V1 0769 Port B: Slim PH 2024

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:

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

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:

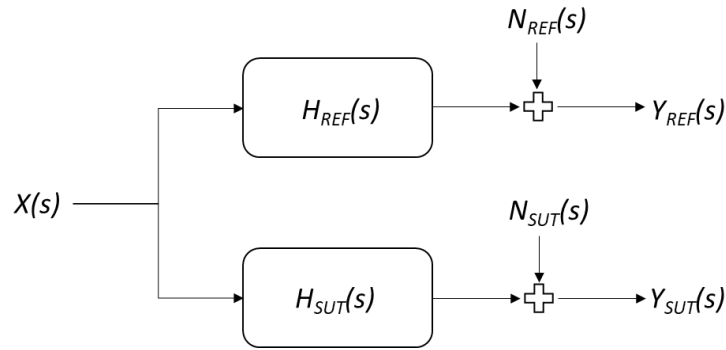


Figure 26 Diagram of two sensors with a common input signal

In equation form, the output signals of the reference 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:

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

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.

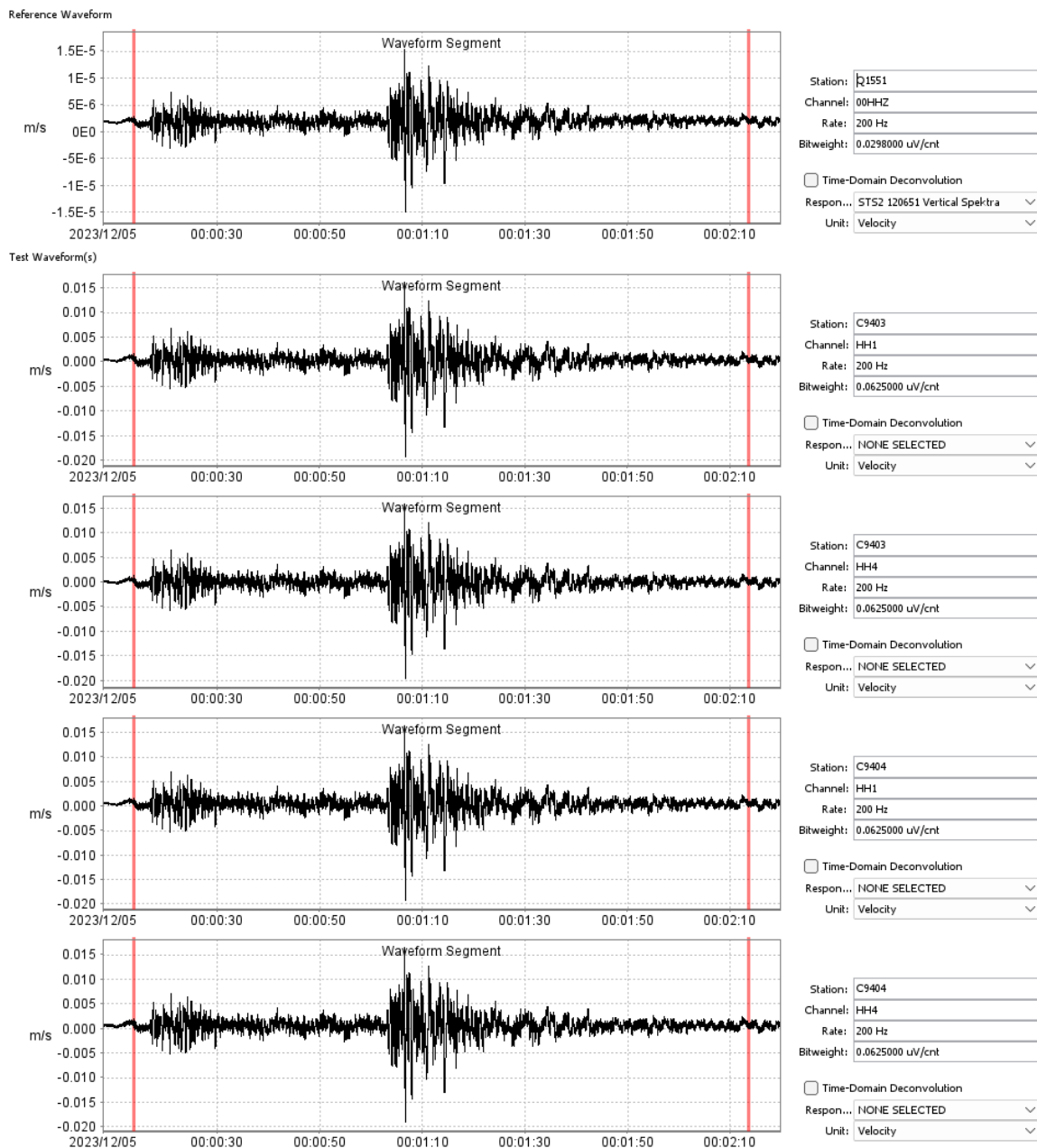


Figure 27 Comparison Sensitivity Time Series

The top waveform is the vertical data from the STS-2 reference sensor and the lower four are the vertical data from the T120 Horizon V2 2029, T120 Horizon V2 2028, T120 Horizon V1 0769, and T120 Slim PH 2024 respectively. For the frequency domain analysis, the two minutes of earthquake data was processed with windows of 1024 samples and 5/8 window overlaps which provided many data segments. The results from these segments are 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 46 and Figure 80 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.

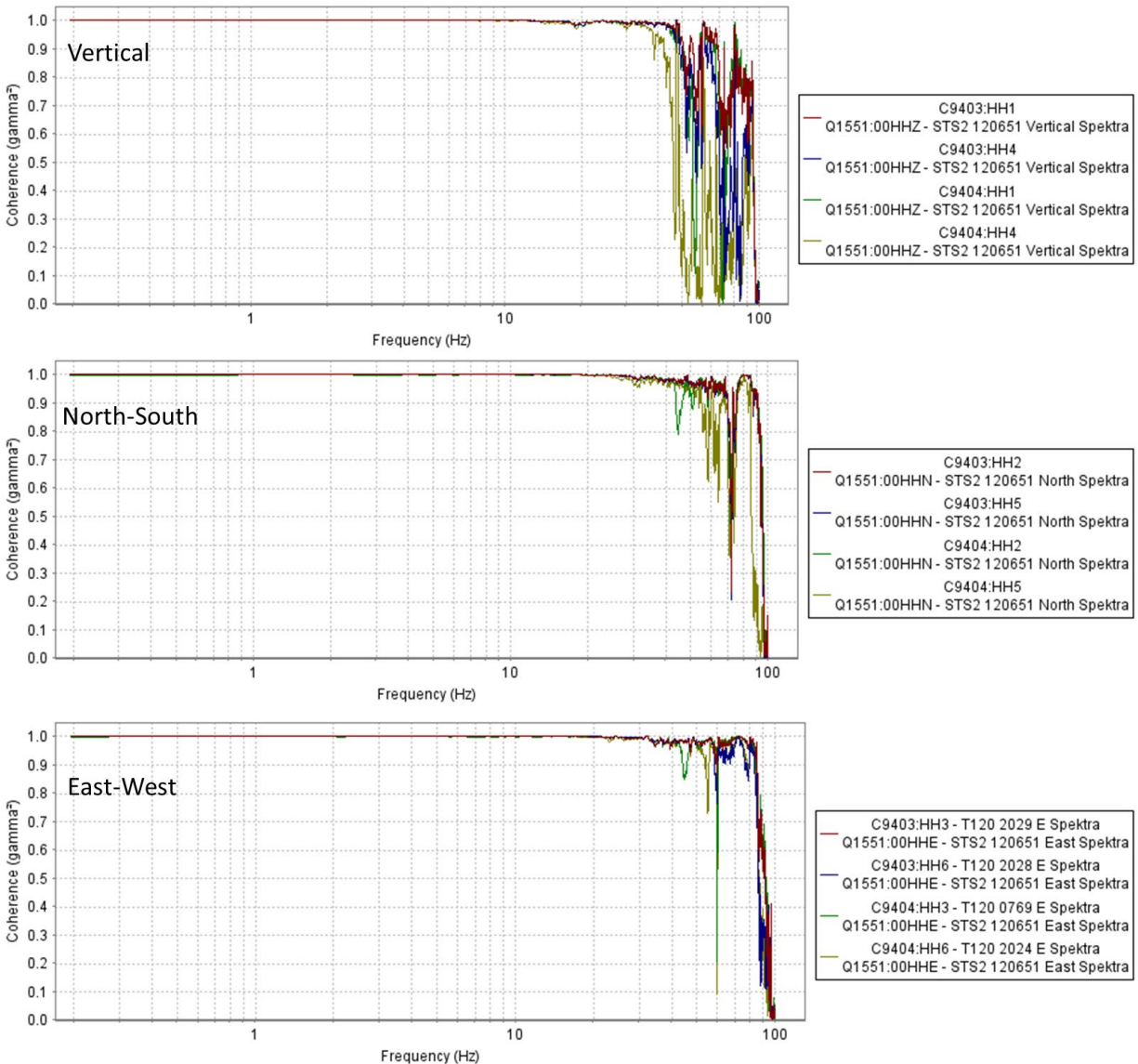


Figure 28 Coherence for M4.0 Earthquake

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 response of the T120 sensors at 1Hz.

Table 12 Vertical Axis Response at 1 Hz

Sensor	Amplitude (V/m/s)	Phase (Degrees)
T120 Horizon 2029	1184.99	0.29
T120 Horizon 2028	1183.95	0.31
T120 Horizon 0769	1187.87	0.45
T120 Slim BH 2024	1184.12	0.22
Nominal	1202.5	0.5

Table 13 North-South Axis Response at 1 Hz

Sensor	Amplitude (V/m/s)	Phase (Degrees)
T120 Horizon 2029	1183.305	0.340
T120 Horizon 2028	1186.243	0.278
T120 Horizon 0769	1163.942	0.877
T120 Slim BH 2024	1185.977	0.241
Nominal	1202.5	0.5

Table 14 East-West Axis Response at 1Hz

Sensor	Amplitude (V/m/s)	Phase (Degrees)
T120 Horizon 2029	1192.54	0.28
T120 Horizon 2028	1190.18	0.28
T120 Horizon 0769	1193.12	0.58
T120 Slim BH 2024	1185.10	0.19
Nominal	1202.5	0.5

The measured amplitude response values are all within 3.2% of the nominal value. The measured phase response values are all within 0.38 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 Comparison 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. For comparison 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 T120 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. Note that the T120 Slim Posthole sensor is installed in a simulation borehole that is coupled to the seismic pier that the three T120 Horizon sensors and the reference seismometer are installed on.

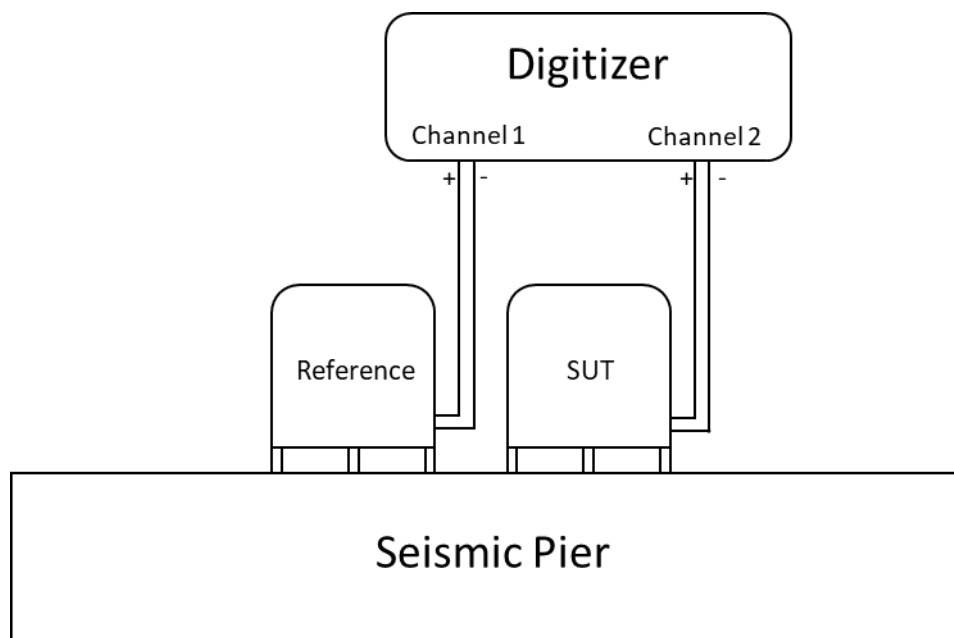


Figure 29 Comparison Frequency Response Configuration Diagram

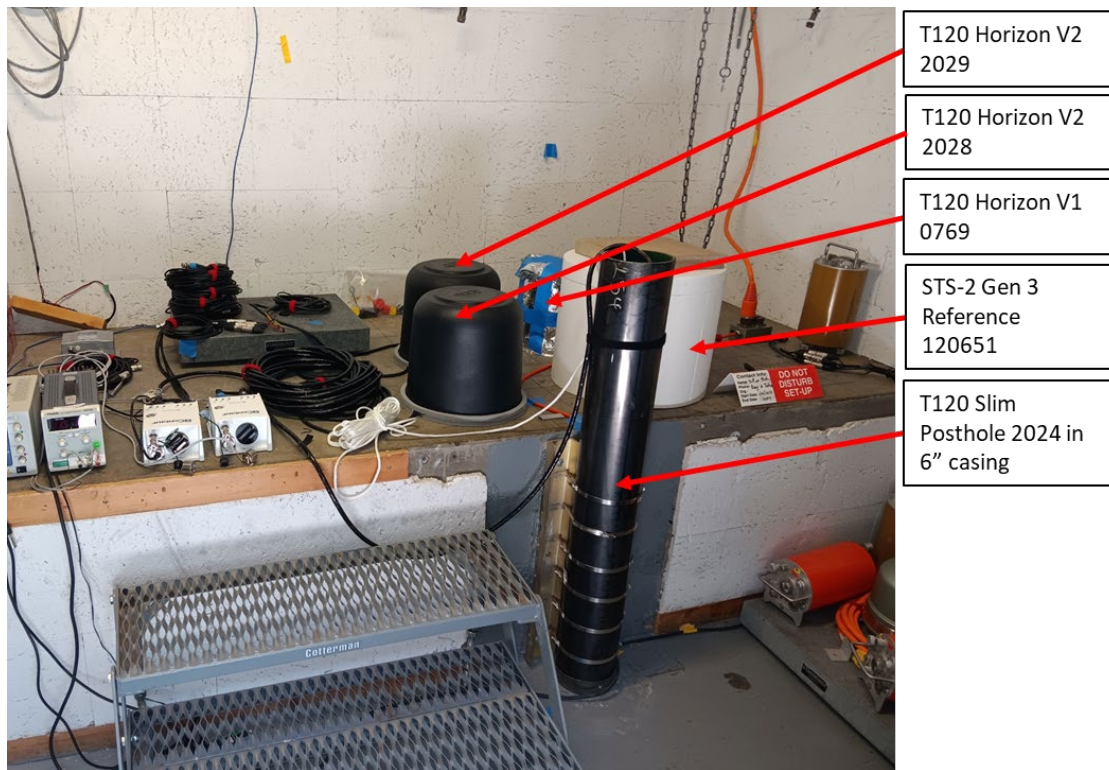


Figure 30 Sensors installed for Comparison Frequency Response Test

Table 15 Comparison 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	Nanometrics / Centaur	9403	200Hz, 40x gain Port A: Horizon V2 2029 Port A: Horizon V2 2028
SUT Digitizer 2	Nanometrics / Centaur	9404	200Hz, 40x gain Port A: Horizon V1 0769 Port A: Slim PH 2024

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:

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

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:

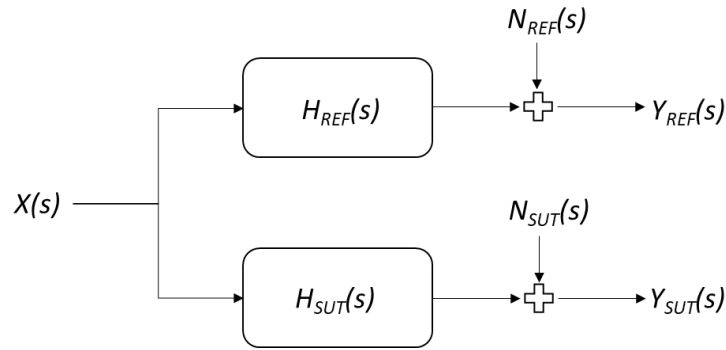


Figure 31 Diagram of two sensors with a common input signal

In equation form, the output signals of the reference 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:

$$H_{Relative}(s) = \frac{P_{Y_{ref}Y_{sut}}^*}{P_{Y_{ref}Y_{ref}} - P_{nn}}$$

Here, $P_{Y_{ref}Y_{sut}}^*$ represents the complex conjugate of the cross power spectral density between the output of the reference and the sensor under test. $P_{Y_{ref}Y_{ref}}$ 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:

$$P_{nn} = \frac{1}{2}(P_{Y_{ref}Y_{ref}} + P_{Y_{sut}Y_{sut}}) - \sqrt{\frac{1}{4}(P_{Y_{ref}Y_{ref}} - P_{Y_{sut}Y_{sut}})^2 + |P_{Y_{ref}Y_{sut}}|^2}$$

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 7.1 in the Philippines that occurred on 7/11/2024 at 02:13:18UTC. This event was used to provide frequency response data from 0.02 Hz to 1Hz. Details on this event are available at:

<https://earthquake.usgs.gov/earthquakes/eventpage/us7000myfa/executive>.

The second event was a M4.9 event in North-Central Texas that occurred on 7/23/2024 at 03:38:42UTC. This event provided frequency response data from 0.1Hz to 20Hz. Details on the event are available at:

<https://earthquake.usgs.gov/earthquakes/eventpage/tx2024oizv/executive>.

Both events overlap from 0.1Hz to 1Hz which allows for verification of a stable response from one event to the next. Figure 32, shows the coherence for the M4.9 Texas event and Figure 33 shows the coherence for the M7.1 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 46 and Figure 80 of the Appendix.

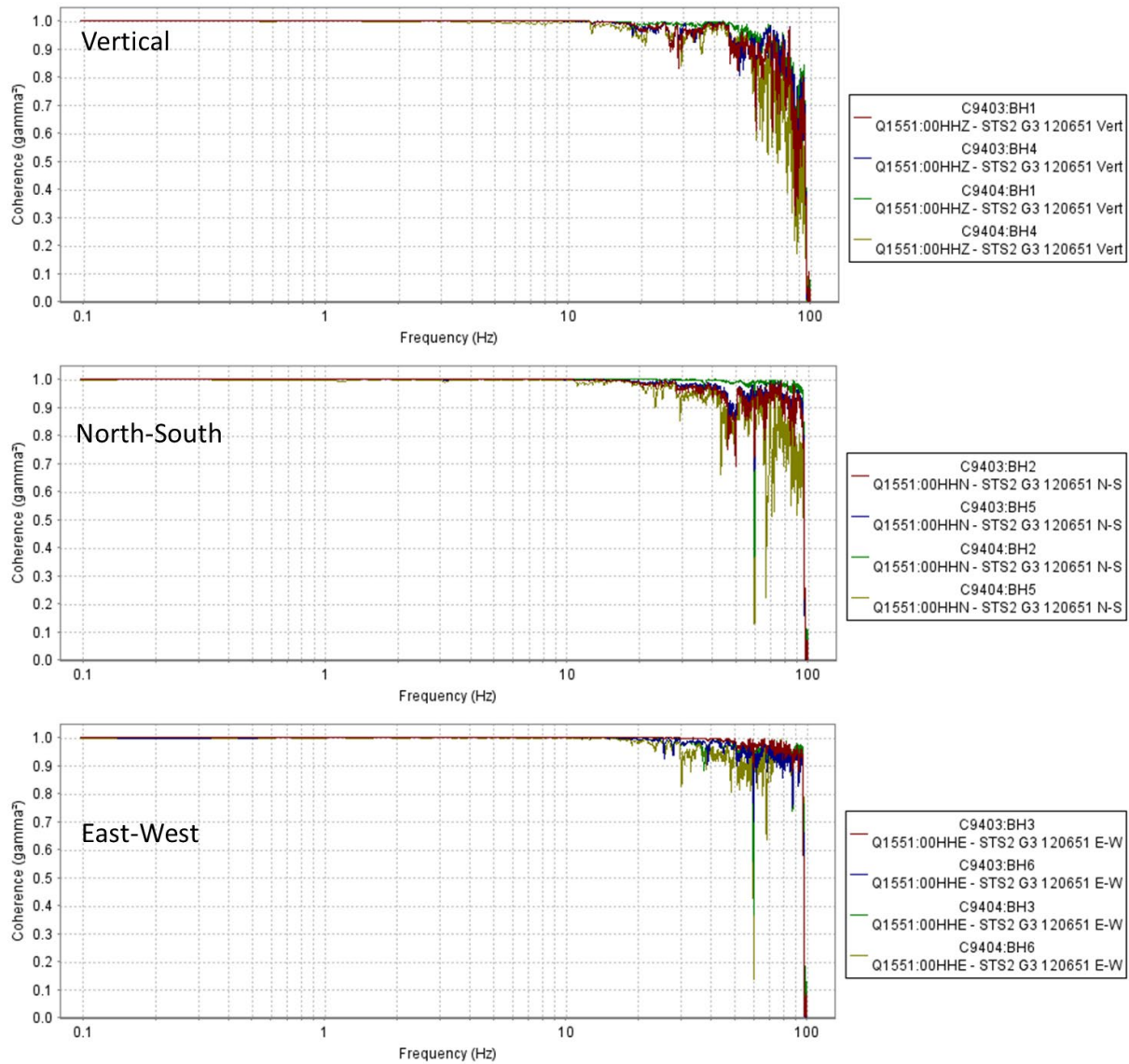


Figure 32 Coherence from the M4.9 Texas Earthquake

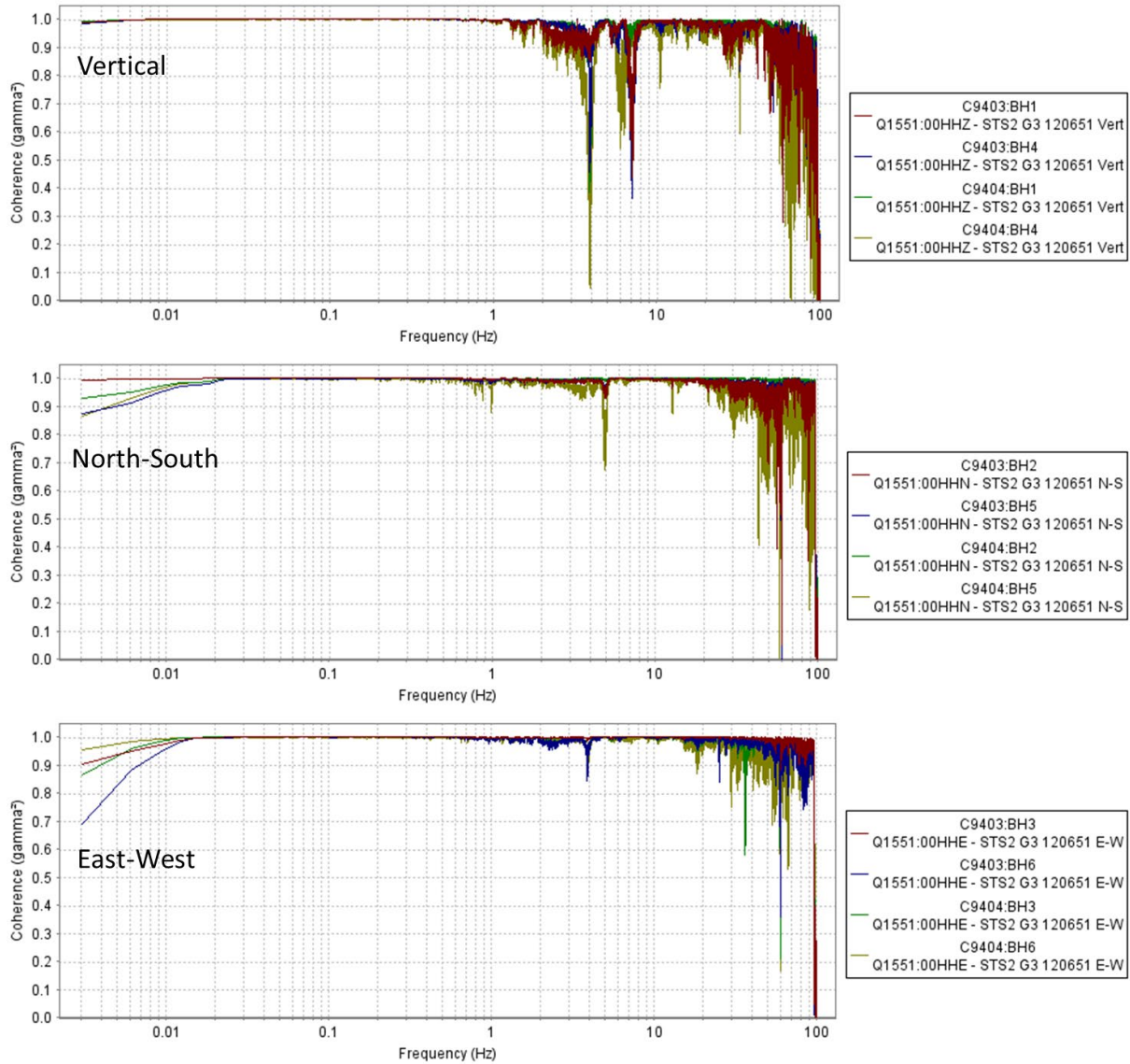


Figure 33 Coherence from the M7.1 Philippines Earthquake

Figure 34, Figure 35, and Figure 36, 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 M7.1 event is marked with triangles and data from the M4.9 event is marked with squares. 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.

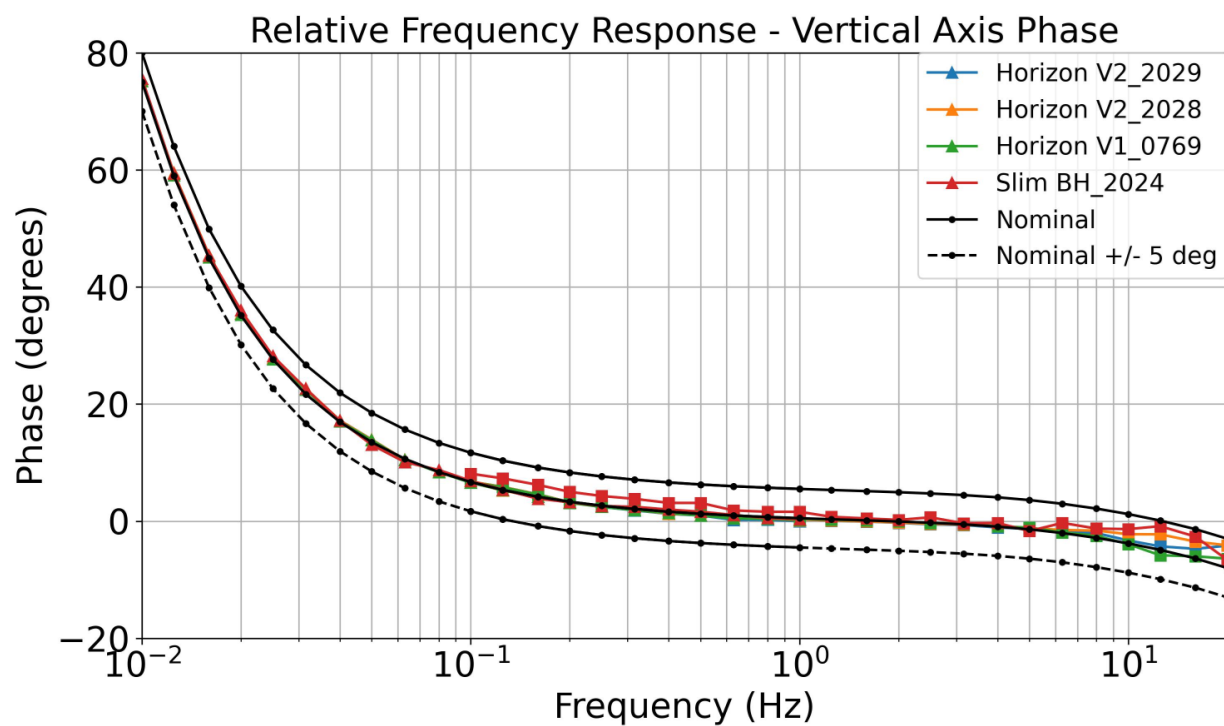
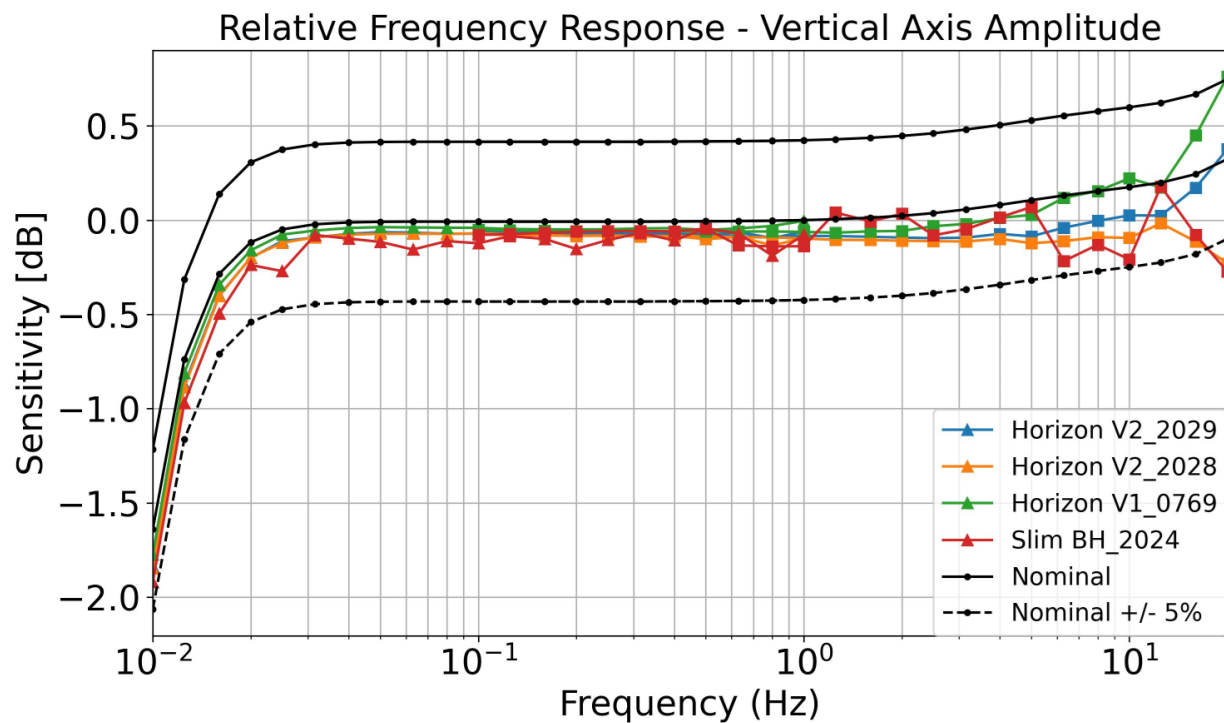


Figure 34 Vertical Axis Comparison Frequency Response

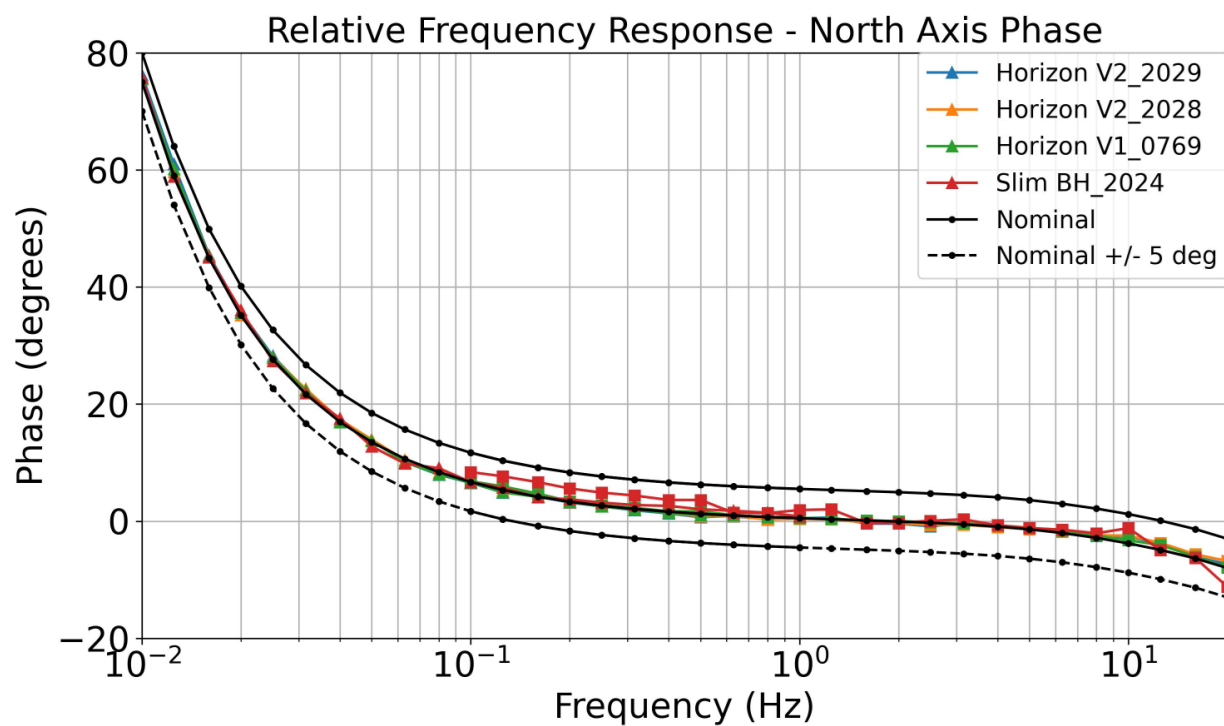
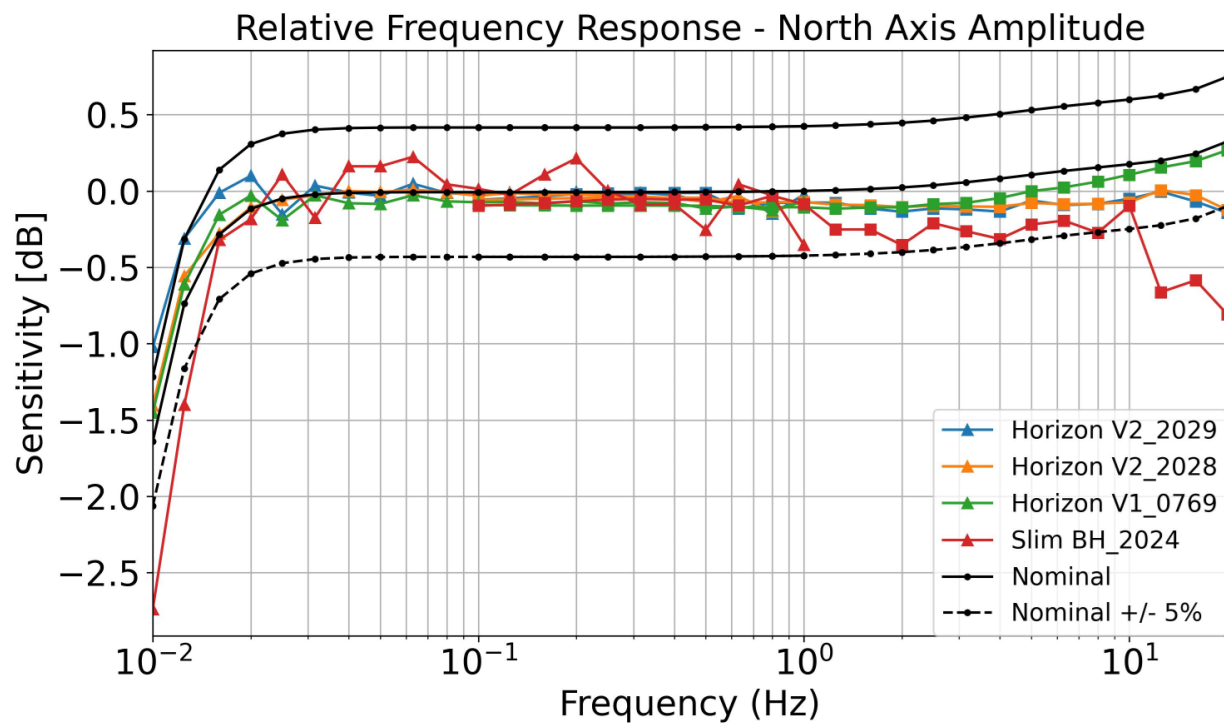


Figure 35 North/South Axis Comparison Frequency Response

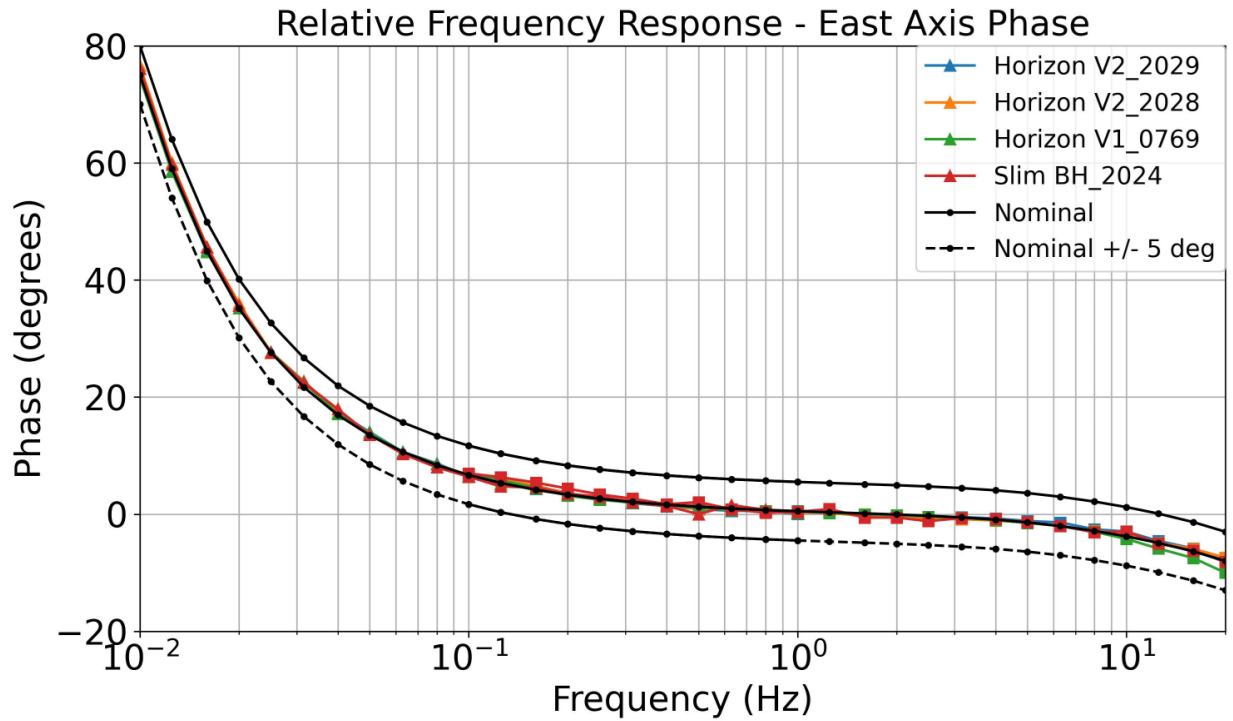
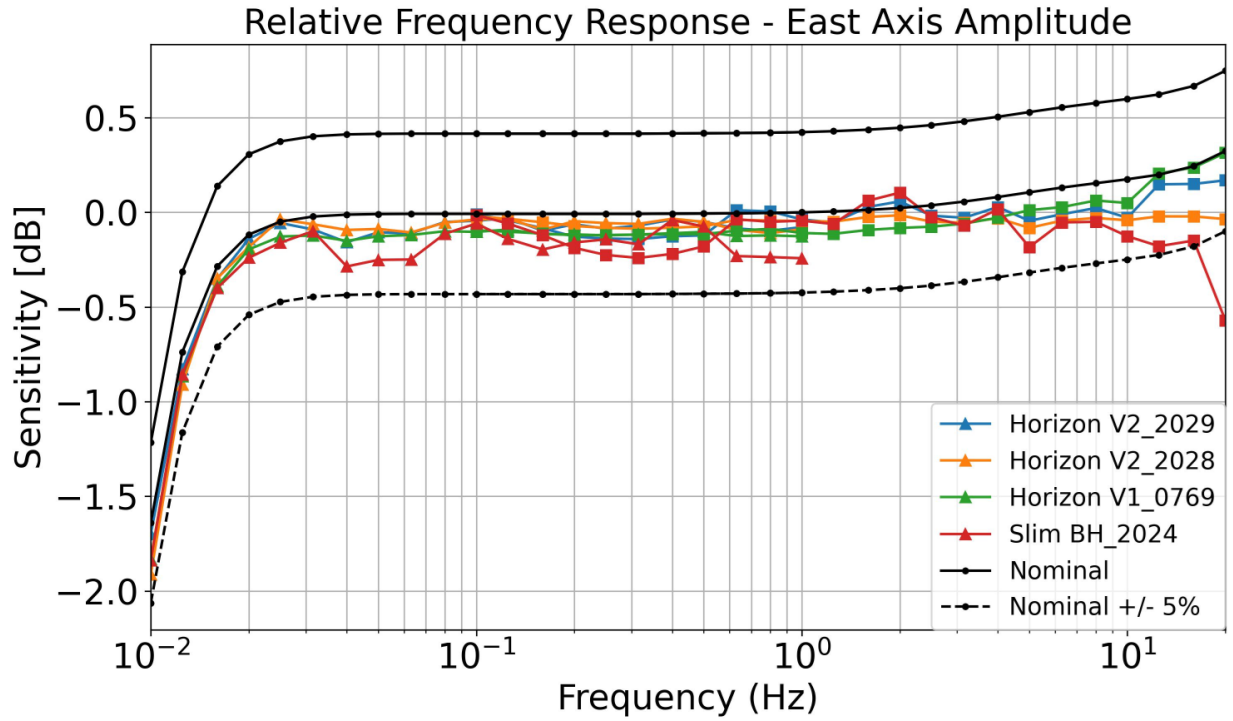


Figure 36 East/West Axis Comparison Frequency Response

The above figures show that the measured phase response of the four T120 sensors for all three axes closely matches the nominal model at all evaluated frequencies. The region of overlap between the two events, 0.1Hz – 1Hz, also shows good agreement and indicates the phase response is consistent between the two events.

The measured amplitude response of the three T120 Horizon sensors is generally consistent with the nominal response model from 0.02Hz to 20Hz. For the east axis, the measured amplitude responses of the three Horizon sensors are within +/-5% of the nominal response model at all evaluated frequencies. The same is true for the north axis except for the response of T120 Horizon V2 sensors 2028 and 2029 at 20Hz. At this frequency the measured response of the two sensors is just below -5% of nominal. For the vertical axis, all T120 Horizon sensors are within +/-5% of nominal except for T120 Horizon V2 2028 at 20Hz. At this frequency the sensor's amplitude response is just below the -5% of nominal bound.

The measured amplitude response of the T120 Slim Posthole is significantly less stable than that of the three T120 Horizon sensors, likely due to its method of installation. It generally follows the nominal response model but with more variability and deviations than the Horizon sensors. This can be explained by the slightly lower coherency between this sensor and the reference STS-2 seismometer. The difference in coherency levels is illustrated in Figure 37 which shows the coherency between the four SUTs and the reference for the vertical axis during the M7.1 Philippines event. This same reduction in coherency between the reference and T120 Slim Posthole occurs during the M4.9 Texas event. Although the coherency between the T120 Slim Posthole and reference sensor is still very high, the slight degradation caused by the fact that the sensor is installed in a simulation borehole that is not perfectly coupled to the seismic pier results in instability in the calculated amplitude response.

The lower coherency means that the amplitude response results for the T120 Posthole should be treated with caution and the deviations from nominal may be an artifact caused by the non-idealities in how the sensors are installed. The collected data is sufficient to demonstrate that the T120 Posthole does track the nominal response model.

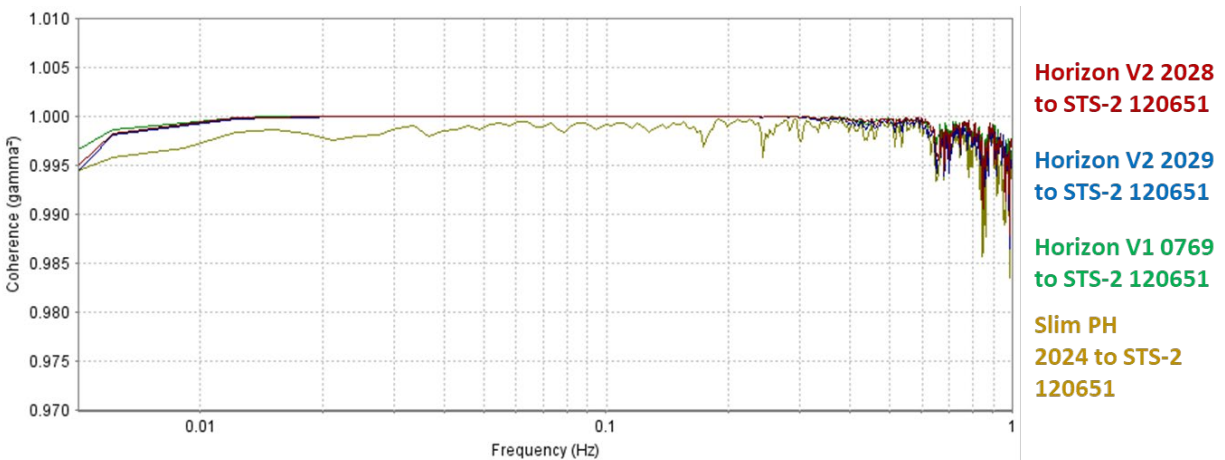


Figure 37 Coherency for M7.1 Philippines Event – Zoom

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

Table 16 Comparison Amplitude Response using M4.0 Event

Vertical Amplitude Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.25	-0.14	-0.15	-0.13	-0.15	-0.01
0.32	-0.14	-0.15	-0.13	-0.15	-0.01
0.40	-0.15	-0.16	-0.13	-0.16	-0.01
0.50	-0.15	-0.16	-0.13	-0.16	-0.01
0.63	-0.15	-0.16	-0.14	-0.16	-0.01
0.80	-0.16	-0.16	-0.14	-0.17	0.00
1.00	-0.16	-0.17	-0.14	-0.17	0.00
1.25	-0.16	-0.18	-0.15	-0.16	0.00
1.60	-0.16	-0.18	-0.14	-0.17	0.01
2.00	-0.16	-0.18	-0.14	-0.16	0.02
2.50	-0.17	-0.18	-0.13	-0.17	0.04
3.15	-0.17	-0.18	-0.11	-0.15	0.06
4.00	-0.15	-0.17	-0.08	-0.13	0.08
5.00	-0.15	-0.15	-0.05	-0.10	0.11
6.30	-0.16	-0.11	-0.04	-0.08	0.13
8.00	-0.13	-0.05	-0.04	-0.04	0.15
10.00	-0.16	0.03	0.00	0.04	0.17
12.50	0.08	-0.10	0.22	0.09	0.20
16.00	-0.16	0.08	0.23	0.57	0.24
20.00	-0.27	0.16	0.47	1.24	0.32

North/South Amplitude Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.25	-0.12	-0.13	-0.17	-0.14	-0.01
0.32	-0.12	-0.13	-0.17	-0.14	-0.01
0.40	-0.14	-0.14	-0.24	-0.15	-0.01
0.50	-0.14	-0.14	-0.24	-0.14	-0.01
0.63	-0.16	-0.14	-0.29	-0.14	-0.01
0.80	-0.18	-0.15	-0.33	-0.16	0.00
1.00	-0.17	-0.15	-0.32	-0.15	0.00
1.25	-0.16	-0.16	-0.26	-0.17	0.00
1.60	-0.18	-0.16	-0.31	-0.17	0.01
2.00	-0.15	-0.16	-0.22	-0.18	0.02
2.50	-0.12	-0.14	-0.13	-0.16	0.04
3.15	-0.13	-0.14	-0.12	-0.14	0.06
4.00	-0.12	-0.14	-0.11	-0.13	0.08
5.00	-0.09	-0.11	-0.02	-0.11	0.11
6.30	-0.09	-0.10	-0.05	-0.07	0.13
8.00	-0.07	-0.07	-0.07	-0.02	0.15
10.00	-0.01	-0.01	0.02	0.11	0.17
12.50	-0.03	-0.04	0.07	0.26	0.20
16.00	-0.01	0.00	0.17	0.51	0.24
20.00	-0.04	0.01	0.34	0.96	0.32

East/West Amplitude Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.25	-0.12	-0.12	-0.17	-0.15	-0.01
0.32	-0.12	-0.12	-0.17	-0.15	-0.01
0.40	-0.13	-0.13	-0.18	-0.16	-0.01
0.50	-0.12	-0.12	-0.14	-0.16	-0.01
0.63	-0.12	-0.12	-0.17	-0.16	-0.01
0.80	-0.11	-0.13	-0.12	-0.16	0.00
1.00	-0.11	-0.12	-0.10	-0.16	0.00
1.25	-0.11	-0.12	-0.10	-0.16	0.00
1.60	-0.10	-0.12	-0.05	-0.16	0.01
2.00	-0.13	-0.14	-0.14	-0.16	0.02
2.50	-0.16	-0.15	-0.20	-0.16	0.04
3.15	-0.15	-0.14	-0.16	-0.14	0.06
4.00	-0.15	-0.13	-0.14	-0.12	0.08
5.00	-0.16	-0.13	-0.16	-0.08	0.11
6.30	-0.13	-0.11	-0.07	-0.05	0.13
8.00	-0.07	-0.10	0.02	0.03	0.15
10.00	-0.03	-0.12	0.01	0.15	0.17
12.50	-0.02	-0.04	0.06	0.37	0.20
16.00	-0.01	-0.01	0.06	0.69	0.24
20.00	0.11	-0.01	0.20	1.37	0.32

Table 17 Comparison Phase Response using M4.0 Event

Vertical Phase Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.25	2.15	2.04	2.03	2.20	2.63
0.32	2.15	2.04	2.03	2.20	2.07
0.40	1.47	1.50	1.57	1.51	1.61
0.50	1.47	1.50	1.57	1.51	1.26
0.63	0.93	0.83	0.88	0.90	0.96
0.80	0.55	0.46	0.54	0.53	0.70
1.00	0.29	0.31	0.45	0.22	0.50
1.25	0.10	0.04	0.16	0.02	0.31
1.60	-0.06	-0.17	0.00	-0.16	0.12
2.00	-0.22	-0.35	-0.21	-0.41	-0.07
2.50	-0.48	-0.52	-0.36	-0.78	-0.28
3.15	-0.64	-0.77	-0.49	-0.87	-0.56
4.00	-0.84	-0.99	-0.89	-1.34	-0.94
5.00	-1.03	-1.43	-1.38	-1.76	-1.41
6.30	-1.38	-2.19	-1.79	-2.06	-2.04
8.00	-2.14	-2.59	-2.50	-2.89	-2.86
10.00	-2.52	-3.89	-2.70	-3.71	-3.80
12.50	-2.80	-6.91	-2.44	-4.64	-4.91
16.00	-5.12	-6.27	-5.69	-6.55	-6.37
20.00	-11.08	-7.64	-7.73	-5.41	-8.01

North/South Phase Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.25	1.92	2.12	1.52	2.24	2.63
0.32	1.92	2.12	1.52	2.24	2.07
0.40	1.23	1.40	0.79	1.45	1.61
0.50	1.23	1.40	0.79	1.45	1.26
0.63	0.74	0.93	0.80	1.05	0.96
0.80	0.49	0.51	0.81	0.53	0.70
1.00	0.34	0.28	0.88	0.24	0.50
1.25	0.23	0.10	0.89	0.00	0.31
1.60	-0.25	-0.15	-0.27	-0.20	0.12
2.00	-0.45	-0.39	-0.44	-0.49	-0.07
2.50	-0.56	-0.66	-0.11	-0.91	-0.28
3.15	-0.83	-0.80	-0.63	-1.10	-0.56
4.00	-1.49	-1.35	-1.61	-1.53	-0.94
5.00	-1.62	-1.63	-1.45	-1.88	-1.41
6.30	-2.27	-2.16	-2.60	-2.46	-2.04
8.00	-3.04	-2.87	-3.18	-3.39	-2.86
10.00	-4.10	-4.06	-3.50	-3.94	-3.80
12.50	-5.22	-5.13	-5.16	-5.24	-4.91
16.00	-6.96	-6.69	-7.99	-8.23	-6.37
20.00	-9.41	-9.37	-9.32	-10.21	-8.01

East/West Phase Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.25	2.04	2.08	1.88	2.09	2.63
0.32	2.04	2.08	1.88	2.09	2.07
0.40	1.41	1.46	1.34	1.44	1.61
0.50	1.41	1.46	1.34	1.44	1.26
0.63	0.85	0.80	0.79	0.78	0.96
0.80	0.46	0.46	0.75	0.42	0.70
1.00	0.28	0.28	0.58	0.19	0.50
1.25	0.29	0.14	0.84	-0.07	0.31
1.60	-0.22	-0.26	-0.25	-0.34	0.12
2.00	-0.42	-0.44	-0.38	-0.55	-0.07
2.50	-0.59	-0.66	-0.19	-0.85	-0.28
3.15	-0.75	-0.90	-0.51	-1.12	-0.56
4.00	-1.31	-1.33	-1.50	-1.51	-0.94
5.00	-1.38	-1.65	-1.25	-1.98	-1.41
6.30	-1.94	-2.12	-2.02	-2.51	-2.04
8.00	-2.47	-2.84	-2.80	-3.40	-2.86
10.00	-2.82	-3.85	-2.95	-4.87	-3.80
12.50	-3.78	-5.37	-4.08	-6.04	-4.91
16.00	-5.25	-6.68	-6.12	-7.79	-6.37
20.00	-7.19	-8.59	-7.86	-9.75	-8.01

Table 18 Comparison Amplitude Response using M7.6 Event

Vertical Amplitude Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.010	-1.87	-1.89	-1.83	-1.87	-1.64
0.013	-0.88	-0.89	-0.84	-0.88	-0.74
0.016	-0.44	-0.45	-0.41	-0.45	-0.29
0.020	-0.24	-0.26	-0.23	-0.25	-0.12
0.025	-0.17	-0.19	-0.16	-0.17	-0.05
0.032	-0.13	-0.15	-0.13	-0.14	-0.02
0.040	-0.12	-0.14	-0.11	-0.14	-0.01
0.050	-0.12	-0.14	-0.11	-0.13	-0.01
0.063	-0.12	-0.14	-0.12	-0.13	-0.01
0.080	-0.12	-0.14	-0.12	-0.13	-0.01
0.100	-0.12	-0.14	-0.12	-0.13	-0.01
0.125	-0.12	-0.14	-0.12	-0.14	-0.01
0.160	-0.13	-0.14	-0.12	-0.14	-0.01
0.200	-0.13	-0.14	-0.12	-0.15	-0.01
0.250	-0.13	-0.15	-0.13	-0.14	-0.01
0.315	-0.13	-0.15	-0.13	-0.14	-0.01
0.400	-0.14	-0.15	-0.13	-0.14	-0.01
0.500	-0.14	-0.15	-0.13	-0.15	-0.01
0.630	-0.14	-0.16	-0.13	-0.15	-0.01
0.800	-0.14	-0.16	-0.12	-0.15	0.00
1.000	-0.14	-0.16	-0.13	-0.14	0.00
1.250	-0.15	-0.18	-0.09	-0.11	0.00
1.600	-0.17	-0.18	-0.07	-0.05	0.01
2.000	-0.21	-0.20	-0.03	0.08	0.02
2.500	-0.16	-0.18	-0.01	0.00	0.04

North/South Amplitude Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.01	-1.72	-1.72	-1.75	-1.72	-1.64
0.0125	-0.83	-0.81	-0.91	-0.82	-0.74
0.016	-0.45	-0.42	-0.63	-0.42	-0.29
0.020	-0.23	-0.22	-0.36	-0.23	-0.12
0.025	-0.13	-0.15	-0.16	-0.17	-0.05
0.032	-0.07	-0.10	-0.04	-0.12	-0.02
0.040	-0.01	-0.07	0.11	-0.10	-0.01
0.050	-0.04	-0.08	0.03	-0.11	-0.01
0.063	-0.05	-0.09	-0.02	-0.12	-0.01
0.080	-0.08	-0.10	-0.11	-0.12	-0.01
0.100	-0.09	-0.10	-0.13	-0.13	-0.01
0.125	-0.09	-0.11	-0.13	-0.12	-0.01
0.160	-0.08	-0.10	-0.11	-0.14	-0.01
0.200	-0.09	-0.10	-0.12	-0.12	-0.01
0.250	-0.09	-0.12	-0.11	-0.14	-0.01
0.315	-0.10	-0.12	-0.14	-0.14	-0.01
0.400	-0.11	-0.12	-0.16	-0.15	-0.01
0.500	-0.10	-0.12	-0.13	-0.15	-0.01
0.630	-0.09	-0.12	-0.10	-0.15	-0.01
0.800	-0.12	-0.13	-0.15	-0.12	0.00
1.000	-0.13	-0.12	-0.22	-0.08	0.00
1.250	-0.14	-0.14	-0.23	-0.13	0.00
1.600	-0.14	-0.14	-0.19	-0.11	0.01
2.000	-0.12	-0.14	-0.14	-0.12	0.02
2.500	-0.13	-0.14	-0.10	-0.06	0.04

East/West Amplitude Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.01	-1.88	-1.87	-1.86	-1.96	-1.64
0.0125	-0.92	-0.93	-0.92	-0.97	-0.74
0.016	-0.37	-0.40	-0.33	-0.44	-0.29
0.020	-0.23	-0.24	-0.23	-0.28	-0.12
0.025	-0.21	-0.19	-0.29	-0.20	-0.05
0.032	-0.17	-0.13	-0.32	-0.14	-0.02
0.040	-0.17	-0.13	-0.35	-0.14	-0.01
0.050	-0.19	-0.13	-0.41	-0.13	-0.01
0.063	-0.13	-0.11	-0.24	-0.13	-0.01
0.080	-0.12	-0.10	-0.20	-0.13	-0.01
0.100	-0.09	-0.10	-0.18	-0.13	-0.01
0.125	-0.12	-0.12	-0.19	-0.14	-0.01
0.160	-0.12	-0.10	-0.25	-0.13	-0.01
0.200	-0.14	-0.12	-0.24	-0.15	-0.01
0.250	-0.13	-0.11	-0.24	-0.13	-0.01
0.315	-0.13	-0.12	-0.20	-0.15	-0.01
0.400	-0.12	-0.12	-0.19	-0.14	-0.01
0.500	-0.12	-0.12	-0.19	-0.14	-0.01
0.630	-0.15	-0.12	-0.26	-0.13	-0.01
0.800	-0.12	-0.11	-0.18	-0.09	0.00
1.000	-0.10	-0.08	-0.13	-0.07	0.00
1.250	-0.10	-0.10	-0.11	-0.07	0.00
1.600	-0.10	-0.10	-0.08	-0.01	0.01
2.000	-0.13	-0.11	-0.16	-0.02	0.02
2.500	-0.13	-0.12	-0.15	-0.05	0.04

Table 19 Comparison Phase Response using M7.6 Event

Vertical Phase Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.0100	75.33	75.39	75.08	75.24	74.99
0.0125	59.17	59.23	58.92	59.09	59.01
0.0160	45.26	45.29	44.98	45.21	44.88
0.0200	35.50	35.47	35.21	35.40	35.13
0.0250	28.49	28.52	28.33	28.40	27.64
0.0315	22.51	22.55	22.39	22.38	21.67
0.0400	17.15	17.16	17.03	17.00	16.93
0.0500	13.84	13.88	13.77	13.68	13.47
0.0630	10.48	10.50	10.41	10.34	10.65
0.0800	8.40	8.44	8.37	8.37	8.37
0.1000	6.59	6.60	6.55	6.54	6.68
0.1250	5.27	5.30	5.27	5.22	5.33
0.1600	4.12	4.12	4.09	4.11	4.15
0.2000	3.20	3.22	3.21	3.20	3.31
0.2500	2.55	2.58	2.58	2.57	2.63
0.3150	1.99	1.98	1.94	1.99	2.07
0.4000	1.51	1.53	1.52	1.47	1.61
0.5000	1.09	1.13	1.13	1.10	1.26
0.6300	0.78	0.85	0.87	0.74	0.96
0.8000	0.52	0.56	0.59	0.48	0.70
1.0000	0.30	0.34	0.40	0.26	0.50
1.2500	0.13	0.19	0.24	0.03	0.31
1.6000	-0.18	0.05	0.04	-0.11	0.12
2.0000	-0.34	-0.13	-0.25	-0.30	-0.07
2.5000	-0.67	-0.20	-0.46	-0.41	-0.28

North/South Phase Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.0100	76.02	76.03	75.85	75.93	74.99
0.0125	59.31	59.29	59.24	59.18	59.01
0.0160	45.17	45.13	45.13	45.01	44.88
0.0200	35.46	35.40	35.50	35.29	35.13
0.0250	28.44	28.40	28.30	28.30	27.64
0.0315	22.41	22.44	21.90	22.28	21.67
0.0400	17.07	17.00	16.79	16.77	16.93
0.0500	13.72	13.71	13.31	13.53	13.47
0.0630	10.29	10.32	9.76	10.16	10.65
0.0800	8.36	8.36	8.35	8.28	8.37
0.1000	6.60	6.55	6.64	6.49	6.68
0.1250	5.58	5.50	5.71	5.38	5.33
0.1600	4.45	4.28	4.79	4.21	4.15
0.2000	3.16	3.14	3.28	3.16	3.31
0.2500	2.58	2.61	2.62	2.57	2.63
0.3150	1.99	2.04	2.01	2.08	2.07
0.4000	1.54	1.47	1.76	1.54	1.61
0.5000	1.21	1.21	1.39	1.15	1.26
0.6300	0.80	0.77	0.86	0.77	0.96
0.8000	0.55	0.58	0.65	0.63	0.70
1.0000	0.46	0.39	0.82	0.33	0.50
1.2500	0.24	0.16	0.52	0.00	0.31
1.6000	-0.14	-0.09	0.00	-0.17	0.12
2.0000	-0.32	-0.26	-0.14	-0.37	-0.07
2.5000	-0.44	-0.46	-0.20	-0.64	-0.28

East/West Phase Response					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 769	T120 Slim PH2024	Nominal
0.0100	74.88	74.95	74.74	74.79	74.99
0.0125	59.41	59.45	59.25	59.36	59.01
0.0160	45.32	45.34	45.18	45.26	44.88
0.0200	35.41	35.35	35.33	35.33	35.13
0.0250	28.61	28.47	28.59	28.50	27.64
0.0315	22.39	22.32	21.84	22.45	21.67
0.0400	17.27	17.06	17.10	17.13	16.93
0.0500	13.83	13.68	13.39	13.81	13.47
0.0630	10.40	10.34	9.91	10.45	10.65
0.0800	8.39	8.40	8.29	8.40	8.37
0.1000	6.73	6.63	6.94	6.59	6.68
0.1250	5.37	5.30	5.74	5.20	5.33
0.1600	4.25	4.19	4.68	4.04	4.15
0.2000	3.14	3.29	3.33	3.24	3.31
0.2500	2.49	2.58	2.67	2.55	2.63
0.3150	1.89	1.99	1.89	1.90	2.07
0.4000	1.49	1.52	1.66	1.46	1.61
0.5000	1.11	1.03	1.24	0.94	1.26
0.6300	0.84	0.86	0.85	0.74	0.96
0.8000	0.50	0.45	0.63	0.39	0.70
1.0000	0.30	0.23	0.61	0.11	0.50
1.2500	0.15	0.07	0.46	-0.04	0.31
1.6000	-0.25	-0.21	-0.01	-0.35	0.12
2.0000	-0.47	-0.48	-0.48	-0.60	-0.07
2.5000	-0.55	-0.59	-0.26	-0.80	-0.28

3.6 Passband

The passband of a sensor is defined as 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).

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.

3.6.1 Configuration

There is no test configuration for the passband test. The amplitude response used in computing the passband is determined in section 3.3 Primary Frequency Response and 3.5 Comparison Frequency Response.

3.6.2 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.

3.6.3 Result

The following table contains the passband limits of the T120 sensors.

Table 20 Passband

	Lower Limit	Upper Limit
T120 Horizon V2 2029 (all axis)	<0.02	> 20 Hz
T120 Horizon V2 2028 (all axis)	<0.02	> 20 Hz
T120 Horizon V1 0769 (all axis)	<0.02	> 20 Hz
T120 Slim PH 2024 (all axis)	<0.02	> 20 Hz

All the T120 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.

3.7 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 (up to 30V). At each input voltage setpoint, the seismometer is calibrated at 1Hz and 10Hz.

3.7.1 Measurand

The quantity being measured is the change in ground motion sensitivity as a function of the sensor's input voltage. The amplitude response of the sensor at different input 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.

3.7.2 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.

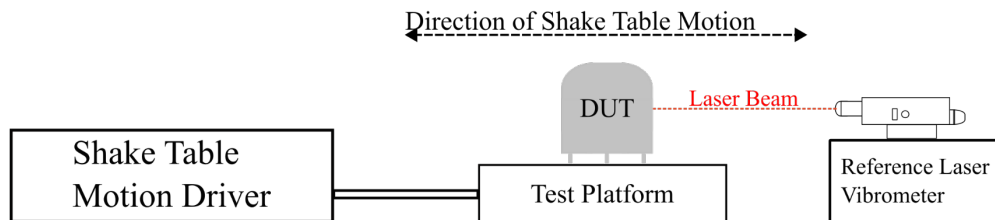


Figure 38 Sensitivity vs Input Voltage Configuration Diagram

Table 21 Sensitivity vs Input Voltage Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.64 mm/s Input Voltage = 9V to 30V Frequency = 1Hz and 10Hz Pressure = 822.8 ± 7.6hPa Temperature = 22.7 ± 0.7C Humidity = 24.6 ± 3.4%

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 following figure shows the change in amplitude and phase for the four T120 sensors at 1Hz and 10Hz when the input voltage ranged from 9V to 30V. 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.

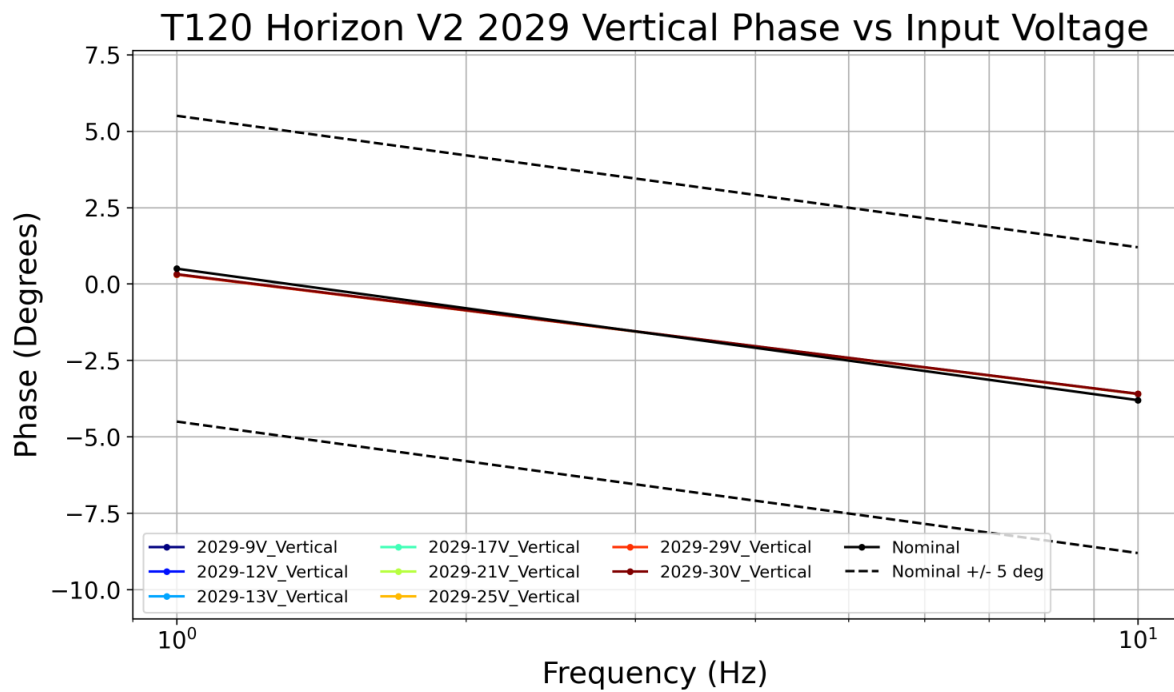
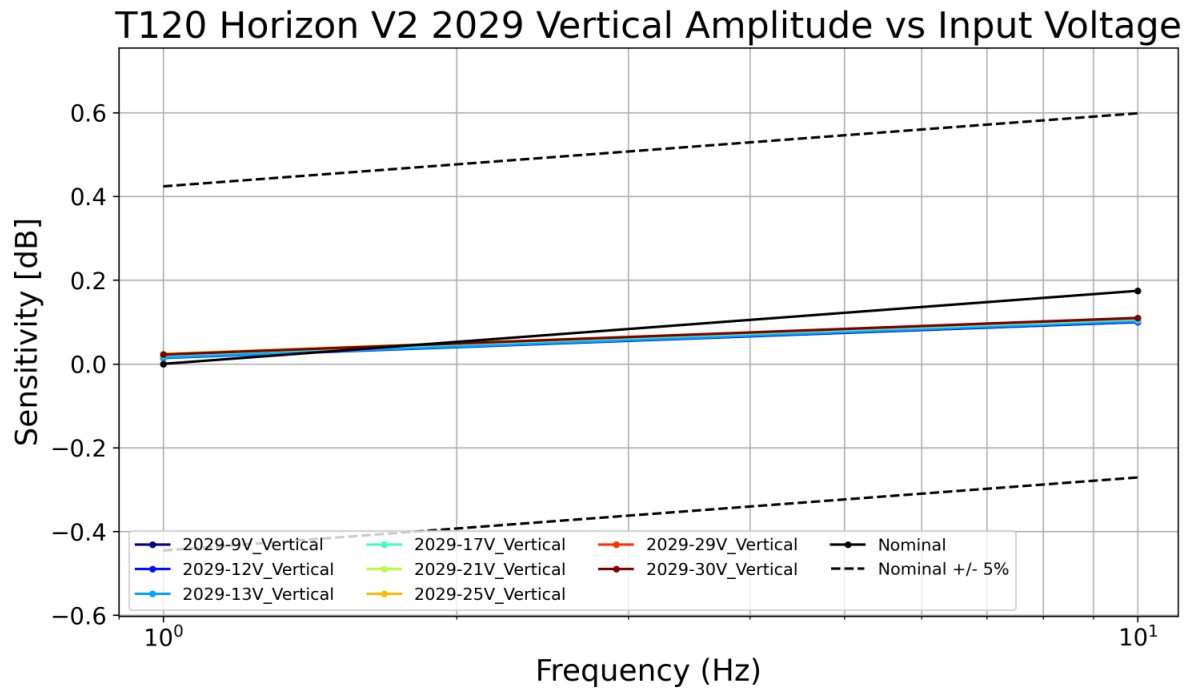


Figure 39 T120 Horizon V2 2029 Vertical Axis Response vs Input Voltage

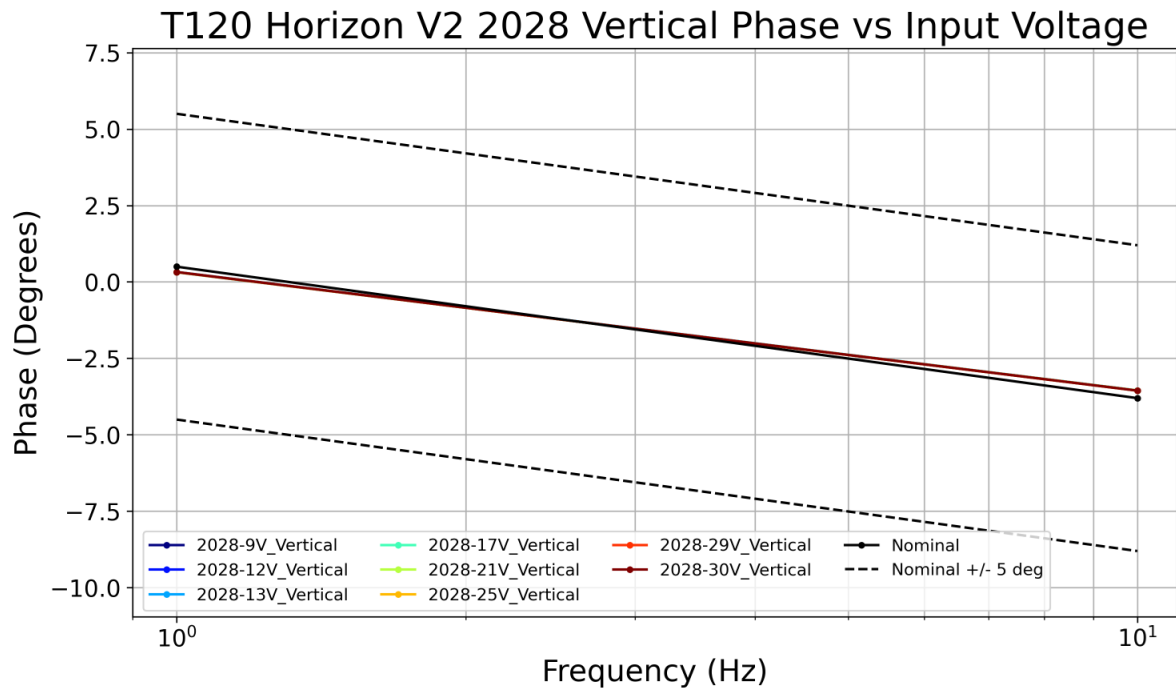
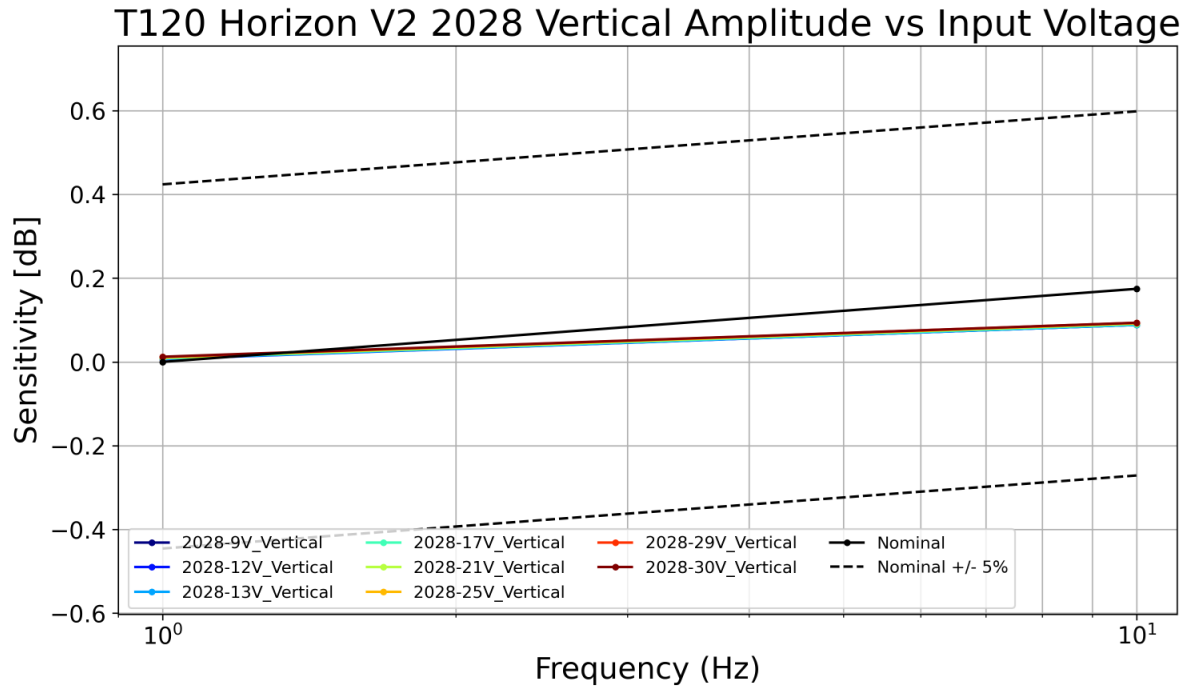


Figure 40 T120 Horizon V2 2028 Vertical Axis Response vs Input Voltage

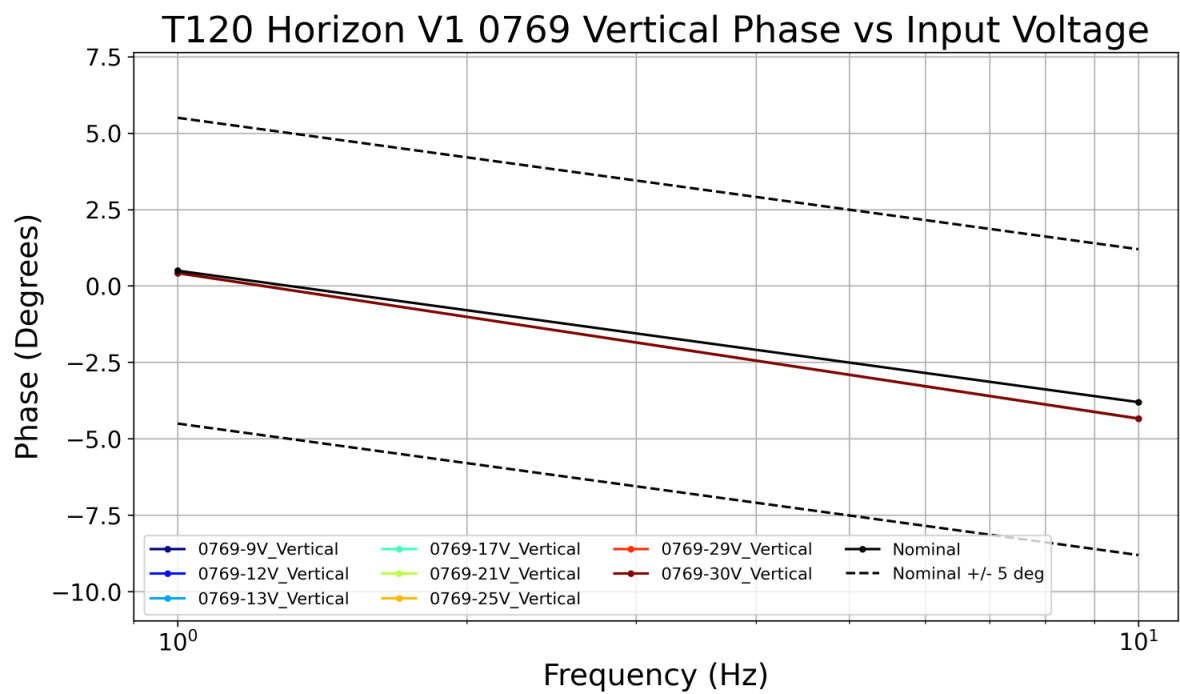
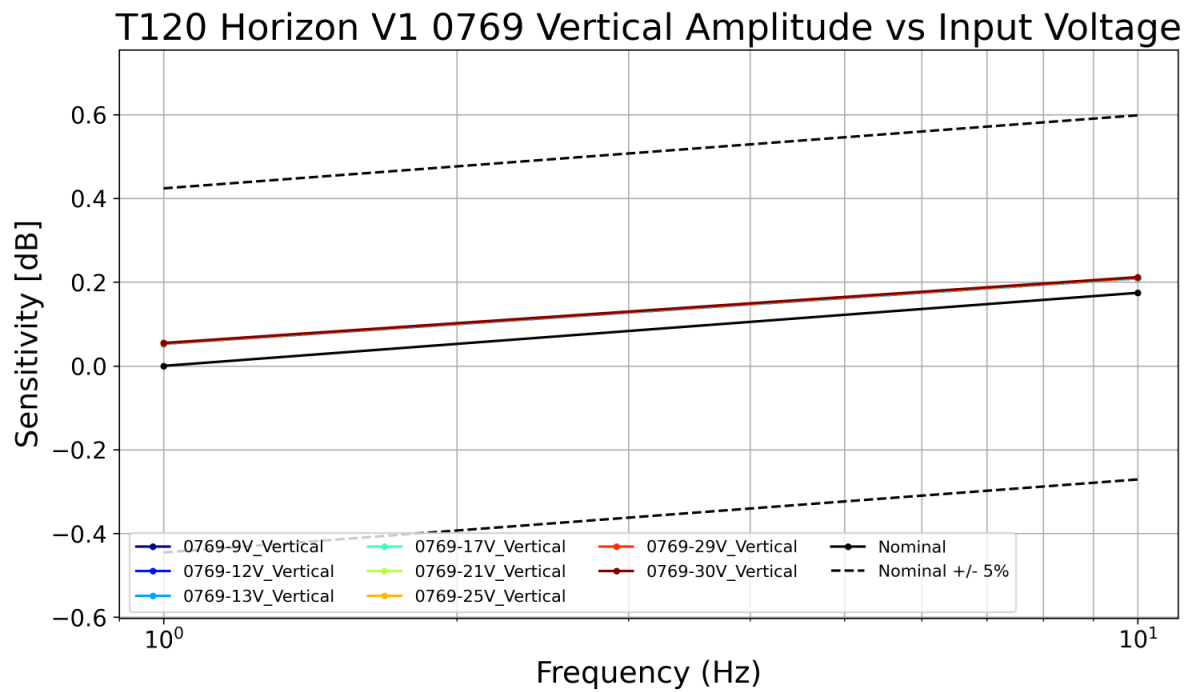


Figure 41 T120 Horizon V1 0769 Vertical Axis Response vs Input Voltage

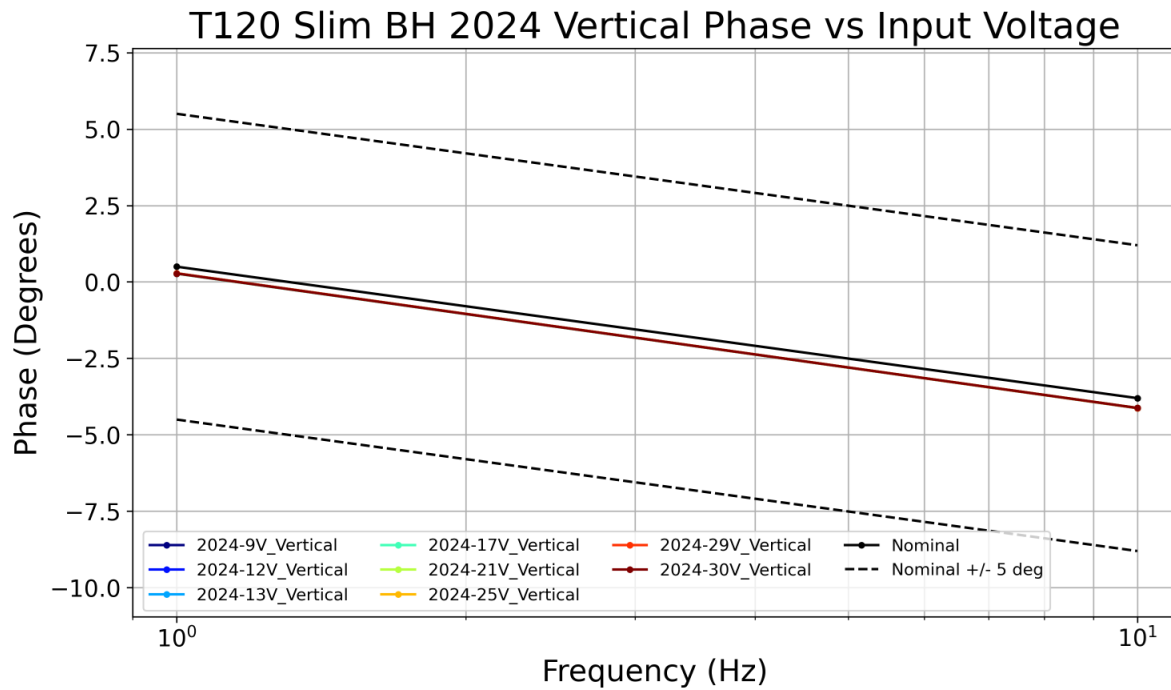
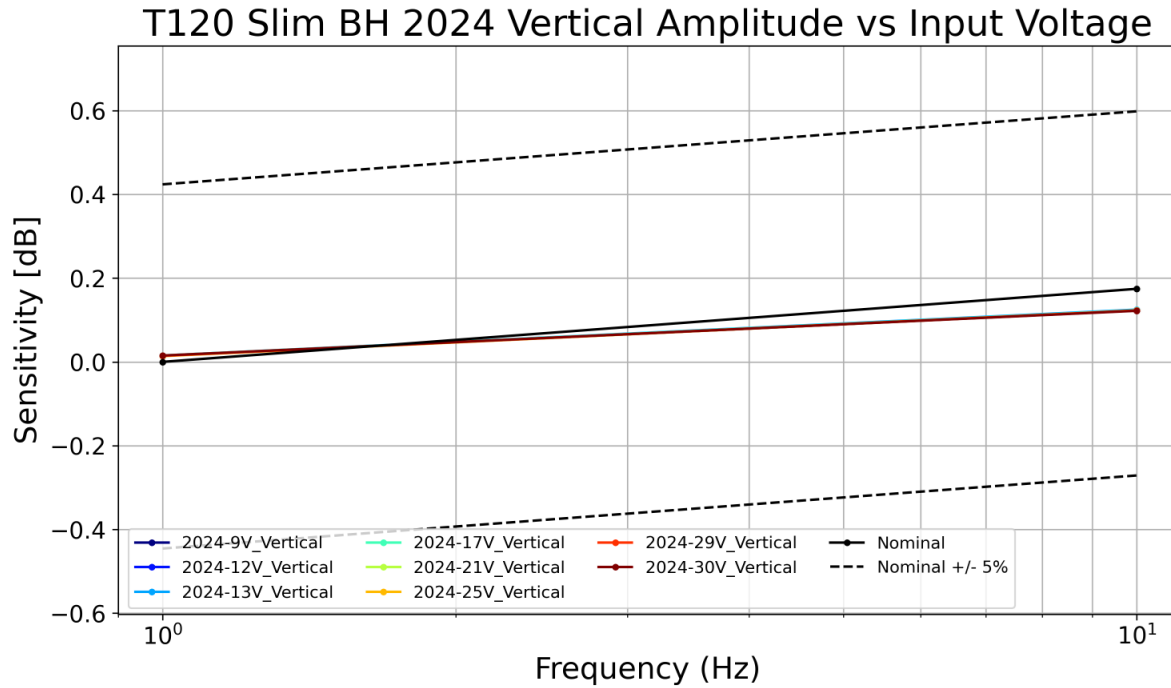


Figure 42 T120 Slim BH 2024 Vertical Axis Response vs Input Voltage

We observe that there is no variation in the 1Hz and 10Hz amplitude or phase response due to changes in the power supply voltage from 9V to 30V.

The following tables contains the values 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 22 Change in Response vs Power Supply Voltage

T120 Horizon 2029				
	1Hz		10Hz	
Input Voltage	Amplitude (dB)	Phase (degrees)	Amplitude (dB)	Phase (degrees)
9	0.02	0.31	0.10	-3.60
12	0.01	0.31	0.10	-3.60
13	0.02	0.31	0.10	-3.60
17	0.02	0.31	0.11	-3.60
21	0.02	0.31	0.11	-3.60
25	0.02	0.31	0.11	-3.60
29	0.02	0.30	0.11	-3.60
30	0.02	0.32	0.11	-3.59
Nominal	0.00	0.50	0.17	-3.80

T120 Horizon 2028				
	1Hz		10Hz	
Input Voltage	Amplitude (dB)	Phase (degrees)	Amplitude (dB)	Phase (degrees)
9	0.01	0.32	0.09	-3.55
12	0.01	0.32	0.09	-3.55
13	0.01	0.33	0.09	-3.55
17	0.01	0.32	0.09	-3.55
21	0.01	0.32	0.09	-3.55
25	0.01	0.32	0.09	-3.56
29	0.01	0.32	0.09	-3.56
30	0.01	0.32	0.09	-3.56
Nominal	0.00	0.50	0.17	-3.80

T120 Horizon 0769				
	1Hz		10Hz	
Input Voltage	Amplitude (dB)	Phase (degrees)	Amplitude (dB)	Phase (degrees)
9	0.05	0.42	0.21	-4.35
12	0.05	0.42	0.21	-4.34
13	0.05	0.42	0.21	-4.34
17	0.05	0.43	0.21	-4.34
21	0.05	0.42	0.21	-4.34
25	0.05	0.42	0.21	-4.34
29	0.05	0.42	0.21	-4.34
30	0.05	0.42	0.21	-4.33
Nominal	0.00	0.50	0.17	-3.80

T120 Slim PH 2024				
	1Hz		10Hz	
Input Voltage	Amplitude (dB)	Phase (degrees)	Amplitude (dB)	Phase (degrees)
9	0.01	0.27	0.12	-4.13
12	0.01	0.28	0.12	-4.13
13	0.02	0.28	0.12	-4.12
17	0.02	0.27	0.12	-4.12
21	0.01	0.28	0.12	-4.13
25	0.01	0.28	0.12	-4.12
29	0.01	0.28	0.12	-4.12
30	0.02	0.27	0.12	-4.12
Nominal	0.00	0.50	0.17	-3.80

3.8 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.

3.8.1 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.

3.8.2 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 T120s is specified as 16.6 mm/s up to 10Hz and then 0.12g above 10Hz. 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 0.12g limit.

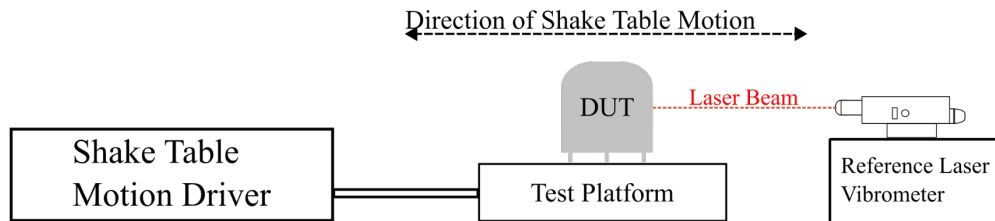


Figure 43 Sensitivity vs Input Amplitude Test Configuration

Table 23 Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.64 to 16.3 mm/s Input Voltage = 12V Frequency = 1Hz to 10Hz Pressure = 820.9 ± 9.5 hPa Temperature = 22.7 ± 1.1 C Humidity = 20.4 ± 9.8 %

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.

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.

3.8.4 Result

The figures below show how the amplitude and phase response of each axis of the four 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.

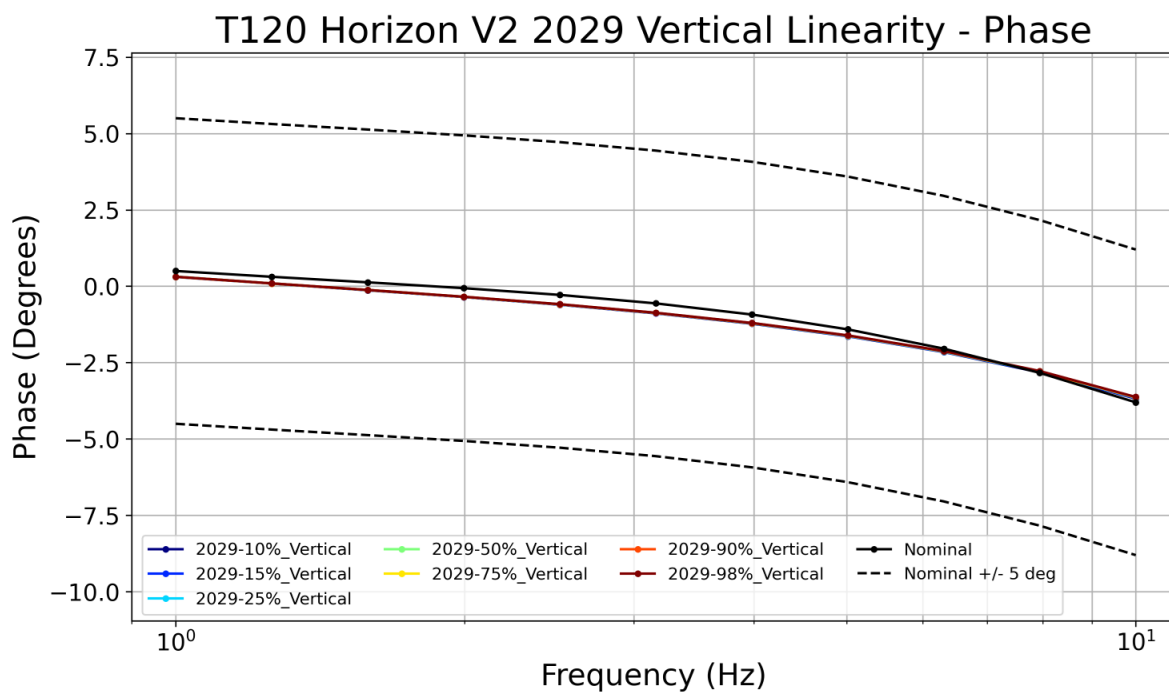
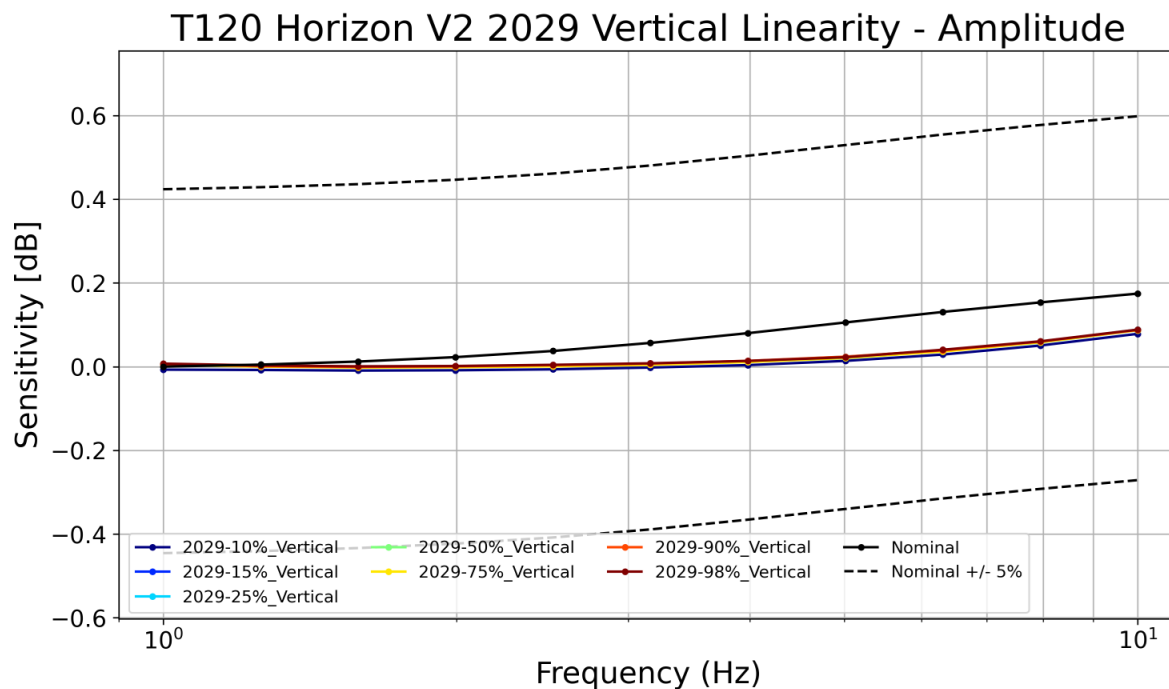


Figure 44 Response vs Input Signal Amplitude for Vertical Axis of T120 Horizon V2 2029

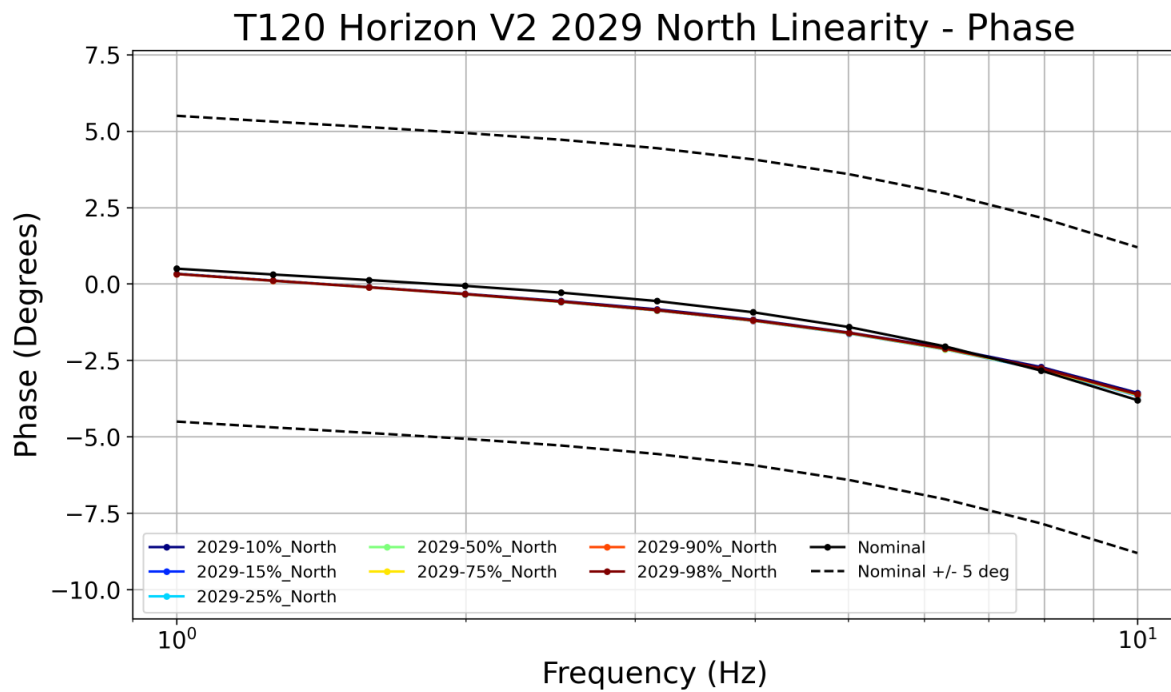
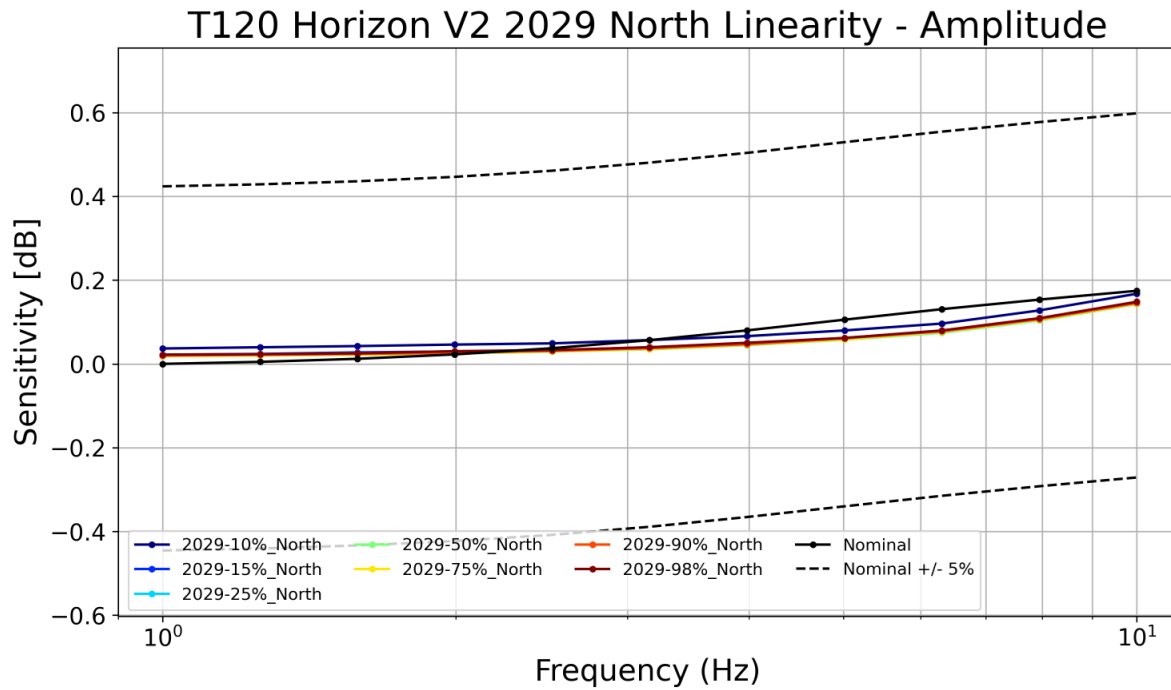


Figure 45 Response vs Input Signal Amplitude for N/S Axis of T120 Horizon V2 2029

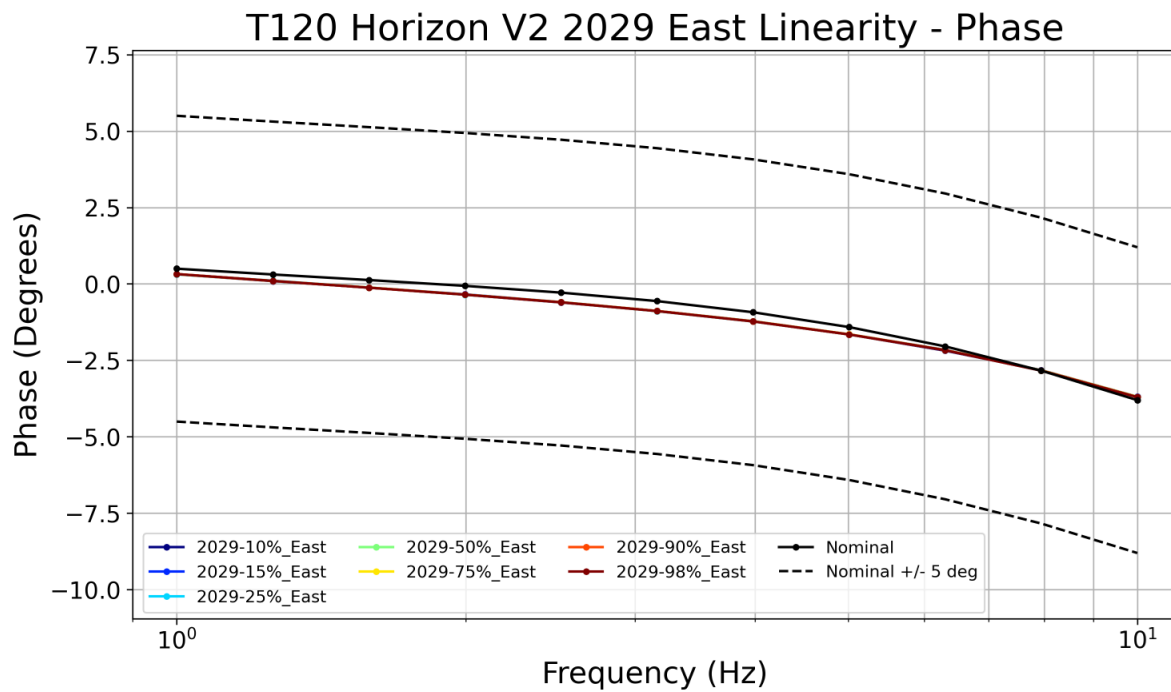
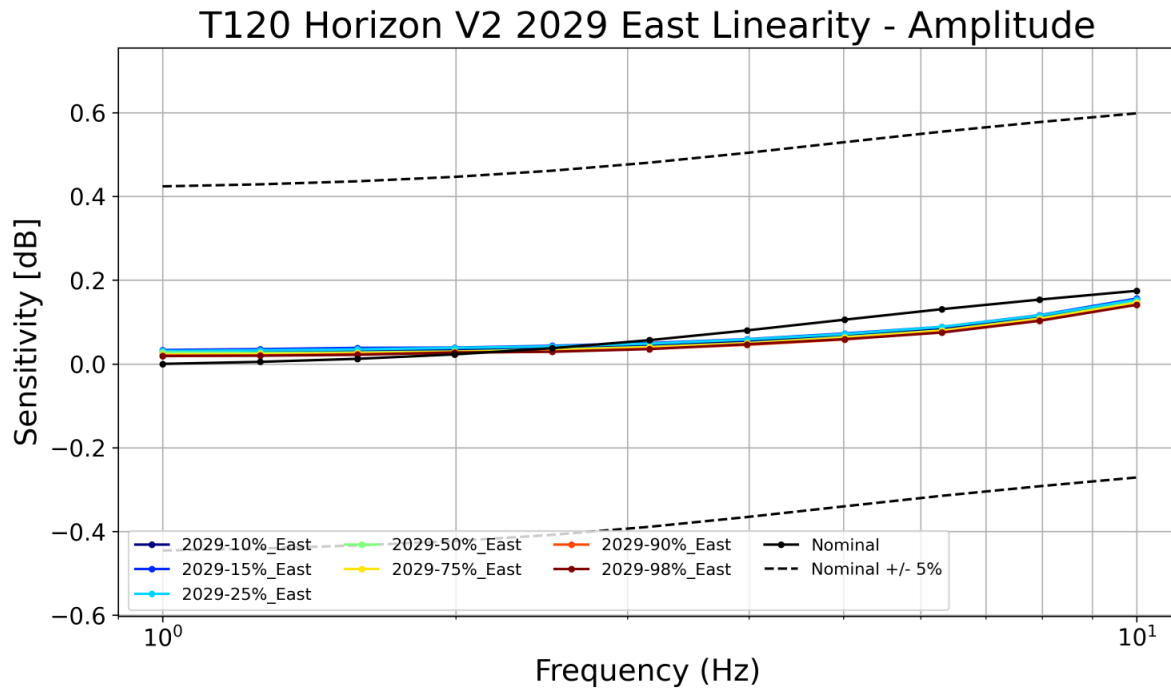


Figure 46 Response vs Input Signal Amplitude for E/W Axis of T120 Horizon V2 2029

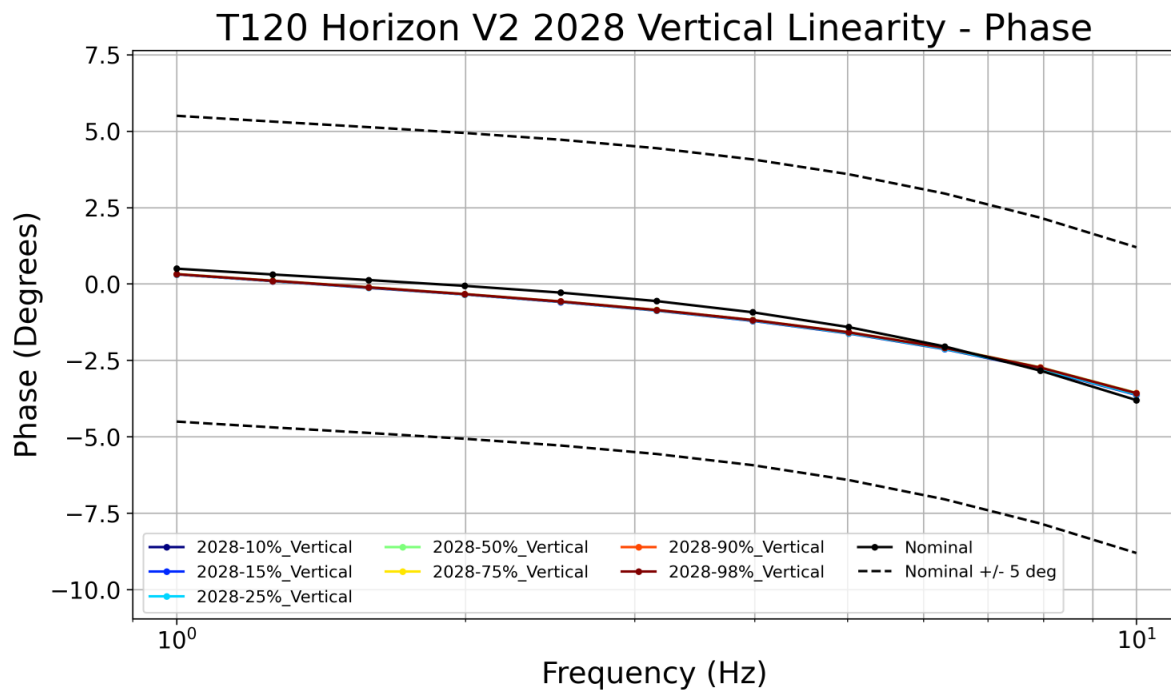
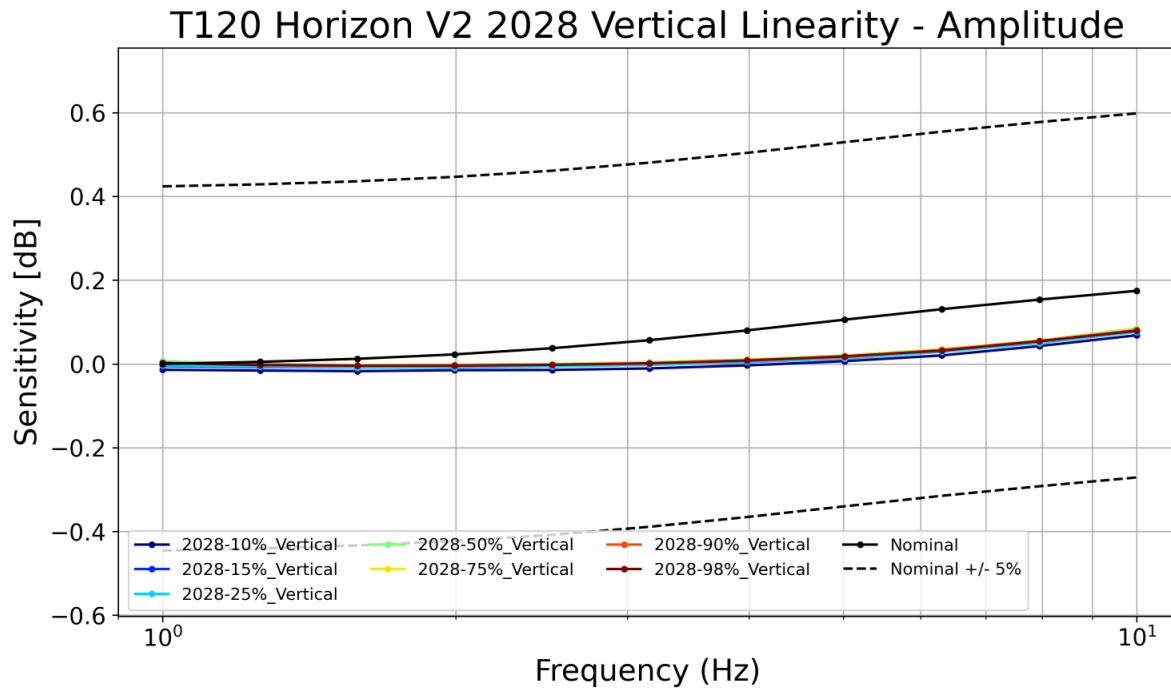


Figure 47 Response vs Input Signal Amplitude for Vertical Axis of T120 Horizon V2 2028

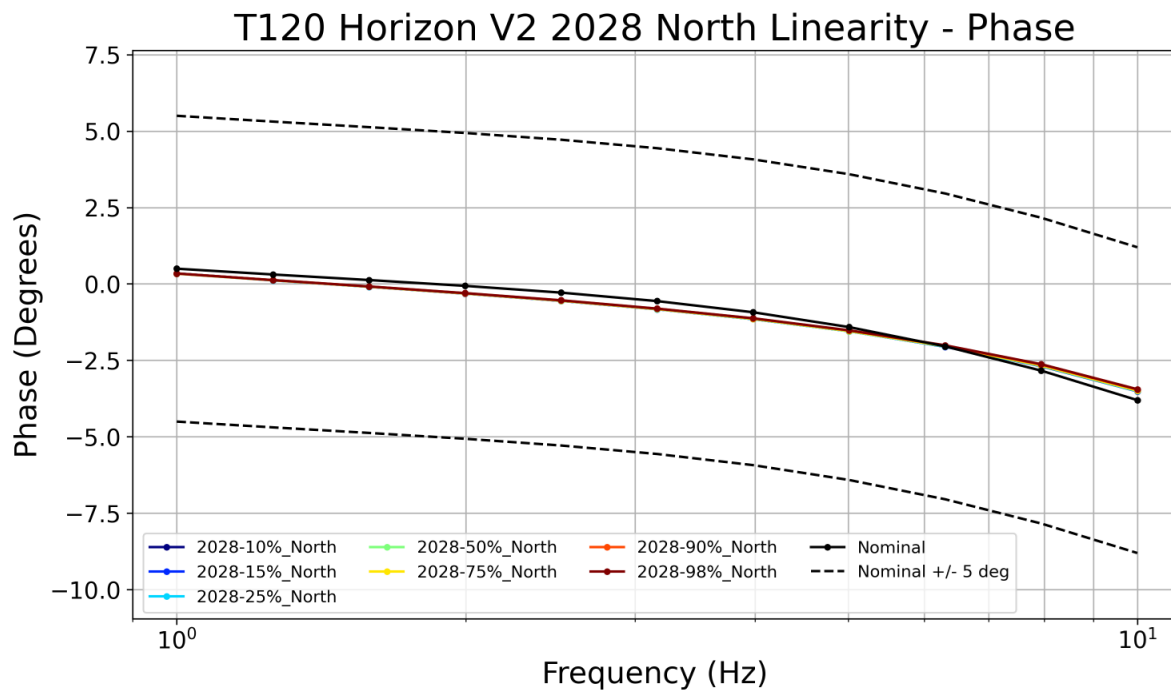
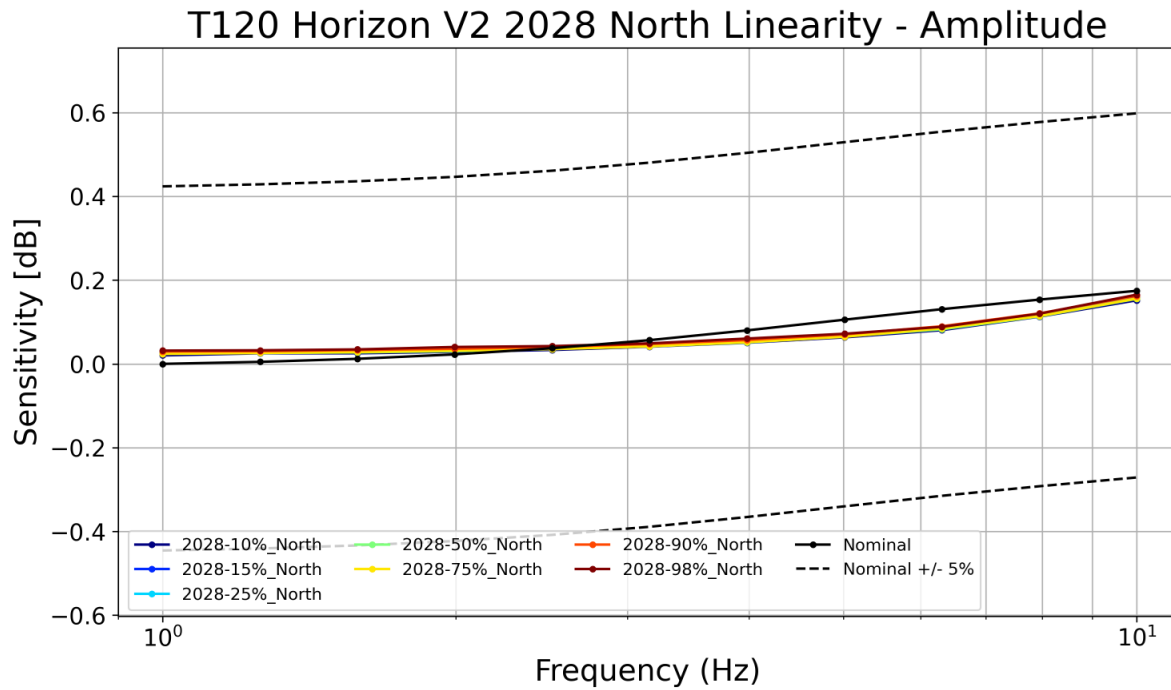


Figure 48 Response vs Input Signal Amplitude for N/S Axis of T120 Horizon V2 2028

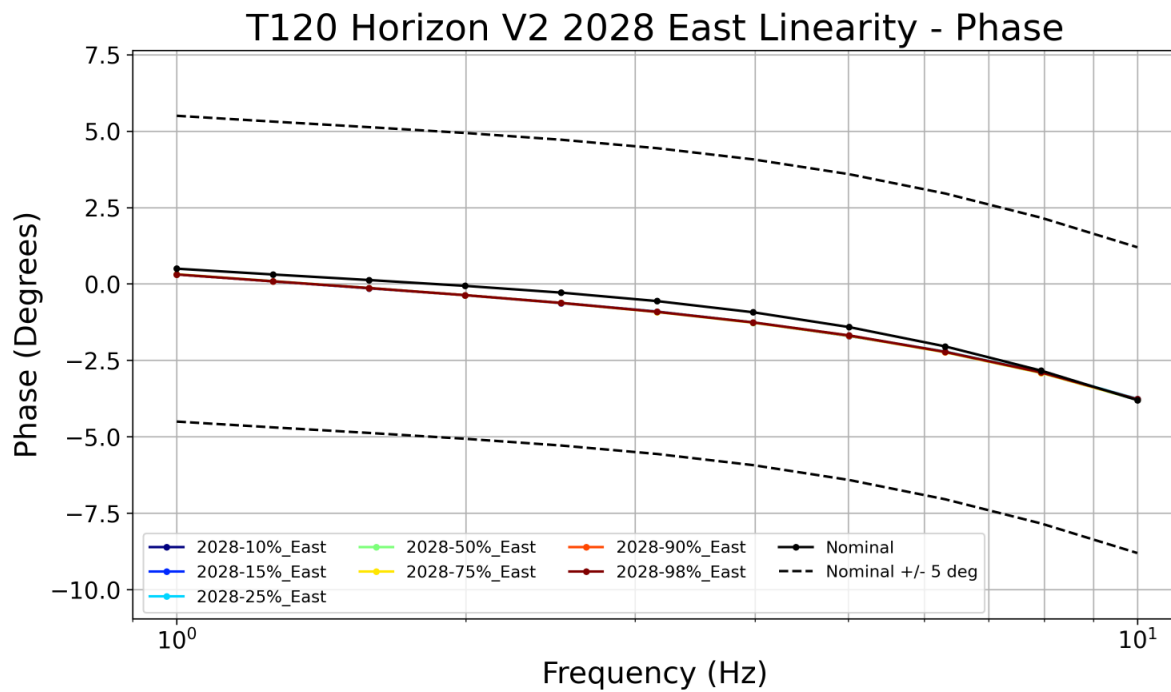
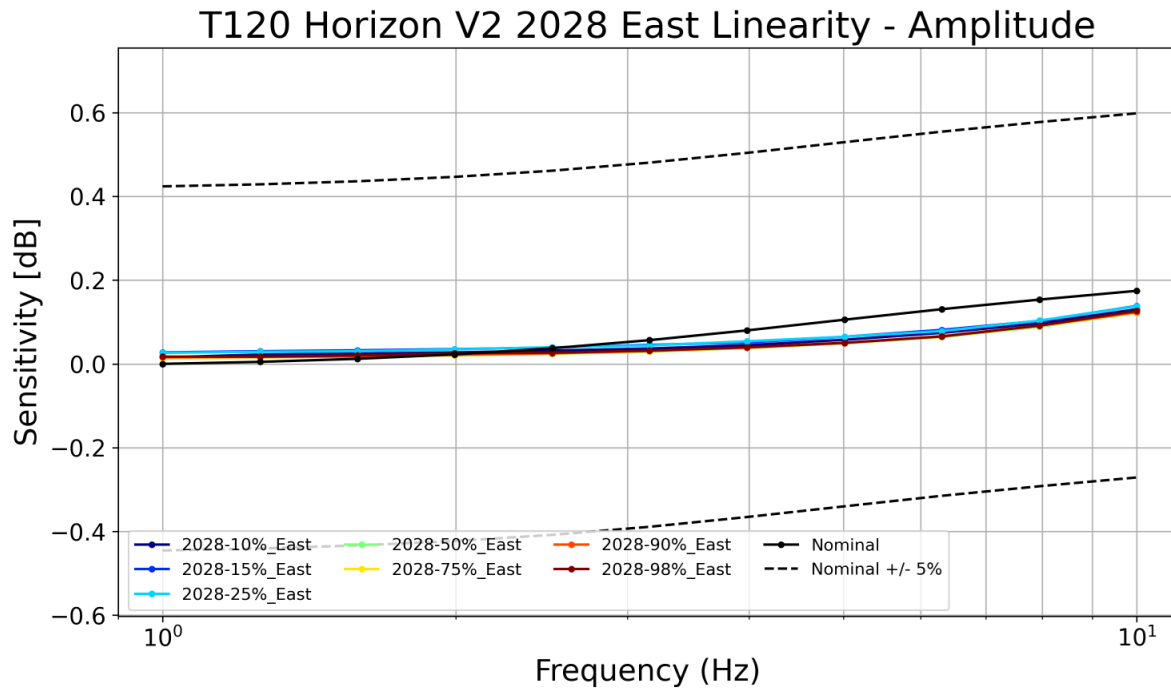


Figure 49 Response vs Input Signal Amplitude for E/W Axis of T120 Horizon V2 2028

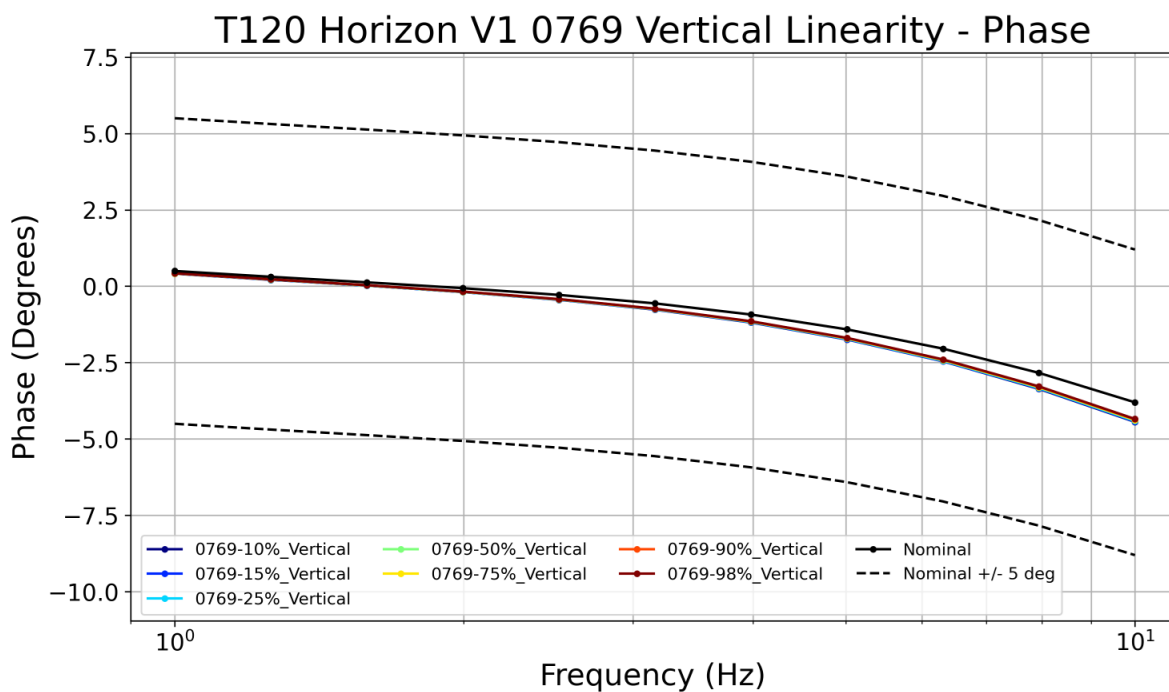
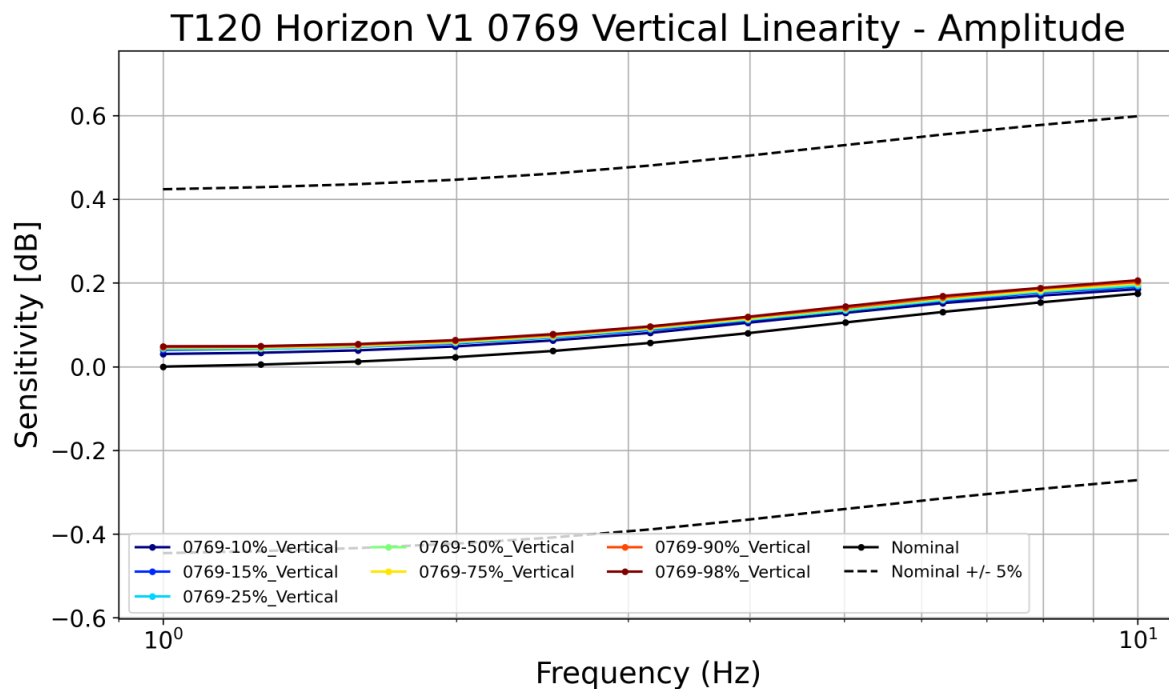


Figure 50 Response vs Input Signal Amplitude for Vertical Axis of T120 Horizon V1 0769

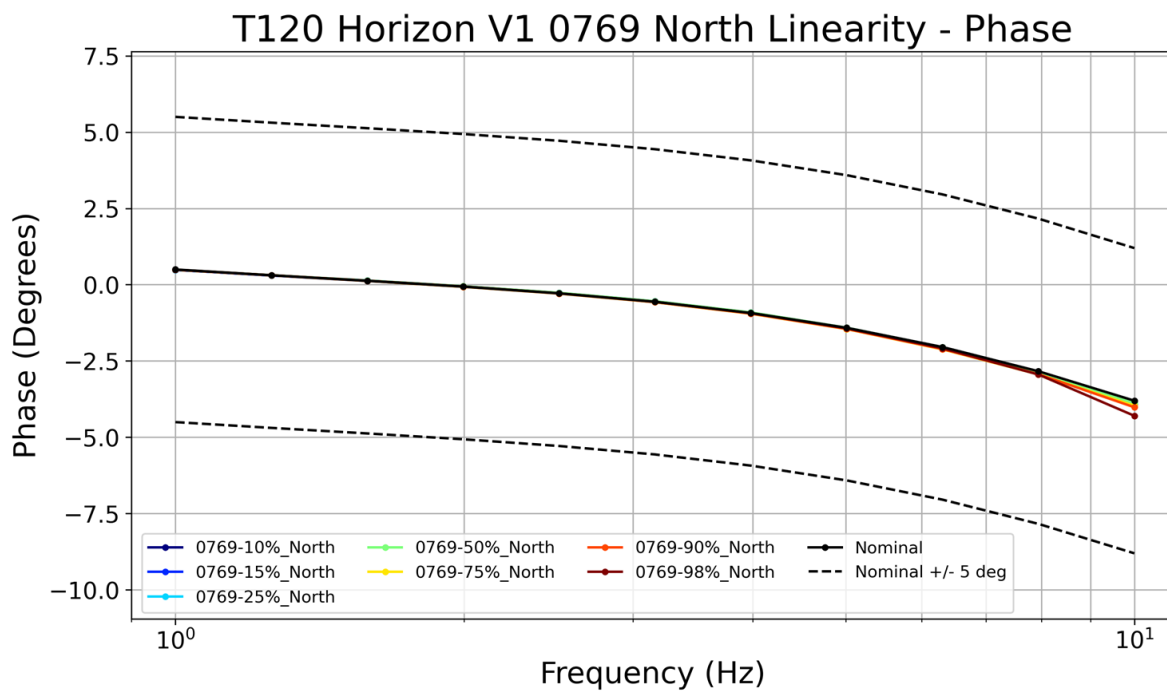
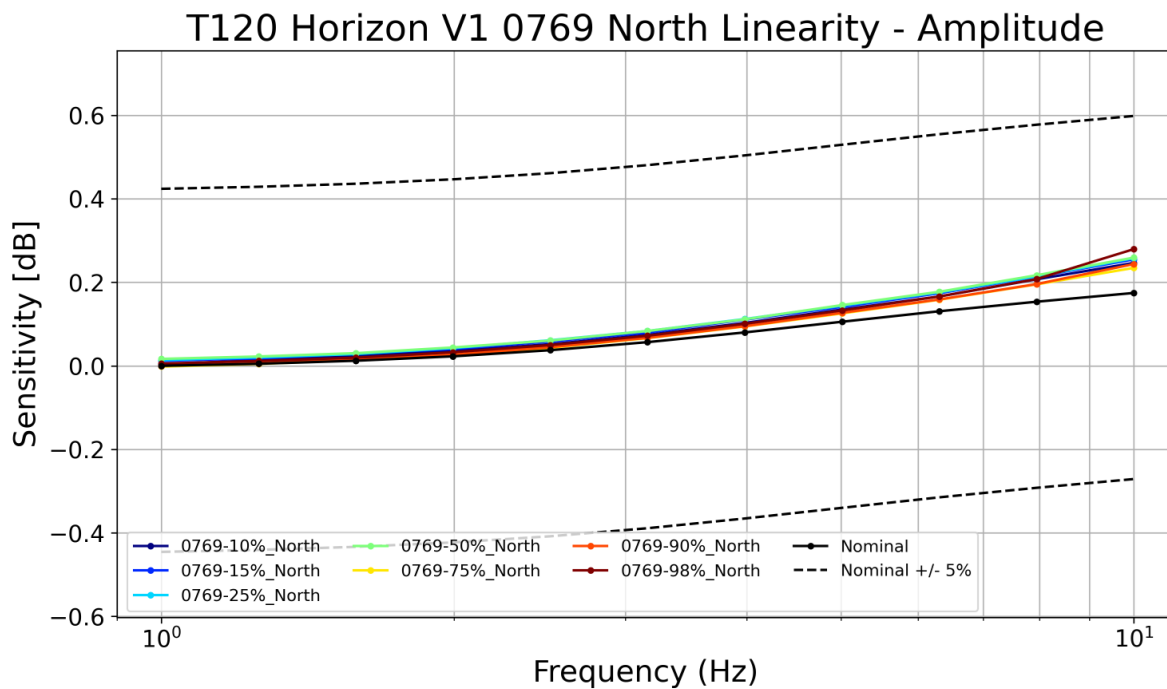


Figure 51 Response vs Input Signal Amplitude for N/S Axis of T120 Horizon V1 0769

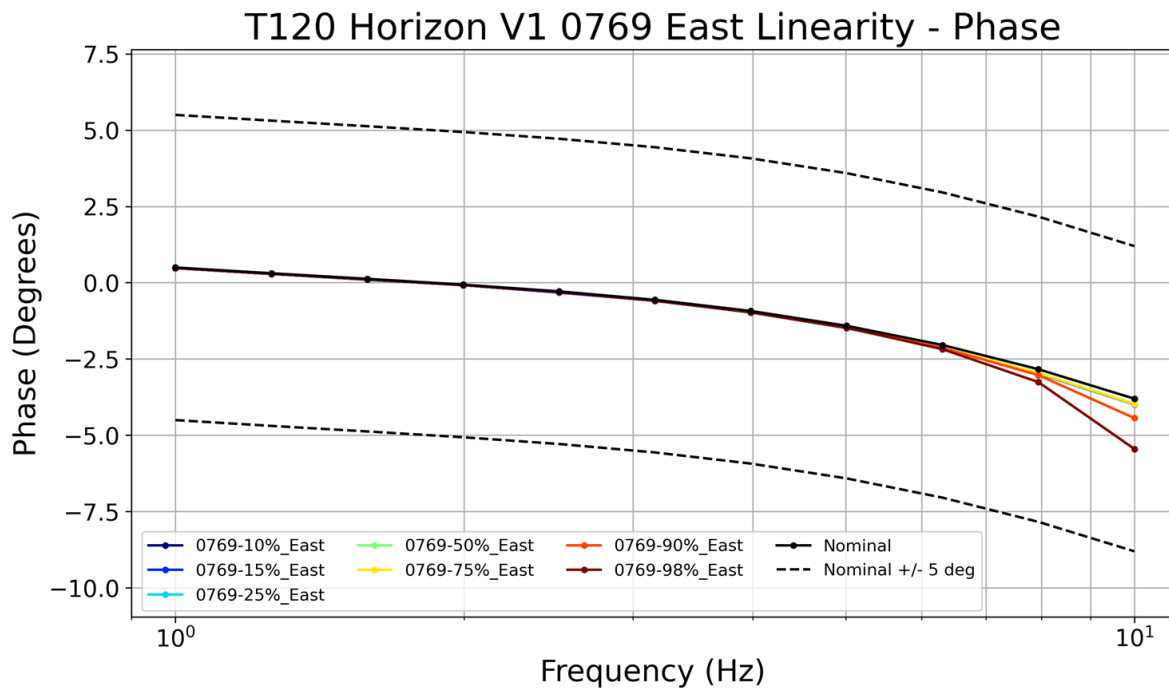
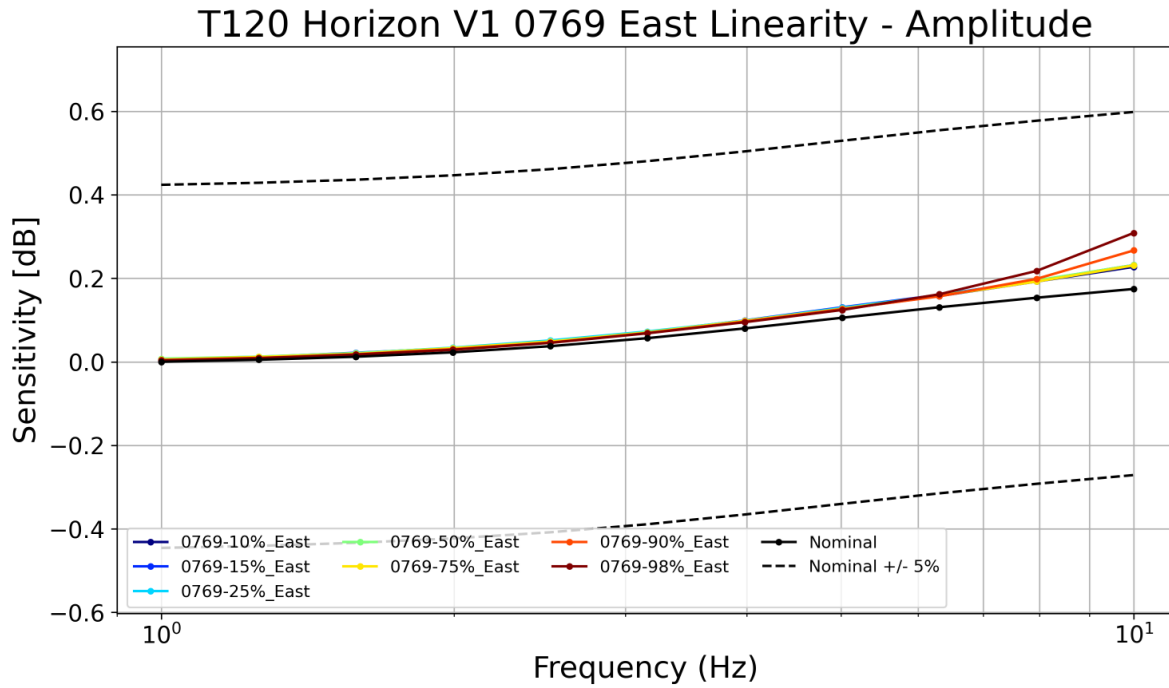


Figure 52 Response vs Input Signal Amplitude for E/W Axis of T120 Horizon V1 0769

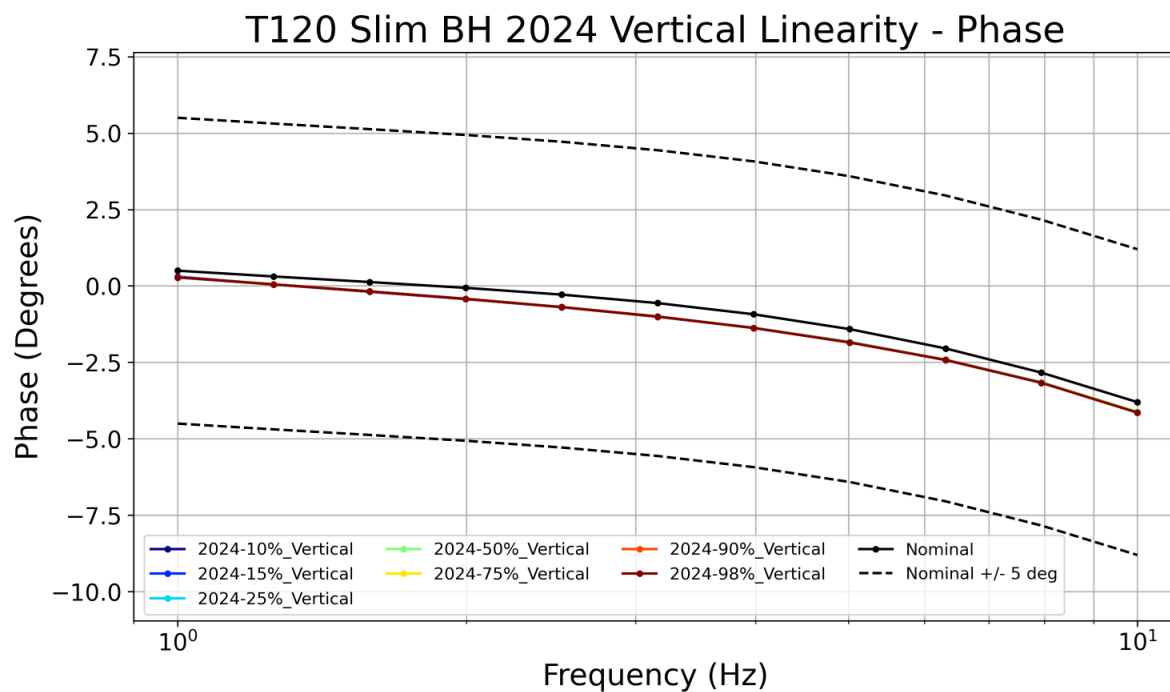
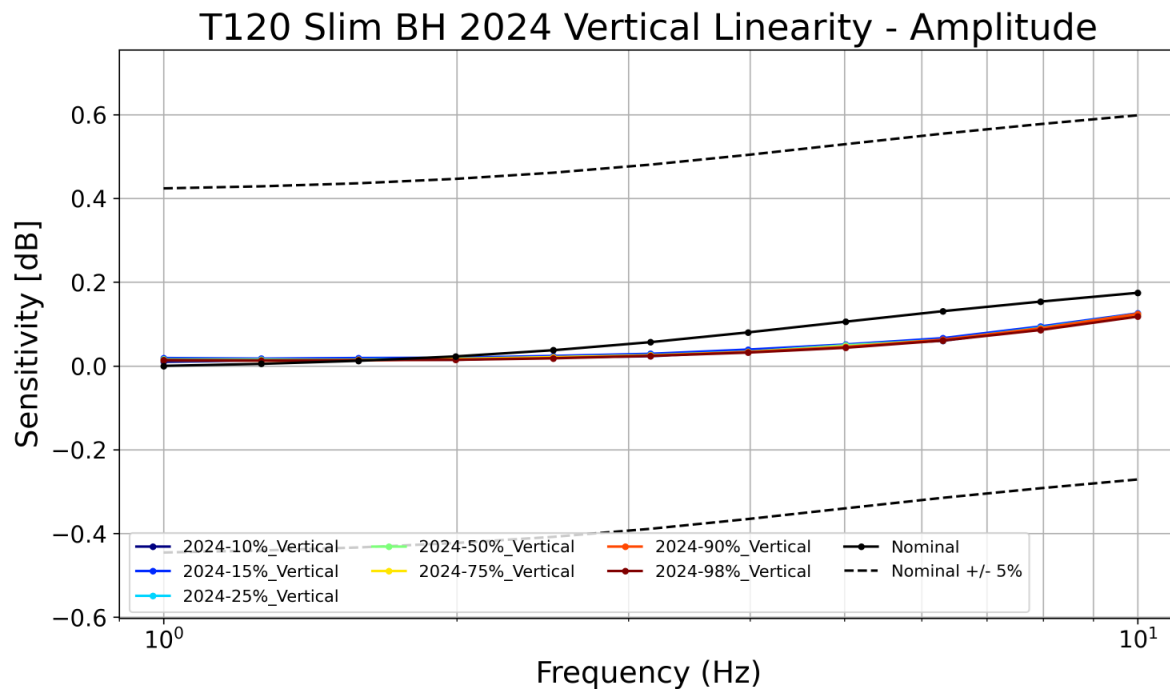


Figure 53 Response vs Input Signal Amplitude for Vertical Axis of T120 Slim BH 2024

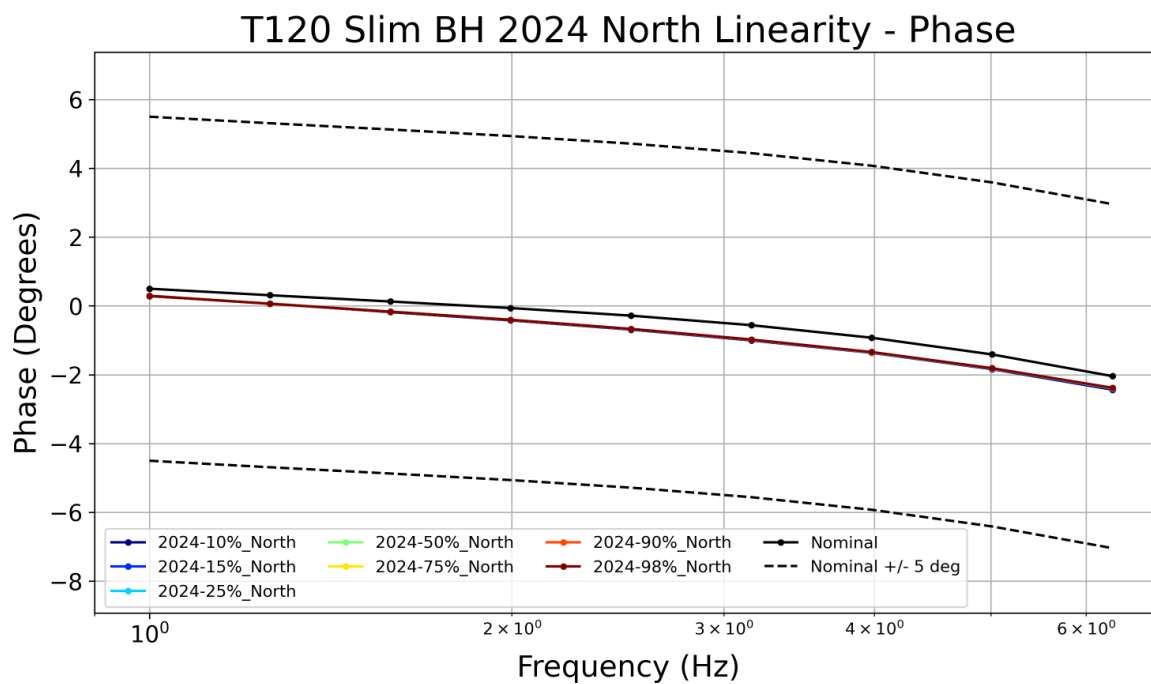
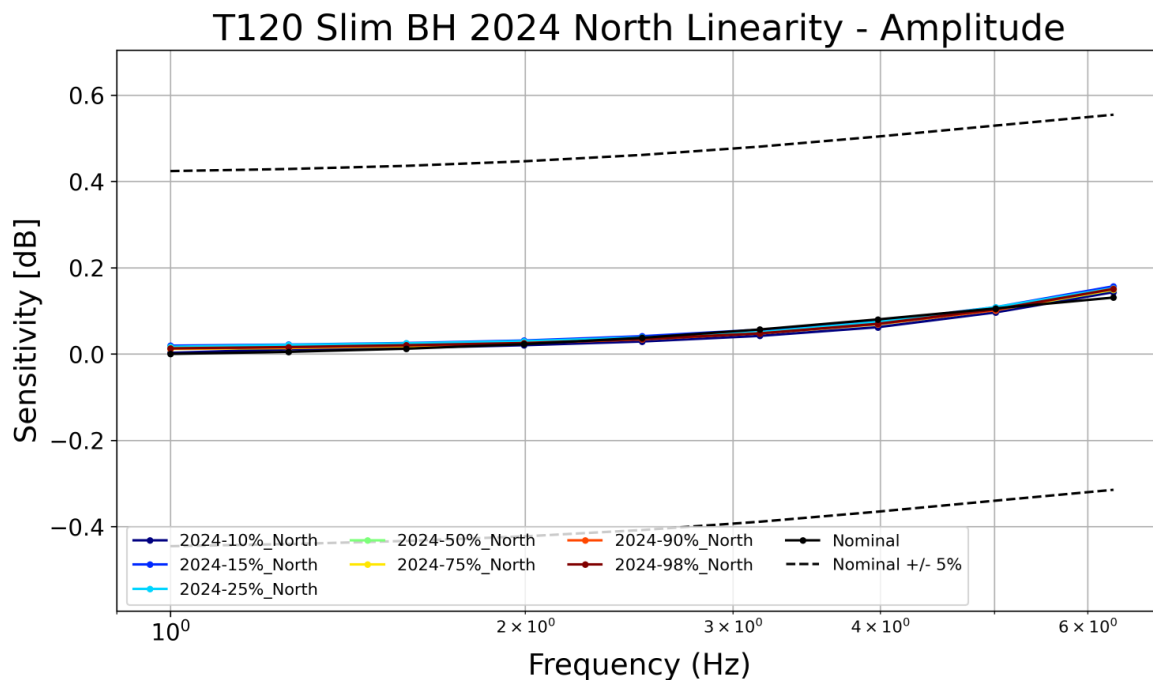


Figure 54 Response vs Input Signal Amplitude for N/S Axis of T120 Slim BH 2024

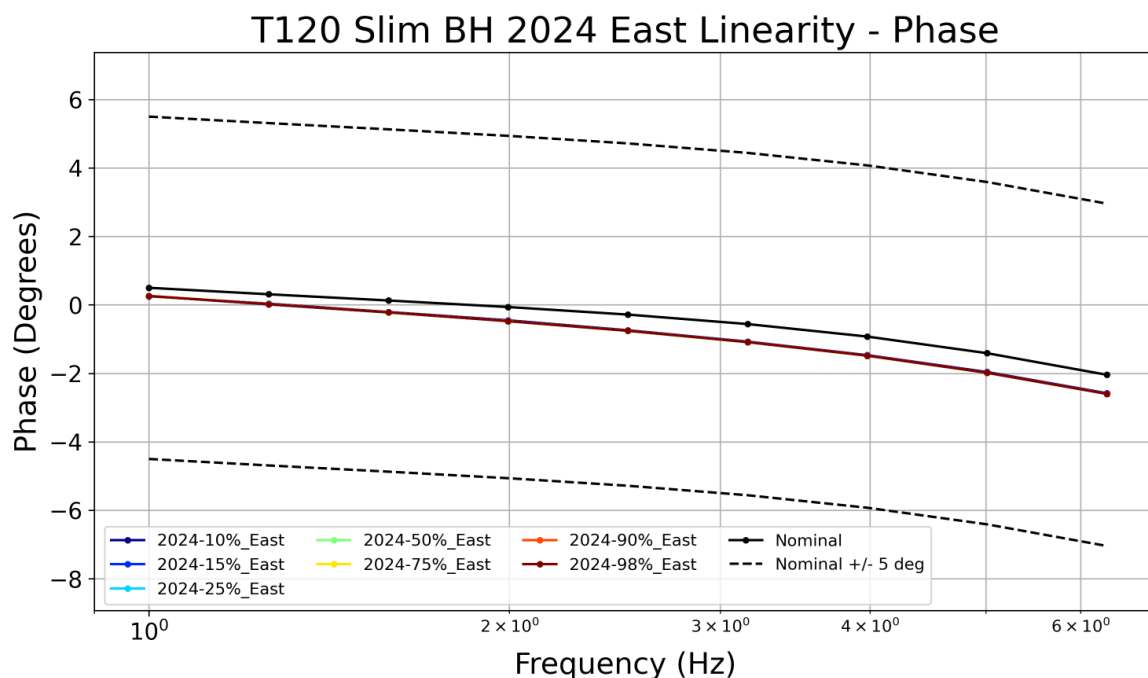
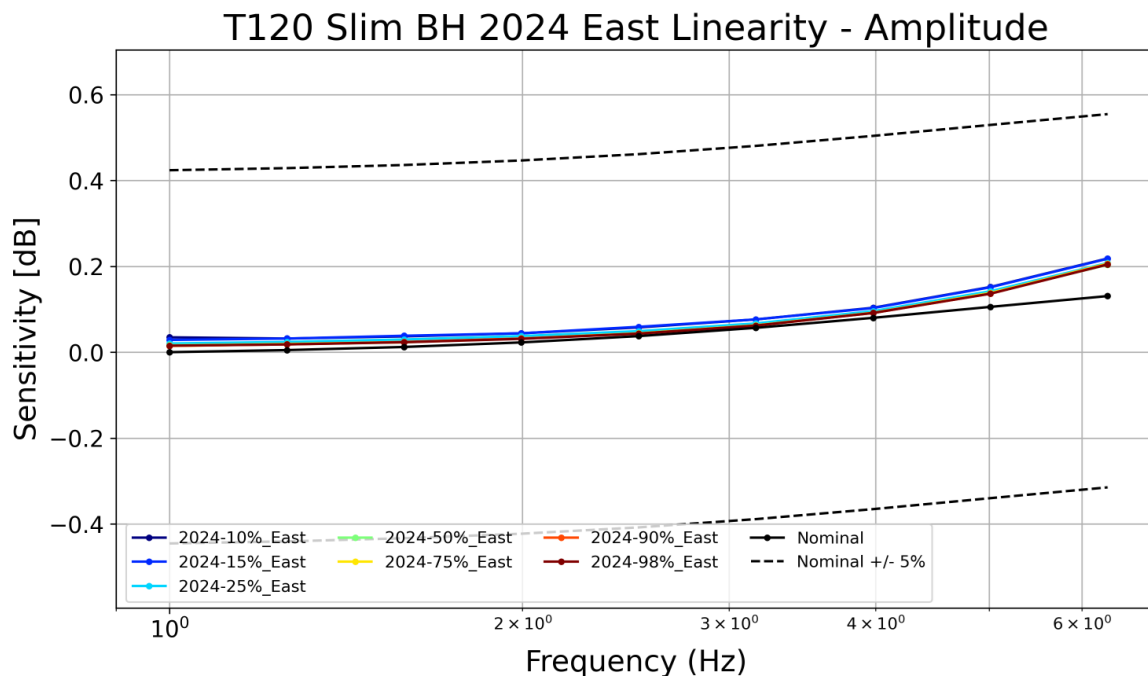


Figure 55 Response vs Input Signal Amplitude for E/W Axis of T120 Slim BH 2024

The above figures show that T120 Horizon V2 sensors 2029, 2028 and T120 Slim PH 2024 had no measurable change in amplitude or phase response as the input amplitude signal level increased. T120 Horizon V1 0769 appeared to have a small change in its horizontal axis response for frequencies above 8Hz when the input signal level was at 90% and 98% of full scale. The following tables contain the values used to generate the above plots.

Table 24 T120 Horizon 2029 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	-0.01	0.30	0.00	0.31	0.00	0.31	0.01	0.31	0.00	0.31	0.01	0.31	0.01	0.31
1.26	-0.01	0.09	0.00	0.09	0.00	0.09	0.00	0.09	0.00	0.09	0.00	0.09	0.00	0.09
1.59	-0.01	-0.14	0.00	-0.13	0.00	-0.12	0.00	-0.13	0.00	-0.13	0.00	-0.12	0.00	-0.12
2.00	-0.01	-0.36	0.00	-0.35	0.00	-0.35	0.00	-0.35	0.00	-0.35	0.00	-0.35	0.00	-0.34
2.51	-0.01	-0.61	0.00	-0.60	0.00	-0.59	0.00	-0.59	0.00	-0.59	0.00	-0.59	0.00	-0.59
3.16	0.00	-0.89	0.01	-0.88	0.01	-0.88	0.01	-0.88	0.00	-0.87	0.01	-0.87	0.01	-0.87
3.98	0.00	-1.23	0.01	-1.22	0.01	-1.21	0.01	-1.21	0.01	-1.21	0.01	-1.21	0.01	-1.20
5.01	0.01	-1.64	0.02	-1.63	0.02	-1.62	0.02	-1.62	0.02	-1.62	0.02	-1.61	0.02	-1.61
6.31	0.03	-2.16	0.04	-2.15	0.04	-2.14	0.04	-2.13	0.04	-2.13	0.04	-2.13	0.04	-2.12
7.94	0.05	-2.82	0.06	-2.81	0.06	-2.80	0.06	-2.79	0.06	-2.79	0.06	-2.78	0.06	-2.78
10.00	0.08	-3.68	0.09	-3.66	0.09	-3.65	0.09	-3.64	0.09	-3.64	0.09	-3.63	0.09	-3.63
12.59	0.11	-4.78	0.12	-4.76	0.12	-4.74	0.12	-4.74	-	-	-	-	-	-
15.85	0.16	-6.18	0.17	-6.15	0.17	-6.14	0.17	-6.13	-	-	-	-	-	-
19.95	0.24	-7.96	0.25	-7.92	0.25	-7.92	0.25	-7.92	-	-	-	-	-	-

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	0.04	0.34	0.02	0.33	0.02	0.33	0.02	0.32	0.02	0.32	0.02	0.32	0.02	0.32
1.26	0.04	0.11	0.02	0.11	0.02	0.10	0.02	0.10	0.02	0.11	0.02	0.10	0.02	0.11
1.59	0.04	-0.10	0.03	-0.11	0.03	-0.11	0.02	-0.11	0.02	-0.11	0.02	-0.11	0.03	-0.11
2.00	0.05	-0.32	0.03	-0.33	0.03	-0.34	0.02	-0.34	0.03	-0.34	0.03	-0.33	0.03	-0.33
2.51	0.05	-0.56	0.03	-0.59	0.03	-0.59	0.03	-0.58	0.03	-0.58	0.03	-0.58	0.03	-0.58
3.16	0.06	-0.83	0.04	-0.87	0.04	-0.87	0.03	-0.87	0.04	-0.86	0.04	-0.86	0.04	-0.86
3.98	0.07	-1.17	0.05	-1.21	0.05	-1.20	0.04	-1.20	0.05	-1.20	0.05	-1.19	0.05	-1.19
5.01	0.08	-1.59	0.06	-1.62	0.06	-1.62	0.06	-1.62	0.06	-1.61	0.06	-1.61	0.06	-1.60
6.31	0.10	-2.09	0.08	-2.14	0.08	-2.14	0.07	-2.14	0.08	-2.12	0.08	-2.12	0.08	-2.11
7.94	0.13	-2.72	0.11	-2.80	0.10	-2.79	0.10	-2.79	0.11	-2.78	0.11	-2.77	0.11	-2.76
10.00	0.17	-3.56	0.15	-3.65	0.14	-3.65	0.14	-3.64	0.14	-3.62	0.15	-3.61	0.15	-3.61
12.59	0.22	-4.64	0.20	-4.74	0.20	-4.74	0.19	-4.73	-	-	-	-	-	-
15.85	0.30	-6.01	0.27	-6.14	0.27	-6.13	0.27	-6.11	-	-	-	-	-	-
19.95	0.42	-7.75	0.38	-7.89	0.38	-7.88	0.38	-7.86	-	-	-	-	-	-

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	0.03	0.32	0.03	0.32	0.03	0.31	0.03	0.32	0.02	0.32	0.02	0.32	0.02	0.32
1.26	0.03	0.09	0.04	0.10	0.03	0.11	0.03	0.10	0.02	0.10	0.02	0.10	0.02	0.10
1.59	0.03	-0.12	0.04	-0.12	0.03	-0.12	0.03	-0.12	0.03	-0.12	0.02	-0.12	0.02	-0.12
2.00	0.03	-0.35	0.04	-0.34	0.04	-0.35	0.03	-0.35	0.03	-0.35	0.03	-0.35	0.03	-0.35
2.51	0.04	-0.61	0.04	-0.60	0.04	-0.60	0.03	-0.60	0.03	-0.60	0.03	-0.60	0.03	-0.60
3.16	0.04	-0.89	0.05	-0.89	0.05	-0.89	0.04	-0.89	0.04	-0.89	0.04	-0.89	0.04	-0.89
3.98	0.05	-1.22	0.06	-1.23	0.06	-1.23	0.05	-1.22	0.05	-1.22	0.05	-1.23	0.05	-1.23
5.01	0.07	-1.65	0.07	-1.65	0.07	-1.65	0.06	-1.65	0.06	-1.65	0.06	-1.65	0.06	-1.65
6.31	0.08	-2.18	0.09	-2.16	0.09	-2.17	0.08	-2.17	0.08	-2.16	0.08	-2.17	0.07	-2.17
7.94	0.11	-2.82	0.12	-2.83	0.12	-2.84	0.11	-2.83	0.11	-2.83	0.10	-2.83	0.10	-2.84
10.00	0.15	-3.69	0.16	-3.69	0.15	-3.70	0.15	-3.69	0.15	-3.69	0.14	-3.70	0.14	-3.70
12.59	0.20	-4.81	0.21	-4.80	0.21	-4.81	0.20	-4.80	-	-	-	-	-	-
15.85	0.28	-6.22	0.28	-6.22	0.28	-6.22	0.27	-6.22	-	-	-	-	-	-
19.95	0.39	-8.02	0.39	-8.01	0.39	-8.01	0.38	-8.01	-	-	-	-	-	-

Table 25 T120 Horizon 2028 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	-0.01	0.31	-0.01	0.31	0.00	0.31	0.01	0.32	0.00	0.32	0.00	0.32	0.00	0.32
1.26	-0.02	0.09	-0.01	0.09	-0.01	0.09	0.00	0.11	0.00	0.10	0.00	0.10	0.00	0.10
1.59	-0.02	-0.13	-0.01	-0.12	-0.01	-0.12	0.00	-0.11	0.00	-0.11	0.00	-0.11	0.00	-0.11
2.00	-0.02	-0.34	-0.01	-0.34	-0.01	-0.34	0.00	-0.33	0.00	-0.33	0.00	-0.33	0.00	-0.33
2.51	-0.01	-0.59	-0.01	-0.59	-0.01	-0.59	0.00	-0.57	0.00	-0.58	0.00	-0.58	0.00	-0.58
3.16	-0.01	-0.87	0.00	-0.87	0.00	-0.87	0.00	-0.85	0.00	-0.85	0.00	-0.85	0.00	-0.85
3.98	0.00	-1.21	0.00	-1.20	0.01	-1.20	0.01	-1.18	0.01	-1.18	0.01	-1.18	0.01	-1.18
5.01	0.01	-1.62	0.01	-1.61	0.01	-1.61	0.02	-1.58	0.02	-1.58	0.02	-1.58	0.02	-1.58
6.31	0.02	-2.13	0.03	-2.12	0.03	-2.12	0.04	-2.08	0.03	-2.09	0.03	-2.09	0.03	-2.09
7.94	0.04	-2.79	0.05	-2.78	0.05	-2.77	0.06	-2.73	0.06	-2.73	0.05	-2.74	0.05	-2.74
10.00	0.07	-3.63	0.08	-3.62	0.08	-3.61	0.08	-3.56	0.08	-3.57	0.08	-3.57	0.08	-3.58
12.59	0.10	-4.71	0.11	-4.71	0.11	-4.69	0.12	-4.64	-	-	-	-	-	-
15.85	0.15	-6.09	0.16	-6.08	0.16	-6.07	0.17	-6.01	-	-	-	-	-	-
19.95	0.21	-7.83	0.22	-7.83	0.22	-7.82	0.24	-7.74	-	-	-	-	-	-

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	0.02	0.34	0.03	0.34	0.03	0.34	0.03	0.33	0.02	0.34	0.03	0.34	0.03	0.34
1.26	0.03	0.12	0.03	0.12	0.03	0.12	0.03	0.12	0.03	0.12	0.03	0.12	0.03	0.12
1.59	0.03	-0.09	0.03	-0.09	0.03	-0.09	0.03	-0.09	0.03	-0.09	0.03	-0.08	0.03	-0.08
2.00	0.03	-0.32	0.04	-0.31	0.04	-0.31	0.03	-0.31	0.03	-0.31	0.04	-0.30	0.04	-0.30
2.51	0.03	-0.56	0.04	-0.55	0.04	-0.55	0.04	-0.55	0.04	-0.55	0.04	-0.54	0.04	-0.54
3.16	0.04	-0.83	0.05	-0.83	0.05	-0.83	0.04	-0.82	0.04	-0.82	0.05	-0.81	0.05	-0.81
3.98	0.05	-1.15	0.06	-1.15	0.06	-1.15	0.05	-1.14	0.05	-1.14	0.06	-1.13	0.06	-1.12
5.01	0.06	-1.55	0.07	-1.55	0.07	-1.55	0.07	-1.55	0.06	-1.54	0.07	-1.52	0.07	-1.52
6.31	0.08	-2.06	0.09	-2.06	0.08	-2.05	0.08	-2.04	0.08	-2.04	0.09	-2.02	0.09	-2.01
7.94	0.11	-2.69	0.12	-2.68	0.12	-2.68	0.11	-2.67	0.11	-2.67	0.12	-2.64	0.12	-2.63
10.00	0.15	-3.51	0.16	-3.51	0.16	-3.51	0.16	-3.50	0.16	-3.49	0.16	-3.46	0.17	-3.44
12.59	0.21	-4.58	0.21	-4.57	0.21	-4.57	0.21	-4.55	-	-	-	-	-	-
15.85	0.29	-5.93	0.29	-5.93	0.29	-5.92	0.29	-5.90	-	-	-	-	-	-
19.95	0.41	-7.65	0.41	-7.64	0.41	-7.64	1261.10	-7.62	-	-	-	-	-	-

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	0.02	-89.69	0.03	0.31	0.03	0.31	0.02	0.32	0.01	0.31	0.02	0.31	0.02	0.31
1.26	0.02	-89.92	0.03	0.08	0.03	0.09	0.02	0.09	0.02	0.09	0.02	0.08	0.02	0.08
1.59	0.02	-90.15	0.03	-0.14	0.03	-0.13	0.02	-0.14	0.02	-0.14	0.02	-0.14	0.02	-0.14
2.00	0.03	-90.37	0.04	-0.37	0.03	-0.37	0.02	-0.37	0.02	-0.37	0.02	-0.37	0.03	-0.37
2.51	0.03	-90.62	0.04	-0.63	0.04	-0.62	0.02	-0.62	0.02	-0.62	0.03	-0.62	0.03	-0.62
3.16	0.04	-90.90	0.05	-0.91	0.04	-0.91	0.03	-0.92	0.03	-0.92	0.03	-0.91	0.03	-0.91
3.98	0.04	-91.26	0.05	-1.26	0.05	-1.26	0.04	-1.27	0.04	-1.27	0.04	-1.26	0.04	-1.26
5.01	0.06	-91.71	0.06	-1.69	0.06	-1.69	0.05	-1.70	0.05	-1.69	0.05	-1.69	0.05	-1.69
6.31	0.07	-92.22	0.08	-2.22	0.08	-2.22	0.06	-2.24	0.06	-2.23	0.07	-2.23	0.07	-2.22
7.94	0.10	-92.90	0.10	-2.89	0.10	-2.88	0.09	-2.91	0.09	-2.91	0.09	-2.90	0.09	-2.89
10.00	0.13	-93.77	0.14	-3.77	0.14	-3.76	0.12	-3.79	0.12	-3.79	0.12	-3.78	0.13	-3.77
12.59	0.18	-94.90	0.18	-4.88	0.18	-4.87	0.16	-4.91	-	-	-	-	-	-
15.85	0.24	-96.31	0.25	-6.29	0.24	-6.28	0.23	-6.33	-	-	-	-	-	-
19.95	0.33	-98.07	0.34	-8.04	0.33	-8.03	0.32	-8.08	-	-	-	-	-	-

Table 26 T120 Horizon 0769 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	0.41	0.04	0.42	0.04	0.42	0.05	0.42	0.05	0.42	0.05	0.42	0.05	0.42
1.26	0.03	0.21	0.04	0.22	0.04	0.22	0.04	0.22	0.05	0.22	0.05	0.22	0.05	0.23
1.59	0.04	0.02	0.05	0.02	0.05	0.02	0.05	0.03	0.05	0.03	0.05	0.03	0.05	0.03
2.00	0.05	-0.19	0.06	-0.19	0.06	-0.19	0.06	-0.18	0.06	-0.18	0.06	-0.18	0.06	-0.18
2.51	0.06	-0.45	0.07	-0.44	0.07	-0.44	0.07	-0.43	0.07	-0.43	0.08	-0.43	0.08	-0.42
3.16	0.08	-0.77	0.09	-0.76	0.09	-0.75	0.09	-0.75	0.09	-0.74	0.09	-0.74	0.10	-0.73
3.98	0.10	-1.19	0.11	-1.18	0.11	-1.17	0.11	-1.16	0.12	-1.16	0.12	-1.15	0.12	-1.15
5.01	0.13	-1.74	0.14	-1.74	0.13	-1.72	0.14	-1.71	0.14	-1.70	0.14	-1.70	0.14	-1.69
6.31	0.15	-2.46	0.16	-2.45	0.16	-2.44	0.16	-2.42	0.16	-2.41	0.17	-2.40	0.17	-2.40
7.94	0.17	-3.36	0.18	-3.34	0.18	-3.33	0.18	-3.31	0.18	-3.30	0.19	-3.29	0.19	-3.28
10.00	0.19	-4.44	0.19	-4.43	0.19	-4.41	0.20	-4.39	0.20	-4.37	0.20	-4.36	0.21	-4.35
12.59	0.20	-5.72	0.21	-5.70	0.21	-5.68	0.21	-5.66	-	-	-	-	-	-
15.85	0.23	-7.24	0.24	-7.21	0.24	-7.19	0.25	-7.16	-	-	-	-	-	-
19.95	0.30	-9.08	0.31	-9.06	0.31	-9.04	0.32	-9.00	-	-	-	-	-	-

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	0.00	0.48	0.01	0.48	0.01	0.48	0.02	0.49	0.00	0.49	0.00	0.49	0.01	0.49
1.26	0.01	0.30	0.02	0.30	0.02	0.31	0.02	0.31	0.00	0.31	0.01	0.31	0.01	0.31
1.59	0.02	0.12	0.03	0.14	0.03	0.13	0.03	0.14	0.01	0.12	0.01	0.13	0.02	0.13
2.00	0.04	-0.06	0.04	-0.06	0.04	-0.05	0.04	-0.05	0.03	-0.07	0.03	-0.07	0.03	-0.06
2.51	0.05	-0.28	0.06	-0.27	0.06	-0.27	0.06	-0.27	0.04	-0.29	0.04	-0.29	0.05	-0.28
3.16	0.07	-0.55	0.08	-0.55	0.08	-0.54	0.08	-0.54	0.07	-0.57	0.07	-0.57	0.07	-0.56
3.98	0.10	-0.94	0.11	-0.92	0.11	-0.91	0.11	-0.91	0.09	-0.95	0.09	-0.95	0.10	-0.93
5.01	0.13	-1.44	0.14	-1.43	0.14	-1.41	0.15	-1.41	0.13	-1.46	0.13	-1.45	0.13	-1.43
6.31	0.17	-2.11	0.17	-2.07	0.18	-2.06	0.18	-2.06	0.16	-2.12	0.16	-2.11	0.17	-2.09
7.94	0.21	-2.91	0.21	-2.89	0.21	-2.87	0.22	-2.86	0.19	-2.94	0.20	-2.93	0.21	-2.94
10.00	0.25	-3.92	0.25	-3.90	0.26	-3.88	0.26	-3.87	0.23	-3.96	0.24	-4.02	0.28	-4.30
12.59	0.30	-5.15	0.31	-5.13	0.31	-5.09	0.31	-5.08	-	-	-	-	-	-
15.85	0.39	-6.62	0.39	-6.58	0.40	-6.56	0.40	-6.54	-	-	-	-	-	-
19.95	0.53	-8.46	0.54	-8.43	0.55	-8.40	0.59	-8.54	-	-	-	-	-	-

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	0.00	0.47	0.01	0.47	0.01	0.48	0.01	0.48	0.01	0.48	0.00	0.48	0.00	0.48
1.26	0.01	0.29	0.01	0.28	0.01	0.29	0.01	0.29	0.01	0.29	0.01	0.29	0.01	0.29
1.59	0.02	0.09	0.02	0.11	0.02	0.11	0.02	0.11	0.02	0.11	0.02	0.11	0.02	0.11
2.00	0.03	-0.08	0.03	-0.08	0.03	-0.08	0.03	-0.08	0.03	-0.08	0.03	-0.08	0.03	-0.08
2.51	0.05	-0.32	0.05	-0.33	0.05	-0.30	0.05	-0.30	0.05	-0.30	0.05	-0.31	0.05	-0.31
3.16	0.07	-0.59	0.07	-0.59	0.07	-0.59	0.07	-0.59	0.07	-0.59	0.07	-0.59	0.07	-0.59
3.98	0.10	-0.98	0.10	-0.97	0.10	-0.97	0.10	-0.97	0.10	-0.97	0.10	-0.97	0.09	-0.97
5.01	0.13	-1.49	0.13	-1.48	0.13	-1.48	0.13	-1.48	0.13	-1.47	0.13	-1.47	0.12	-1.48
6.31	0.16	-2.14	0.16	-2.15	0.16	-2.14	0.16	-2.14	0.16	-2.13	0.16	-2.14	0.16	-2.18
7.94	0.19	-2.98	0.19	-2.97	0.19	-2.96	0.19	-2.96	0.19	-2.96	0.20	-3.03	0.22	-3.26
10.00	0.23	-3.99	0.23	-3.98	0.23	-3.97	0.23	-3.97	0.23	-3.98	0.27	-4.44	0.31	-5.45
12.59	0.28	-5.21	0.28	-5.20	0.28	-5.19	0.28	-5.19	-	-	-	-	-	-
15.85	0.35	-6.67	0.36	-6.66	0.36	-6.65	0.36	-6.65	-	-	-	-	-	-
19.95	0.49	-8.49	0.49	-8.48	0.50	-8.46	0.60	-9.50	-	-	-	-	-	-

Table 27 T120 Slim PH 2024 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	0.01	0.27	0.02	0.30	0.02	0.28	0.02	0.28	0.01	0.28	0.01	0.28	0.01	0.28
1.26	0.01	0.05	0.02	0.05	0.01	0.05	0.02	0.05	0.01	0.05	0.01	0.05	0.01	0.05
1.59	0.01	-0.19	0.02	-0.18	0.02	-0.18	0.01	-0.18	0.01	-0.18	0.01	-0.18	0.01	-0.18
2.00	0.01	-0.43	0.02	-0.42	0.02	-0.42	0.02	-0.42	0.02	-0.42	0.02	-0.42	0.01	-0.42
2.51	0.02	-0.70	0.02	-0.69	0.02	-0.69	0.02	-0.69	0.02	-0.69	0.02	-0.69	0.02	-0.69
3.16	0.02	-1.01	0.03	-1.00	0.03	-1.00	0.03	-1.00	0.03	-1.00	0.02	-1.00	0.02	-1.00
3.98	0.03	-1.37	0.04	-1.37	0.03	-1.37	0.03	-1.37	0.03	-1.37	0.03	-1.38	0.03	-1.38
5.01	0.05	-1.83	0.05	-1.83	0.05	-1.83	0.05	-1.84	0.05	-1.85	0.05	-1.85	0.04	-1.85
6.31	0.06	-2.43	0.07	-2.41	0.06	-2.41	0.06	-2.41	0.06	-2.42	0.06	-2.42	0.06	-2.42
7.94	0.09	-3.16	0.09	-3.15	0.09	-3.15	0.09	-3.16	0.09	-3.17	0.09	-3.17	0.09	-3.17
10.00	0.12	-4.14	0.13	-4.12	0.12	-4.12	0.12	-4.11	0.12	-4.14	0.12	-4.14	0.12	-4.14
12.59	0.12	-5.05	0.16	-4.84	0.17	-4.84	0.20	-4.96	-	-	-	-	-	-
15.85	-0.04	-7.42	-0.16	-7.97	-0.22	-8.45	-0.19	-8.26	-	-	-	-	-	-
19.95	0.23	-9.08	0.23	-9.06	0.23	-9.05	0.23	-9.08	-	-	-	-	-	-

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	0.00	0.28	0.02	0.30	0.02	0.29	0.01	0.29	0.01	0.29	0.01	0.29	0.01	0.29
1.26	0.01	0.07	0.02	0.06	0.02	0.07	0.02	0.06	0.01	0.06	0.02	0.06	0.02	0.06
1.59	0.01	-0.18	0.03	-0.17	0.02	-0.17	0.02	-0.17	0.02	-0.17	0.02	-0.17	0.02	-0.17
2.00	0.02	-0.42	0.03	-0.41	0.03	-0.41	0.03	-0.41	0.03	-0.41	0.02	-0.41	0.03	-0.41
2.51	0.03	-0.69	0.04	-0.68	0.04	-0.67	0.03	-0.67	0.03	-0.67	0.03	-0.67	0.03	-0.67
3.16	0.04	-1.01	0.06	-0.98	0.05	-0.99	0.05	-0.98	0.05	-0.98	0.05	-0.98	0.05	-0.98
3.98	0.06	-1.37	0.08	-1.35	0.07	-1.35	0.07	-1.35	0.07	-1.35	0.07	-1.35	0.07	-1.34
5.01	0.10	-1.84	0.11	-1.83	0.11	-1.82	0.10	-1.82	0.10	-1.81	0.10	-1.82	0.10	-1.81
6.31	0.14	-2.44	0.16	-2.40	0.15	-2.40	0.15	-2.39	0.15	-2.39	0.15	-2.39	0.15	-2.38

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	0.03	0.25	0.03	0.26	0.02	0.26	0.02	0.26	0.01	0.26	0.01	0.26	0.02	0.26
1.26	0.03	0.03	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
1.59	0.04	-0.21	0.04	-0.22	0.03	-0.22	0.02	-0.22	0.02	-0.22	0.02	-0.22	0.02	-0.22
2.00	0.04	-0.45	0.04	-0.48	0.04	-0.47	0.03	-0.47	0.03	-0.47	0.03	-0.48	0.03	-0.48
2.51	0.06	-0.74	0.06	-0.75	0.05	-0.76	0.04	-0.76	0.04	-0.76	0.04	-0.76	0.04	-0.76
3.16	0.08	-1.07	0.08	-1.08	0.07	-1.09	0.06	-1.10	0.06	-1.09	0.06	-1.09	0.06	-1.09
3.98	0.10	-1.47	0.10	-1.48	0.10	-1.49	0.09	-1.49	0.09	-1.49	0.09	-1.48	0.09	-1.48
5.01	0.15	-1.96	0.15	-1.98	0.14	-1.99	0.14	-1.99	0.14	-1.99	0.14	-1.99	0.14	-1.98
6.31	0.22	-2.58	0.22	-2.59	0.21	-2.60	0.20	-2.60	0.21	-2.60	0.20	-2.60	0.20	-2.60

3.9 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.

3.9.1 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.

3.9.2 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 56 shows a block diagram of a sensor installed on the shake tables system.

The maximum input velocity signal rating of the T120s is specified as 16.6 mm/s up to 10Hz and then 0.12g above 10Hz.

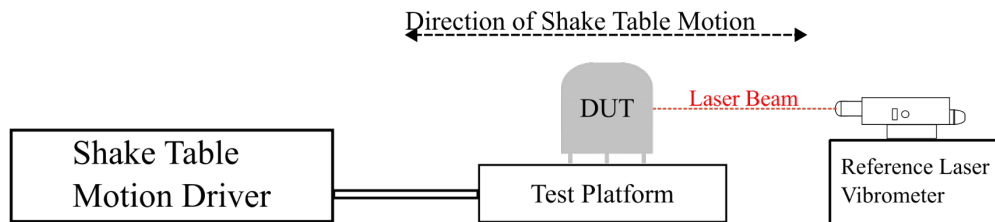


Figure 56 Full Scale Test Configuration

Table 28 Full Scale Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	Amplitude = 1.64 to 16.3 mm/s Input Voltage = 12V Frequency = 1Hz to 10Hz Pressure = 820.9 ± 9.5hPa Temperature = 22.7 ± 1.1C Humidity = 20.4 ± 9.8%

3.9.3 *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.

3.9.4 *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.

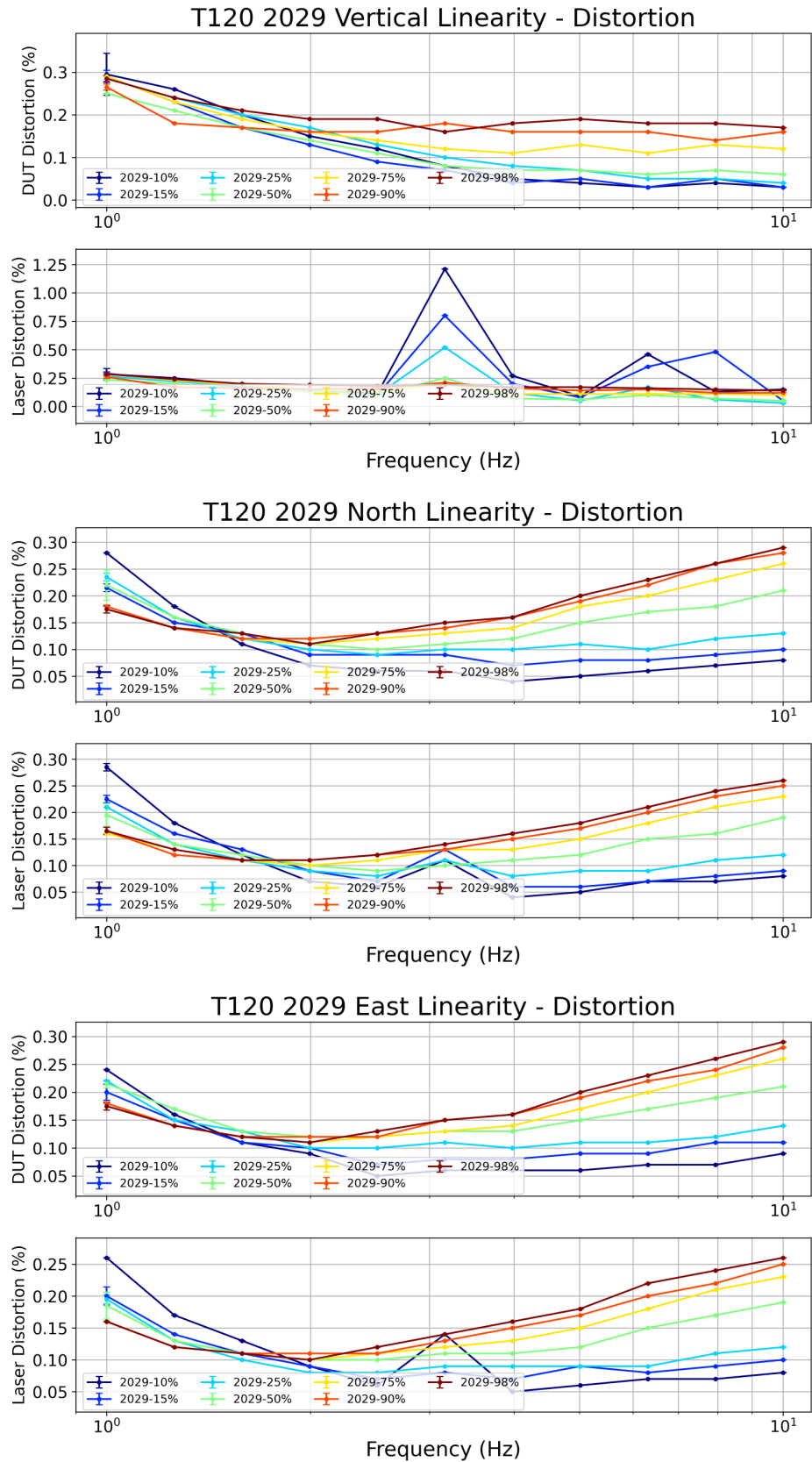


Figure 57 DUT and Laser Distortion Levels for T120 Horizon V2 2029

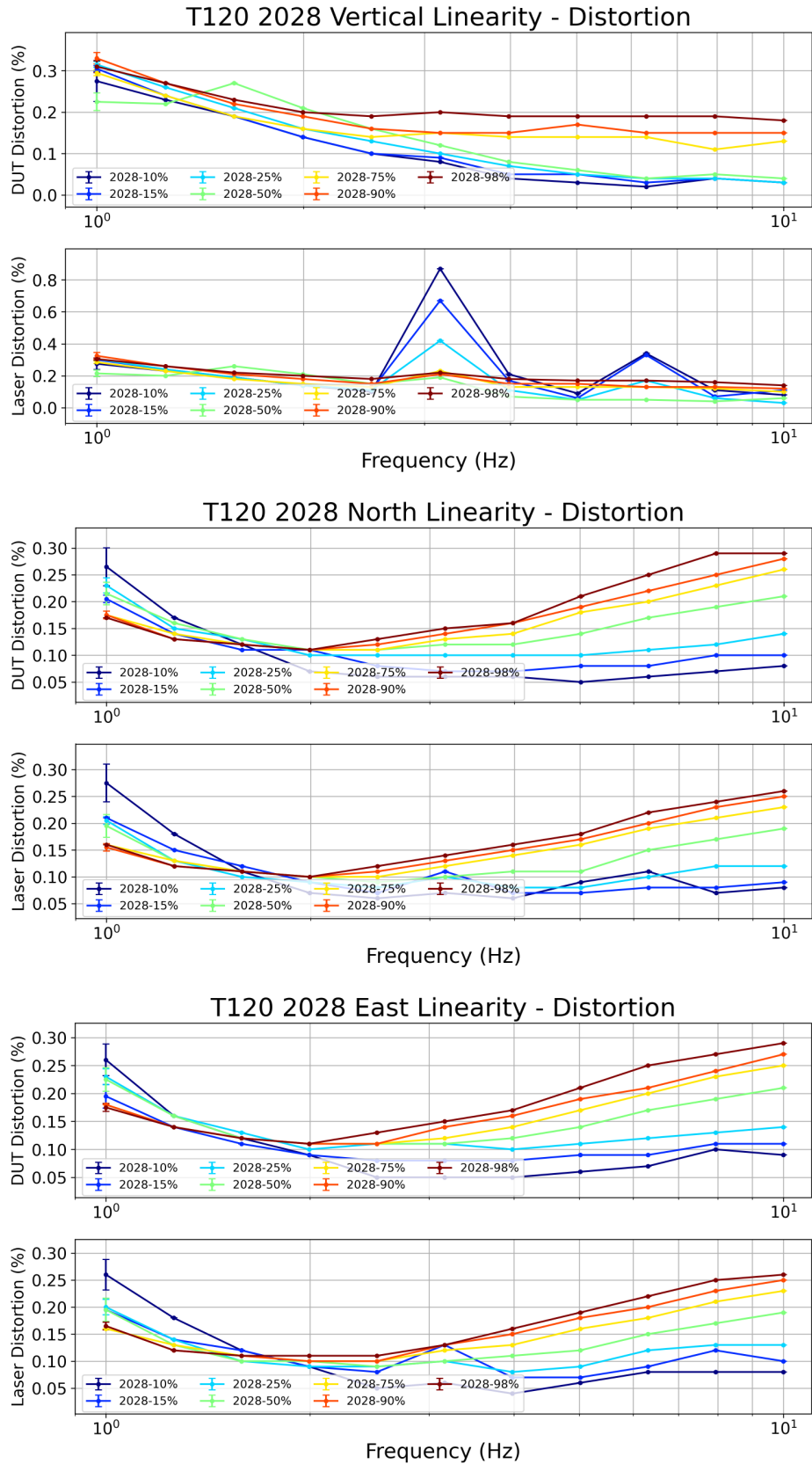


Figure 58 DUT and Laser Distortion Levels for T120 Horizon V2 2028

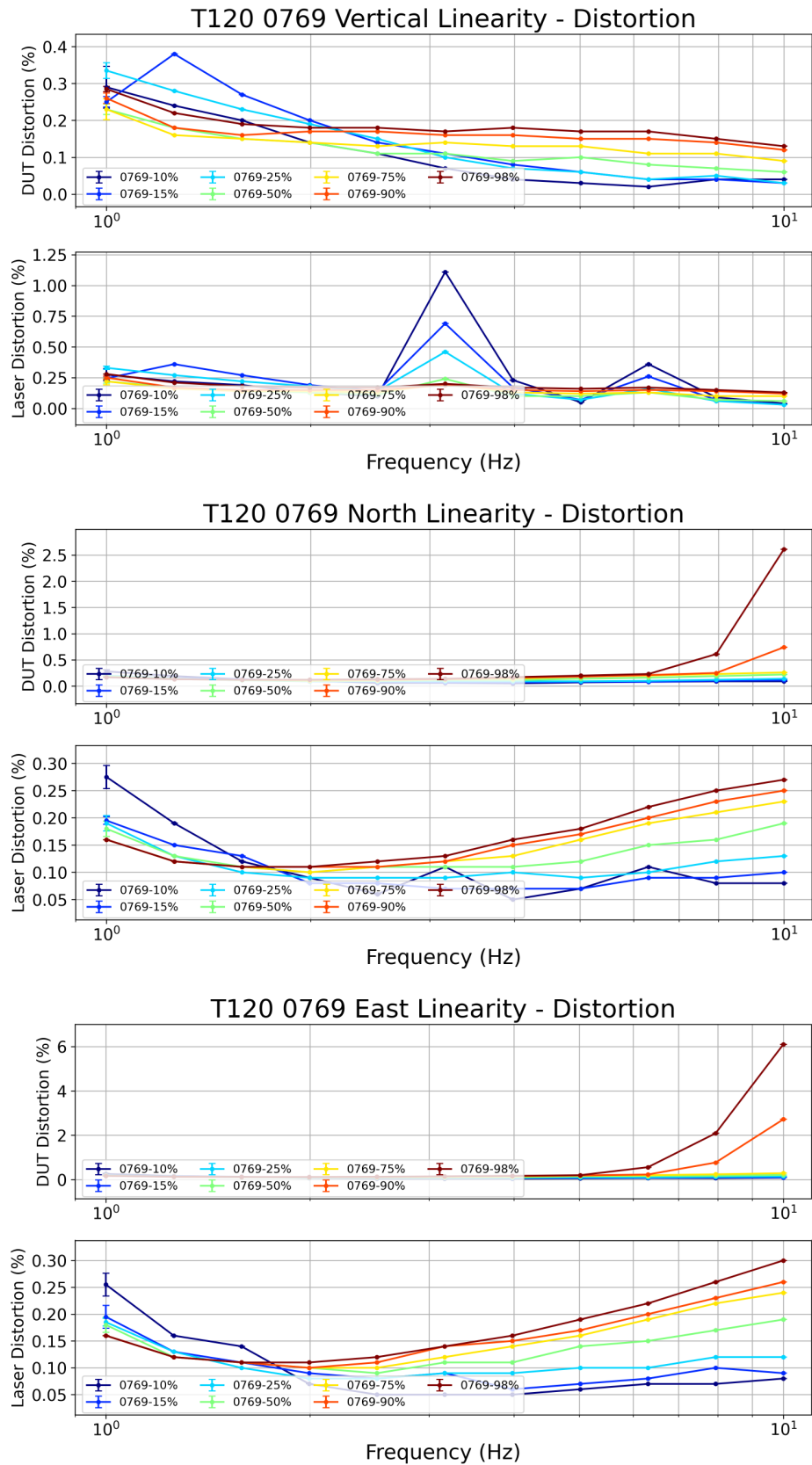


Figure 59 DUT and Laser Distortion Levels for T120 Horizon V2 0769

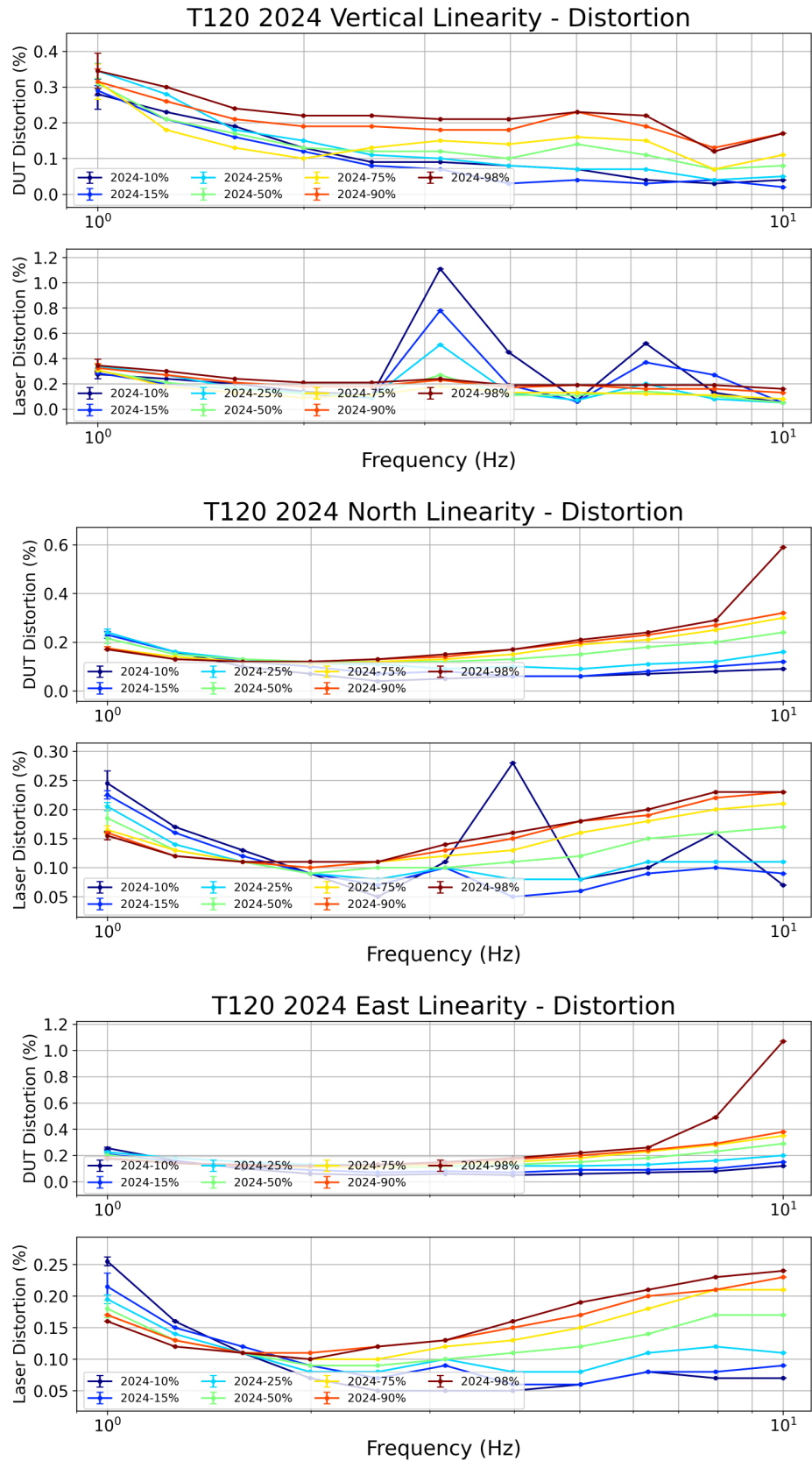


Figure 60 DUT and Laser Distortion Levels for T120 Slim BH 2024

The above figures show that the Laser Distortion levels were well below 1% at all frequencies 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 about 1.25%. 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 0.3%, meaning that all four T120 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.

In some cases, the distortion levels of both the DUT and laser are slightly elevated at 1Hz and then steadily drop to 2Hz before again increasing with frequency. An example of this relationship can be clearly seen in the East component distortion levels of T120 2028 (bottom plot in Figure 58). Because both the laser and the DUT distortion levels are very similar and follow the same pattern, this indicates that the source of distortion is most likely from the operation of the shake table and/or the operating environment. If the distortion of the DUT was elevated at 1Hz only, it could indicate that the source of distortion is internal to the seismometer. That is not the case here and the slightly higher levels of distortion at 1Hz compared to 2Hz can likely be attributed to non-perfect motion of the shake table and/or environmental sources.

Figure 59 and Figure 60 indicate that, for their horizontal axes, T120 Horizon V1 0769 and T120 Slim BH 2024 had higher amounts of distortion at frequencies above about 7Hz when the input amplitude was 90% and 98% of full-scale. This may indicate that the sensors are beginning to operate close to the edge of their linear range. Since the amount of distortion is frequency dependent it indicates that the sensors are likely reaching their acceleration limit. Since this same increase is not as pronounced for T120 Horizon V2 2029 and 2028, this maybe evidence that T120 Horizon V1 0769 and T120 Slim BH 2024 have a slightly lower peak acceleration limit.

Overall, all sensors operated correctly at 98% of their full-scale input when tested from 1Hz to 10Hz.

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

Table 29 Waveform Distortion vs Input Amplitude for T120 Horizon V2 2029

Vertical Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.29	0.27	0.29	0.24	0.25	0.29	0.29	0.26	0.27	0.29	0.29
1.26	0.25	0.26	0.23	0.23	0.22	0.24	0.20	0.21	0.23	0.23	0.17	0.18	0.24	0.24
1.59	0.19	0.20	0.17	0.17	0.18	0.20	0.16	0.17	0.19	0.19	0.16	0.17	0.20	0.21
2.00	0.14	0.15	0.13	0.13	0.14	0.17	0.13	0.14	0.15	0.16	0.15	0.16	0.19	0.19
2.51	0.11	0.12	0.10	0.09	0.10	0.13	0.10	0.11	0.13	0.14	0.16	0.16	0.18	0.19
3.16	1.21	0.08	0.80	0.07	0.52	0.10	0.25	0.08	0.20	0.12	0.21	0.18	0.19	0.16
3.98	0.27	0.05	0.20	0.04	0.12	0.08	0.07	0.07	0.11	0.11	0.16	0.16	0.17	0.18
5.01	0.09	0.04	0.08	0.05	0.05	0.07	0.06	0.07	0.11	0.13	0.14	0.16	0.17	0.19
6.31	0.46	0.03	0.35	0.03	0.17	0.05	0.10	0.06	0.11	0.11	0.15	0.16	0.16	0.18
7.94	0.13	0.04	0.48	0.05	0.06	0.05	0.07	0.07	0.11	0.13	0.12	0.14	0.15	0.18
10.00	0.15	0.03	0.05	0.03	0.03	0.04	0.05	0.06	0.10	0.12	0.12	0.16	0.14	0.17
12.59	0.16	0.04	0.07	0.02	0.05	0.05	0.06	0.06	-	-	-	-	-	-
15.85	0.75	0.02	0.05	0.03	0.04	0.04	0.06	0.08	-	-	-	-	-	-
19.95	0.07	0.04	0.05	0.04	0.05	0.05	0.07	0.09	-	-	-	-	-	-

North-South Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.28	0.23	0.22	0.21	0.24	0.20	0.22	0.16	0.18	0.17	0.18	0.17	0.18
1.26	0.18	0.18	0.16	0.15	0.14	0.16	0.14	0.16	0.13	0.14	0.12	0.14	0.13	0.14
1.59	0.12	0.11	0.13	0.13	0.11	0.12	0.12	0.13	0.11	0.12	0.11	0.12	0.11	0.13
2.00	0.07	0.07	0.09	0.09	0.09	0.10	0.10	0.11	0.10	0.11	0.11	0.12	0.11	0.11
2.51	0.06	0.06	0.07	0.09	0.08	0.09	0.09	0.10	0.11	0.12	0.12	0.13	0.12	0.13
3.16	0.11	0.06	0.13	0.09	0.11	0.10	0.10	0.11	0.13	0.13	0.13	0.14	0.14	0.15
3.98	0.04	0.04	0.06	0.07	0.08	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.16	0.16
5.01	0.05	0.05	0.06	0.08	0.09	0.11	0.12	0.15	0.15	0.18	0.17	0.19	0.18	0.20
6.31	0.07	0.06	0.07	0.08	0.09	0.10	0.15	0.17	0.18	0.20	0.20	0.22	0.21	0.23
7.94	0.07	0.07	0.08	0.09	0.11	0.12	0.16	0.18	0.21	0.23	0.23	0.26	0.24	0.26
10.00	0.08	0.08	0.09	0.10	0.12	0.13	0.19	0.21	0.23	0.26	0.25	0.28	0.26	0.29
12.59	0.09	0.10	0.10	0.12	0.14	0.16	0.20	0.24	-	-	-	-	-	-
15.85	0.09	0.11	0.11	0.14	0.16	0.18	0.23	0.28	-	-	-	-	-	-
19.95	0.11	0.13	0.12	0.16	0.19	0.23	0.25	0.33	-	-	-	-	-	-

East-West Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.26	0.24	0.20	0.20	0.20	0.22	0.19	0.22	0.16	0.18	0.16	0.18	0.16	0.18
1.26	0.17	0.16	0.14	0.15	0.13	0.15	0.13	0.17	0.12	0.14	0.12	0.14	0.12	0.14
1.59	0.13	0.11	0.11	0.11	0.10	0.13	0.11	0.13	0.11	0.12	0.11	0.12	0.11	0.12
2.00	0.09	0.09	0.09	0.10	0.08	0.10	0.10	0.12	0.10	0.11	0.11	0.12	0.10	0.11
2.51	0.06	0.05	0.07	0.07	0.08	0.10	0.10	0.12	0.11	0.12	0.11	0.12	0.12	0.13
3.16	0.14	0.06	0.08	0.08	0.09	0.11	0.11	0.13	0.12	0.13	0.13	0.15	0.14	0.15
3.98	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.13	0.13	0.14	0.15	0.16	0.16	0.16
5.01	0.06	0.06	0.09	0.09	0.09	0.11	0.12	0.15	0.15	0.17	0.17	0.19	0.18	0.20
6.31	0.07	0.07	0.08	0.09	0.09	0.11	0.15	0.17	0.18	0.20	0.20	0.22	0.22	0.23
7.94	0.07	0.07	0.09	0.11	0.11	0.12	0.17	0.19	0.21	0.23	0.22	0.24	0.24	0.26
10.00	0.08	0.09	0.10	0.11	0.12	0.14	0.19	0.21	0.23	0.26	0.25	0.28	0.26	0.29
12.59	0.11	0.10	0.10	0.13	0.14	0.15	0.21	0.25	-	-	-	-	-	-
15.85	0.10	0.12	0.12	0.14	0.16	0.19	0.23	0.28	-	-	-	-	-	-
19.95	0.11	0.14	0.14	0.18	0.18	0.22	0.25	0.32	-	-	-	-	-	-

Table 30 Waveform Distortion vs Input Amplitude for T120 Horizon V2 2028

Vertical Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.30	0.31	0.31	0.32	0.22	0.23	0.29	0.30	0.33	0.33	0.31	0.31
1.26	0.23	0.23	0.24	0.24	0.24	0.26	0.20	0.22	0.23	0.24	0.26	0.27	0.26	0.27
1.59	0.19	0.19	0.19	0.19	0.19	0.21	0.26	0.27	0.18	0.19	0.21	0.22	0.22	0.23
2.00	0.14	0.14	0.14	0.14	0.14	0.16	0.21	0.21	0.15	0.16	0.18	0.19	0.20	0.20
2.51	0.10	0.10	0.11	0.10	0.11	0.13	0.15	0.16	0.13	0.14	0.15	0.16	0.18	0.19
3.16	0.87	0.08	0.67	0.09	0.42	0.10	0.19	0.12	0.23	0.15	0.21	0.15	0.22	0.20
3.98	0.21	0.04	0.17	0.05	0.11	0.07	0.07	0.08	0.13	0.14	0.15	0.15	0.18	0.19
5.01	0.09	0.03	0.06	0.05	0.05	0.05	0.05	0.06	0.13	0.14	0.15	0.17	0.17	0.19
6.31	0.34	0.02	0.33	0.03	0.17	0.04	0.05	0.04	0.13	0.14	0.13	0.15	0.17	0.19
7.94	0.11	0.04	0.07	0.04	0.06	0.04	0.04	0.05	0.12	0.11	0.13	0.15	0.16	0.19
10.00	0.08	0.03	0.11	0.03	0.03	0.03	0.06	0.04	0.10	0.13	0.12	0.15	0.14	0.18
12.59	0.07	0.04	0.05	0.03	0.05	0.04	0.06	0.05	-	-	-	-	-	-
15.85	0.06	0.02	0.03	0.02	0.03	0.03	0.13	0.06	-	-	-	-	-	-
19.95	0.06	0.04	0.05	0.04	0.04	0.05	0.06	0.09	-	-	-	-	-	-

North-South Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.21	0.21	0.21	0.23	0.20	0.22	0.16	0.18	0.16	0.18	0.16	0.17
1.26	0.18	0.17	0.15	0.14	0.13	0.15	0.13	0.16	0.13	0.14	0.12	0.13	0.12	0.13
1.59	0.11	0.12	0.12	0.11	0.10	0.13	0.11	0.13	0.11	0.12	0.11	0.12	0.11	0.12
2.00	0.07	0.07	0.09	0.11	0.09	0.10	0.10	0.11	0.10	0.11	0.10	0.11	0.10	0.11
2.51	0.06	0.06	0.07	0.08	0.08	0.10	0.09	0.11	0.10	0.11	0.11	0.12	0.12	0.13
3.16	0.07	0.06	0.11	0.07	0.10	0.10	0.10	0.12	0.12	0.13	0.13	0.14	0.14	0.15
3.98	0.06	0.06	0.07	0.07	0.08	0.10	0.11	0.12	0.14	0.14	0.15	0.16	0.16	0.16
5.01	0.09	0.05	0.07	0.08	0.08	0.10	0.11	0.14	0.16	0.18	0.17	0.19	0.18	0.21
6.31	0.11	0.06	0.08	0.08	0.10	0.11	0.15	0.17	0.19	0.20	0.20	0.22	0.22	0.25
7.94	0.07	0.07	0.08	0.10	0.12	0.12	0.17	0.19	0.21	0.23	0.23	0.25	0.24	0.29
10.00	0.08	0.08	0.09	0.10	0.12	0.14	0.19	0.21	0.23	0.26	0.25	0.28	0.26	0.29
12.59	0.09	0.11	0.11	0.12	0.14	0.16	0.22	0.26	-	-	-	-	-	-
15.85	0.09	0.11	0.11	0.14	0.15	0.19	0.22	0.28	-	-	-	-	-	-
19.95	0.11	0.14	0.13	0.18	0.18	0.23	0.25	0.33	-	-	-	-	-	-

East-West Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.26	0.26	0.20	0.20	0.20	0.23	0.20	0.23	0.16	0.18	0.17	0.18	0.17	0.18
1.26	0.18	0.16	0.14	0.14	0.14	0.16	0.13	0.16	0.13	0.14	0.12	0.14	0.12	0.14
1.59	0.12	0.12	0.12	0.11	0.10	0.13	0.10	0.12	0.11	0.12	0.11	0.12	0.11	0.12
2.00	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.10	0.11	0.10	0.11	0.11	0.11
2.51	0.05	0.05	0.08	0.08	0.09	0.11	0.09	0.11	0.10	0.11	0.10	0.11	0.11	0.13
3.16	0.06	0.05	0.13	0.08	0.10	0.11	0.10	0.11	0.12	0.12	0.13	0.14	0.13	0.15
3.98	0.04	0.05	0.07	0.08	0.08	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.16	0.17
5.01	0.06	0.06	0.07	0.09	0.09	0.11	0.12	0.14	0.16	0.17	0.18	0.19	0.19	0.21
6.31	0.08	0.07	0.09	0.09	0.12	0.12	0.15	0.17	0.18	0.20	0.20	0.21	0.22	0.25
7.94	0.08	0.10	0.12	0.11	0.13	0.13	0.17	0.19	0.21	0.23	0.23	0.24	0.25	0.27
10.00	0.08	0.09	0.10	0.11	0.13	0.14	0.19	0.21	0.23	0.25	0.25	0.27	0.26	0.29
12.59	0.10	0.11	0.13	0.12	0.15	0.16	0.21	0.24	-	-	-	-	-	-
15.85	0.10	0.12	0.12	0.15	0.16	0.19	0.23	0.27	-	-	-	-	-	-
19.95	0.10	0.15	0.15	0.18	0.19	0.23	0.26	0.32	-	-	-	-	-	-

Table 31 Waveform Distortion vs Input Amplitude for T120 Horizon V1 0769

Vertical Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.29	0.25	0.25	0.33	0.34	0.22	0.23	0.22	0.23	0.25	0.26	0.28	0.29
1.26	0.22	0.24	0.36	0.38	0.27	0.28	0.17	0.18	0.16	0.16	0.17	0.18	0.21	0.22
1.59	0.19	0.20	0.27	0.27	0.22	0.23	0.14	0.15	0.14	0.15	0.15	0.16	0.18	0.19
2.00	0.13	0.14	0.19	0.20	0.18	0.19	0.13	0.14	0.14	0.14	0.15	0.17	0.17	0.18
2.51	0.10	0.11	0.14	0.14	0.14	0.15	0.11	0.11	0.13	0.13	0.15	0.17	0.17	0.18
3.16	1.11	0.07	0.69	0.11	0.46	0.10	0.24	0.11	0.20	0.14	0.19	0.16	0.20	0.17
3.98	0.23	0.04	0.17	0.08	0.12	0.07	0.10	0.09	0.13	0.13	0.15	0.16	0.17	0.18
5.01	0.05	0.03	0.07	0.06	0.07	0.06	0.10	0.10	0.12	0.13	0.14	0.15	0.16	0.17
6.31	0.36	0.02	0.26	0.04	0.16	0.04	0.13	0.08	0.13	0.11	0.15	0.15	0.17	0.17
7.94	0.09	0.04	0.07	0.04	0.06	0.05	0.07	0.07	0.10	0.11	0.14	0.14	0.15	0.15
10.00	0.04	0.04	0.03	0.03	0.03	0.03	0.06	0.06	0.10	0.09	0.12	0.12	0.13	0.13
12.59	0.09	0.03	0.06	0.03	0.05	0.03	0.06	0.05	-	-	-	-	-	-
15.85	0.02	0.01	0.03	0.02	0.03	0.02	0.07	0.06	-	-	-	-	-	-
19.95	0.06	0.04	0.06	0.04	0.04	0.04	0.08	0.07	-	-	-	-	-	-

North-South Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.20	0.20	0.19	0.20	0.18	0.19	0.16	0.17	0.16	0.17	0.16	0.17
1.26	0.19	0.19	0.15	0.15	0.13	0.14	0.13	0.14	0.12	0.13	0.12	0.13	0.12	0.13
1.59	0.12	0.13	0.13	0.13	0.10	0.11	0.11	0.11	0.11	0.12	0.11	0.12	0.11	0.12
2.00	0.09	0.10	0.08	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.11	0.12	0.11	0.12
2.51	0.06	0.06	0.08	0.08	0.09	0.09	0.11	0.10	0.11	0.11	0.11	0.12	0.12	0.13
3.16	0.11	0.06	0.07	0.07	0.09	0.09	0.11	0.11	0.12	0.13	0.12	0.13	0.13	0.14
3.98	0.05	0.05	0.07	0.07	0.10	0.09	0.11	0.11	0.13	0.14	0.15	0.16	0.16	0.17
5.01	0.07	0.07	0.07	0.08	0.09	0.09	0.12	0.14	0.16	0.18	0.17	0.18	0.18	0.20
6.31	0.11	0.08	0.09	0.08	0.10	0.10	0.15	0.16	0.19	0.20	0.20	0.21	0.22	0.23
7.94	0.08	0.09	0.09	0.10	0.12	0.12	0.16	0.19	0.21	0.23	0.23	0.25	0.25	0.61
10.00	0.08	0.09	0.10	0.11	0.13	0.14	0.19	0.22	0.23	0.26	0.25	0.74	0.27	2.61
12.59	0.10	0.11	0.11	0.13	0.14	0.17	0.22	0.26	-	-	-	-	-	-
15.85	0.10	0.12	0.12	0.15	0.16	0.21	0.23	0.30	-	-	-	-	-	-
19.95	0.11	0.16	0.13	0.19	0.19	0.26	0.26	1.45	-	-	-	-	-	-

East-West Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.26	0.26	0.20	0.20	0.19	0.19	0.18	0.19	0.16	0.17	0.16	0.17	0.16	0.17
1.26	0.16	0.16	0.13	0.14	0.13	0.14	0.12	0.13	0.12	0.13	0.12	0.13	0.12	0.13
1.59	0.14	0.13	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.12	0.11	0.12	0.11	0.12
2.00	0.07	0.07	0.09	0.09	0.08	0.08	0.10	0.10	0.10	0.11	0.10	0.11	0.11	0.12
2.51	0.05	0.05	0.08	0.08	0.08	0.08	0.09	0.10	0.10	0.11	0.11	0.12	0.12	0.13
3.16	0.05	0.05	0.09	0.08	0.09	0.08	0.11	0.10	0.12	0.13	0.14	0.14	0.14	0.15
3.98	0.05	0.05	0.06	0.07	0.09	0.08	0.11	0.11	0.14	0.14	0.15	0.16	0.16	0.17
5.01	0.06	0.06	0.07	0.08	0.10	0.10	0.14	0.15	0.16	0.18	0.17	0.19	0.19	0.20
6.31	0.07	0.07	0.08	0.08	0.10	0.10	0.15	0.16	0.19	0.20	0.20	0.23	0.22	0.56
7.94	0.07	0.07	0.10	0.10	0.12	0.12	0.17	0.18	0.22	0.24	0.23	0.77	0.26	2.09
10.00	0.08	0.09	0.09	0.10	0.12	0.14	0.19	0.21	0.24	0.29	0.26	2.72	0.30	6.10
12.59	0.09	0.10	0.11	0.13	0.14	0.16	0.22	0.26	-	-	-	-	-	-
15.85	0.10	0.12	0.12	0.15	0.16	0.21	0.23	0.42	-	-	-	-	-	-
19.95	0.11	0.15	0.14	0.18	0.18	0.24	0.28	5.71	-	-	-	-	-	-

Table 32 Waveform Distortion vs Input Amplitude for T120 Slim BH 2024

Vertical Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.29	0.29	0.34	0.35	0.31	0.31	0.31	0.32	0.33	0.32	0.35	0.35
1.26	0.24	0.23	0.20	0.21	0.27	0.28	0.21	0.21	0.18	0.18	0.27	0.26	0.30	0.30
1.59	0.20	0.19	0.16	0.16	0.17	0.18	0.16	0.17	0.13	0.13	0.21	0.21	0.24	0.24
2.00	0.14	0.13	0.12	0.12	0.13	0.15	0.12	0.13	0.09	0.10	0.18	0.19	0.21	0.22
2.51	0.11	0.09	0.09	0.08	0.09	0.11	0.11	0.12	0.11	0.13	0.18	0.19	0.21	0.22
3.16	1.11	0.09	0.78	0.07	0.51	0.10	0.27	0.12	0.18	0.15	0.23	0.18	0.24	0.21
3.98	0.45	0.08	0.19	0.03	0.13	0.08	0.11	0.10	0.13	0.14	0.17	0.18	0.19	0.21
5.01	0.07	0.07	0.06	0.04	0.07	0.07	0.11	0.14	0.13	0.16	0.19	0.23	0.19	0.23
6.31	0.52	0.04	0.37	0.03	0.20	0.07	0.14	0.11	0.12	0.15	0.16	0.19	0.19	0.22
7.94	0.13	0.03	0.27	0.04	0.08	0.04	0.10	0.07	0.11	0.07	0.16	0.13	0.19	0.12
10.00	0.05	0.04	0.05	0.02	0.05	0.05	0.05	0.08	0.08	0.11	0.13	0.17	0.16	0.17
12.59	0.09	0.04	0.07	0.04	0.05	0.05	0.08	0.09	-	-	-	-	-	-
15.85	0.03	0.02	0.37	0.02	0.12	0.03	0.14	0.08	-	-	-	-	-	-
19.95	0.08	0.04	0.06	0.04	0.05	0.05	0.09	0.12	-	-	-	-	-	-

North-South Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.24	0.23	0.23	0.21	0.24	0.19	0.22	0.17	0.18	0.16	0.18	0.16	0.17
1.26	0.17	0.16	0.16	0.16	0.14	0.16	0.13	0.15	0.13	0.14	0.12	0.13	0.12	0.13
1.59	0.13	0.10	0.12	0.12	0.11	0.13	0.11	0.13	0.11	0.12	0.11	0.12	0.11	0.12
2.00	0.09	0.07	0.09	0.10	0.09	0.11	0.09	0.12	0.10	0.11	0.10	0.12	0.11	0.12
2.51	0.05	0.04	0.07	0.07	0.08	0.11	0.10	0.12	0.11	0.12	0.11	0.13	0.11	0.13
3.16	0.11	0.05	0.10	0.08	0.10	0.09	0.10	0.12	0.12	0.13	0.13	0.14	0.14	0.15
3.98	0.28	0.06	0.05	0.06	0.08	0.10	0.11	0.13	0.13	0.15	0.15	0.17	0.16	0.17
5.01	0.08	0.06	0.06	0.06	0.08	0.09	0.12	0.15	0.16	0.19	0.18	0.20	0.18	0.21
6.31	0.10	0.07	0.09	0.08	0.11	0.11	0.15	0.18	0.18	0.21	0.19	0.23	0.20	0.24
7.94	0.16	0.08	0.10	0.10	0.11	0.12	0.16	0.20	0.20	0.25	0.22	0.27	0.23	0.29
10.00	0.07	0.09	0.09	0.12	0.11	0.16	0.17	0.24	0.21	0.30	0.23	0.32	0.23	0.59
12.59	0.10	0.12	0.08	0.15	0.11	0.20	0.17	0.32	-	-	-	-	-	-
15.85	0.07	0.21	0.07	0.25	0.10	0.34	0.14	0.50	-	-	-	-	-	-
19.95	0.26	0.10	0.34	0.13	0.47	0.15	0.62	0.20	-	-	-	-	-	-

East-West Axis														
Freq (Hz)	10% Full-Scale		15% Full-Scale		25% Full-Scale		50% Full-Scale		75% Full-Scale		90% Full-Scale		98% Full-Scale	
	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	0.26	0.26	0.22	0.21	0.20	0.23	0.18	0.21	0.17	0.18	0.17	0.18	0.16	0.18
1.26	0.16	0.16	0.15	0.15	0.14	0.18	0.13	0.14	0.13	0.14	0.13	0.14	0.12	0.14
1.59	0.11	0.10	0.12	0.11	0.11	0.15	0.11	0.12	0.11	0.12	0.11	0.12	0.11	0.13
2.00	0.07	0.06	0.09	0.09	0.08	0.13	0.09	0.11	0.10	0.11	0.11	0.12	0.10	0.12
2.51	0.05	0.05	0.07	0.07	0.08	0.13	0.09	0.11	0.10	0.11	0.12	0.13	0.12	0.13
3.16	0.05	0.06	0.09	0.08	0.10	0.12	0.10	0.11	0.12	0.13	0.13	0.14	0.13	0.15
3.98	0.05	0.05	0.06	0.07	0.08	0.12	0.11	0.13	0.13	0.15	0.15	0.17	0.16	0.18
5.01	0.06	0.06	0.06	0.09	0.08	0.12	0.12	0.15	0.15	0.18	0.17	0.20	0.19	0.22
6.31	0.08	0.07	0.08	0.09	0.11	0.13	0.14	0.18	0.18	0.23	0.20	0.24	0.21	0.26
7.94	0.07	0.08	0.08	0.10	0.12	0.16	0.17	0.23	0.21	0.28	0.21	0.29	0.23	0.49
10.00	0.07	0.12	0.09	0.15	0.11	0.20	0.17	0.29	0.21	0.35	0.23	0.38	0.24	1.07
12.59	0.07	0.18	0.08	0.21	0.11	0.28	0.16	0.42	-	-	-	-	-	-
15.85	0.06	0.36	0.08	0.45	0.10	0.61	0.14	0.86	-	-	-	-	-	-
19.95	0.24	0.25	0.32	0.32	0.40	0.44	0.57	0.58	-	-	-	-	-	-

3.10 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 $1 \text{ (m/s}^2\text{)}^2\text{/Hz}$.

3.10.1 Measurand

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

3.10.2 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 of time 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 61 provides a block diagram showing how the equipment is installed and connected during a self-noise test and Figure 62 shows a picture of how the equipment was installed for the test.

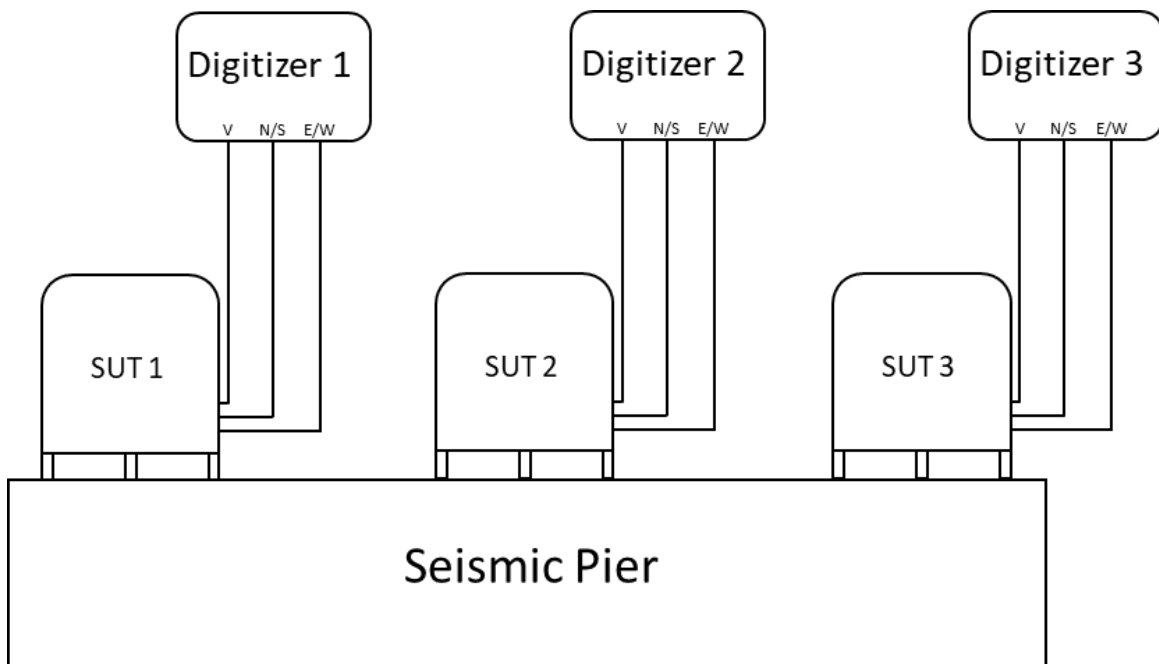


Figure 61 Self-Noise Configuration Diagram



Figure 62 Sensors installed on seismic pier for self-noise test

Table 33 Self-Noise Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Seismic Pier	SNL	Bunker	23C
SUT Digitizer 1	Nanometrics / Centaur	9403	100Hz, 40x gain Port A: Horizon V2 2029 Port B: Horizon V2 2028
SUT Digitizer 2	Nanometrics / Centaur	9404	100Hz, 40x gain Port A: Horizon V1 0769 Port B: Slim BH 2024

The self-noise measurement was taken on December 2, 2023 from the time period of 04:15 to 14:20 UTC

3.10.3 Analysis

The measured sensitivities are applied to the collected data:

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

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

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

Over frequencies (in Hertz):

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

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 0.83 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:

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

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

3.10.4 Result

The figure below shows the vertical waveform time series for the four T120 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.

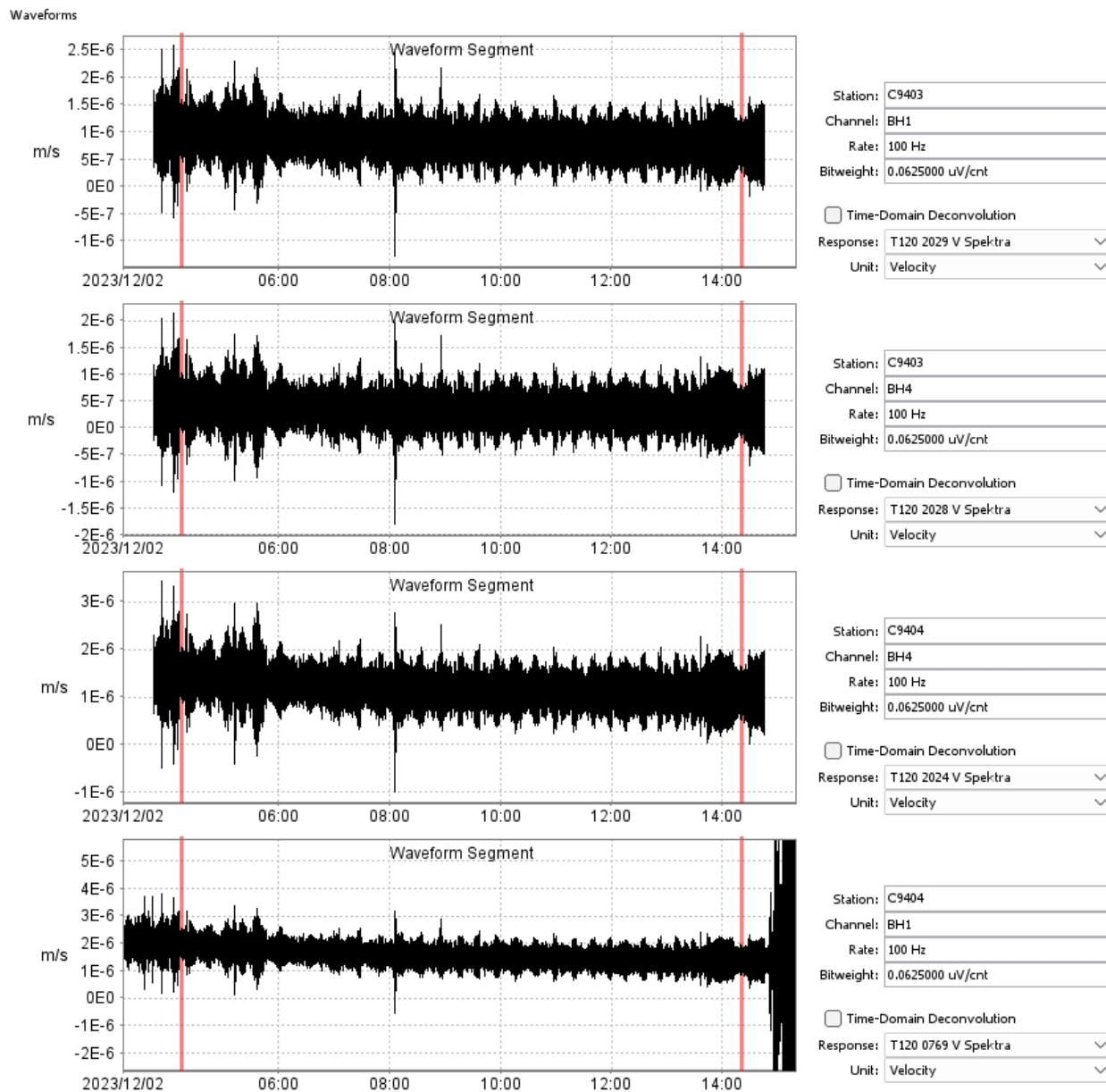


Figure 63 Self-Noise Time Series

The time series data above was used to calculate PSDs which are shown for all three axes in Figure 64.

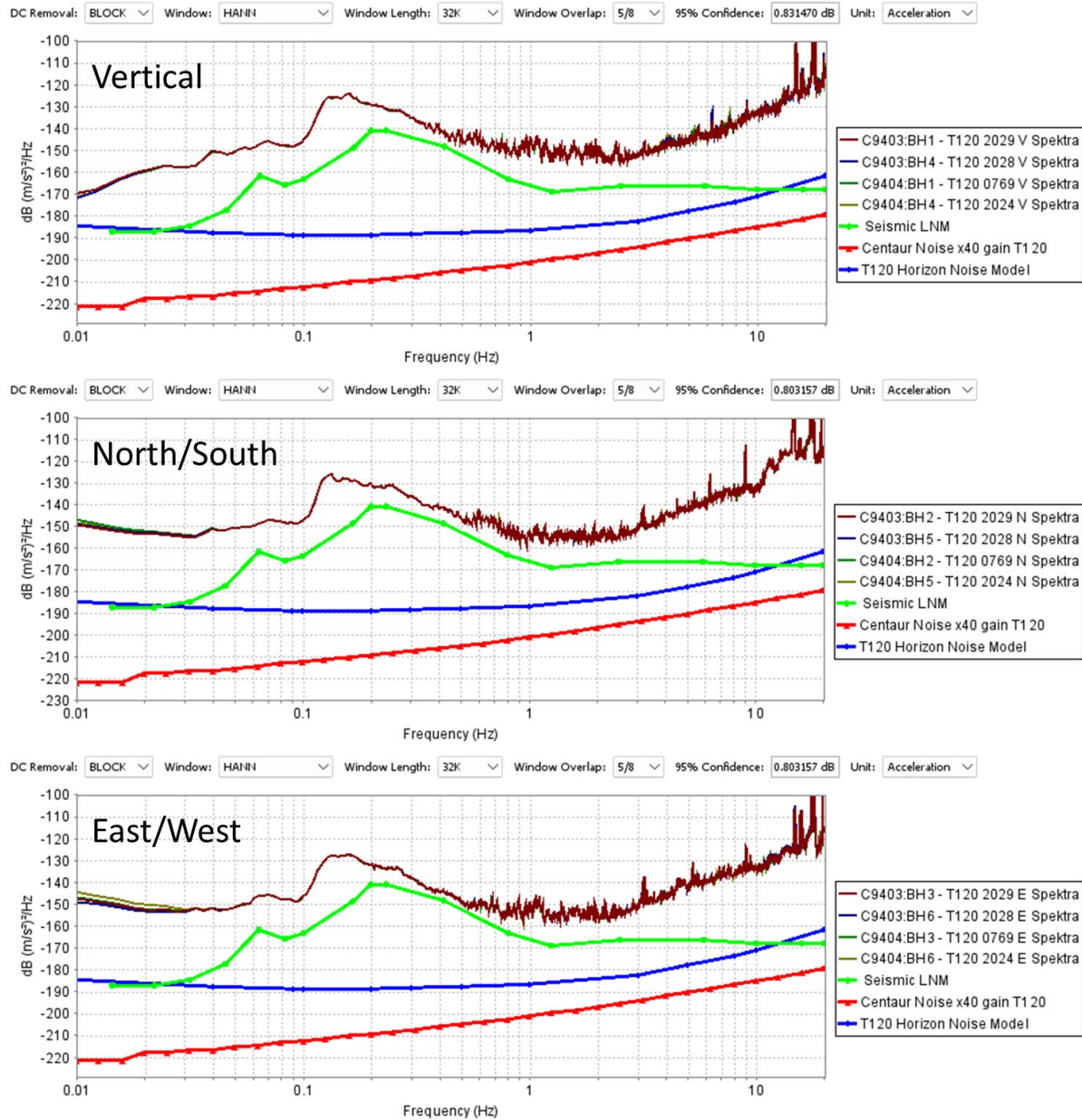


Figure 64 PSD of Self Noise time series data

Figure 65, Figure 66, and Figure 67, below, show the measured self-noise levels for the T120 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 T120 self-noise model in blue. In red is the six channel Centaur noise level when it's configured to operate at x40 gain and 100sps. The Centaur noise model is obtained from the Sandia evaluation of the digitizer (Merchant, 2022) and indicates that the self-noise of the digitizer is well below that of the T120 sensor across the bandwidth of interest and, as a result, is not a significant contributor to the measured noise levels.

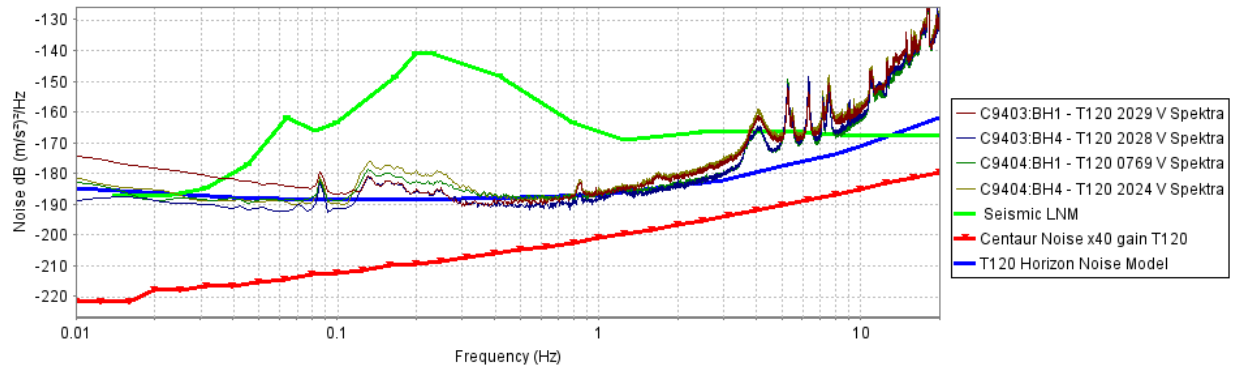


Figure 65 Self-Noise of Vertical Axis

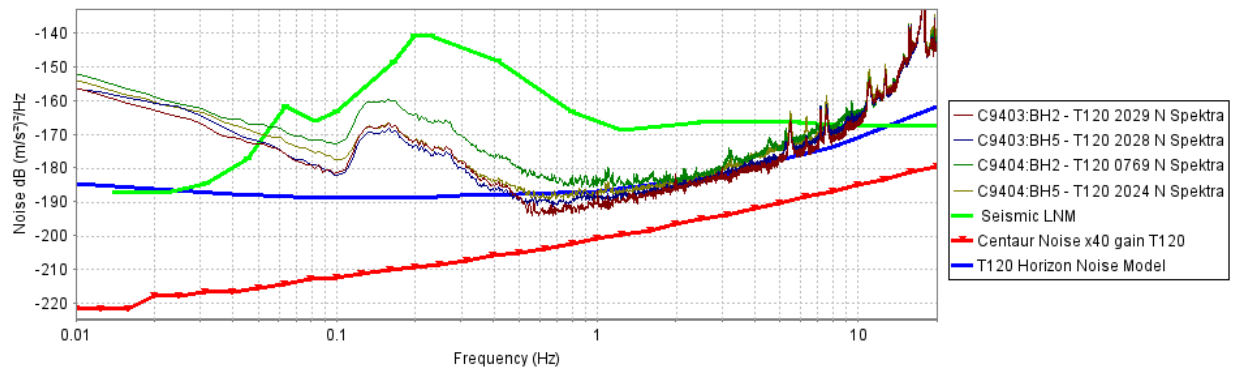


Figure 66 Self-Noise of North-South Axis

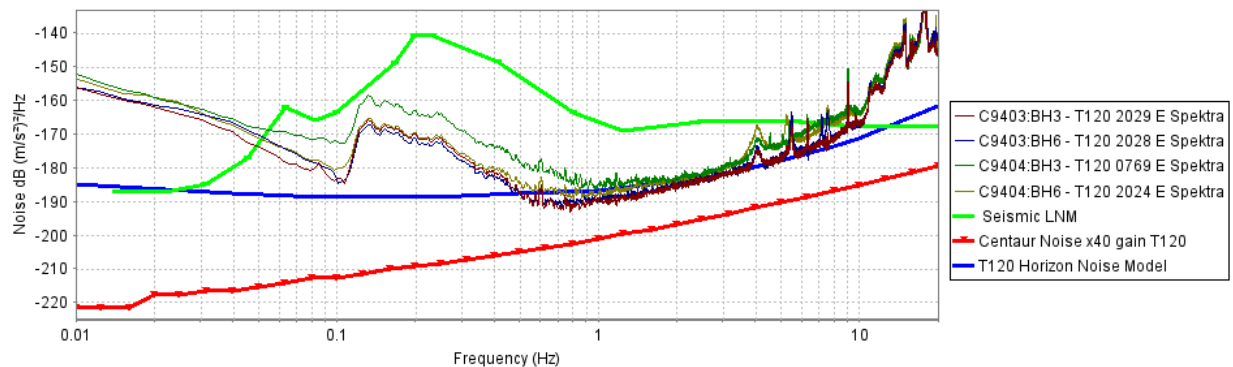


Figure 67 Self-Noise of East-West Axis

Figure 65, showing the self-noise for the vertical axis, indicates from 0.02Hz-1Hz the measured self-noise levels closely match the manufacture's self-noise model. T120 Horizon V2 2029 is noisier than the other three units below 0.1Hz. The FACT site bunker is not located on bedrock and is also not highly isolated from daily temperature variations or other environmental conditions. All sensors show an increase in noise within the microseism which, as expected, indicates a non-perfect removal of coherent signals. At frequencies above 1Hz the measured self-noise is higher than the sensor noise model. This is 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. Despite the non-idealities of the test location, the measured self-noise of the sensors

closely matches the manufacturer's specifications and is below the NLNM across most of the passband of 0.02Hz to 16Hz.

Figure 66 and Figure 67, showing the measured self-noise levels for the horizontal axis, show good agreement between the measured noise levels and the manufactures specifications from 0.5Hz to 5Hz. Below this band 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). At higher frequencies, the incoherent anthropogenic signals around the test location led to elevated estimates of the sensors' self-noise.

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 sensors.

Table 34 Acceleration Self Noise RMS

Sensor	Vertical 0.02Hz - 16Hz	North-South 0.02Hz - 16Hz	East-West 0.02Hz - 16Hz
T120 Horizon 2029	159.9 nm/s ² rms	65.7 nm/s ² rms	95.0 nm/s ² rms
T120 Horizon 2028	128.9 nm/s ² rms	64.3 nm/s ² rms	109.9 nm/s ² rms
T120 Horizon 0769	110.9 nm/s ² rms	66.7 nm/s ² rms	114.4 nm/s ² rms
T120 Slim PH 2024	167.0 nm/s ² rms	70.4 nm/s ² rms	135.3 nm/s ² rms

Table 35 Velocity Self Noise RMS

Sensor	Vertical 0.02Hz - 16Hz	North-South 0.02Hz - 16Hz	East-West 0.02Hz - 16Hz
T120 Horizon 2029	2.1 nm/s rms	4.6 nm/s rms	5.1 nm/s rms
T120 Horizon 2028	1.5 nm/s rms	5.9 nm/s rms	6.0 nm/s rms
T120 Horizon 0769	1.4 nm/s rms	7.8 nm/s rms	7.8 nm/s rms
T120 Slim PH 2024	2.0 nm/s rms	6.3 nm/s rms	7.1 nm/s rms

The following table contains incoherent self-noise levels in acceleration with units of dB relative to 1 (m/s²)/Hz that were used to make the plots shown above. The total combined uncertainty estimate for the PSD is included as well.

Table 36 Vertical Axis Self-Noise Power Spectra

Vertical Noise (dB relative to 1 (m/s ²) ² /Hz)					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 0769	T120 Slim PH 2024	Uncertainty (k=2)
0.02	-178.58	-189.41	-188.41	-185.52	0.84
0.025	-179.29	-189.65	-187.95	-186.86	0.84
0.0315	-180.35	-190.00	-188.48	-188.70	0.84
0.04	-181.71	-190.88	-188.31	-188.70	0.84
0.05	-182.78	-191.50	-188.65	-189.08	0.84
0.063	-184.30	-192.31	-188.58	-189.48	0.84
0.08	-184.60	-190.35	-188.23	-189.38	0.84
0.1	-186.51	-191.46	-188.68	-189.63	0.84
0.125	-184.05	-184.03	-181.09	-179.01	0.84
0.16	-183.33	-183.44	-180.70	-177.99	0.84
0.2	-186.00	-186.35	-183.06	-180.22	0.84
0.25	-186.80	-187.00	-183.19	-180.44	0.84
0.315	-189.61	-189.45	-185.91	-184.68	0.84
0.4	-189.53	-190.13	-187.03	-187.25	0.84
0.5	-189.07	-190.54	-187.60	-188.45	0.84
0.63	-188.98	-190.30	-187.80	-188.14	0.84
0.8	-187.38	-189.35	-187.48	-186.93	0.84
1	-186.50	-188.28	-186.94	-185.90	0.83
1.25	-184.97	-186.14	-185.41	-184.32	0.83
1.6	-182.59	-185.92	-185.03	-181.70	0.83
2	-181.13	-184.18	-183.56	-180.42	0.83
2.5	-178.90	-182.20	-181.92	-178.21	0.83
3.15	-175.64	-179.09	-179.16	-174.63	0.83
4	-164.67	-167.90	-168.29	-163.30	0.83
5	-167.80	-169.09	-169.88	-166.61	0.83
6.3	-166.97	-167.76	-168.62	-165.81	0.83
8	-162.15	-165.34	-166.38	-160.66	0.83
10	-159.16	-161.32	-162.39	-157.91	0.83
12.5	-150.35	-151.00	-153.58	-150.14	0.84
16	-139.29	-139.89	-140.84	-138.68	0.84
20	-135.58	-134.69	-135.79	-133.94	0.84

Table 37 North-South Axis Self-Noise Power Spectra

N/S Noise (dB relative to 1 (m/s ²)/Hz)					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 0769	T120 Slim PH 2024	Uncertainty (k=2)
0.02	-163.66	-161.13	-159.64	-161.21	0.84
0.025	-164.79	-161.82	-160.89	-162.02	0.84
0.0315	-167.12	-164.94	-162.61	-163.63	0.84
0.04	-170.78	-169.16	-165.35	-167.25	0.84
0.05	-172.81	-171.86	-167.03	-169.44	0.84
0.063	-176.03	-175.85	-169.33	-172.39	0.84
0.08	-179.08	-178.89	-171.61	-174.78	0.84
0.1	-180.67	-181.26	-172.39	-176.97	0.84
0.125	-169.84	-171.47	-162.48	-169.80	0.84
0.16	-167.74	-169.25	-160.30	-167.80	0.84
0.2	-172.16	-173.74	-164.52	-171.86	0.84
0.25	-174.23	-175.92	-166.47	-174.19	0.84
0.315	-179.71	-181.36	-171.74	-179.24	0.84
0.4	-184.76	-186.24	-176.28	-183.42	0.84
0.5	-188.78	-189.13	-179.92	-186.07	0.84
0.63	-192.94	-189.71	-182.60	-188.40	0.84
0.8	-191.65	-189.62	-184.26	-187.88	0.84
1	-190.72	-188.58	-183.66	-187.25	0.83
1.25	-189.41	-188.09	-184.43	-186.87	0.83
1.6	-187.67	-186.90	-183.60	-185.49	0.83
2	-186.04	-185.20	-183.17	-184.27	0.83
2.5	-184.05	-183.59	-181.86	-182.37	0.83
3.15	-182.50	-181.39	-177.93	-179.68	0.83
4	-180.06	-179.03	-176.45	-176.54	0.83
5	-177.55	-176.58	-172.86	-174.07	0.83
6.3	-174.64	-172.94	-170.81	-171.75	0.83
8	-170.68	-168.80	-167.20	-168.62	0.83
10	-166.54	-164.86	-163.47	-165.37	0.83
12.5	-158.06	-158.42	-158.40	-157.08	0.84
16	-144.86	-145.31	-145.18	-144.63	0.84
20	-144.07	-143.93	-142.88	-140.63	0.84

Table 38 East-West Axis Self-Noise Power Spectra

E/W Noise (dB relative to 1 (m/s ²) ² /Hz)					
Frequency (Hz)	T120 Horizon 2029	T120 Horizon 2028	T120 Horizon 0769	T120 Slim PH 2024	Uncertainty (k=2)
0.02	-162.70	-161.75	-159.76	-159.56	0.84
0.025	-163.70	-162.36	-160.85	-160.51	0.84
0.0315	-165.89	-164.17	-162.66	-163.65	0.84
0.04	-169.39	-166.56	-165.45	-167.33	0.84
0.05	-173.44	-169.90	-168.23	-170.93	0.84
0.063	-178.57	-174.53	-169.29	-174.29	0.84
0.08	-179.89	-178.27	-171.14	-177.63	0.84
0.1	-183.15	-182.75	-172.49	-179.81	0.84
0.125	-167.76	-169.01	-160.56	-167.22	0.84
0.16	-168.23	-169.55	-161.20	-167.77	0.84
0.2	-171.13	-172.54	-164.14	-170.78	0.84
0.25	-172.28	-173.59	-164.94	-171.62	0.84
0.315	-177.60	-178.84	-169.90	-176.54	0.84
0.4	-181.67	-182.91	-173.67	-180.34	0.84
0.5	-187.04	-187.51	-178.42	-184.29	0.84
0.63	-190.33	-189.72	-180.74	-186.44	0.84
0.8	-191.12	-189.92	-183.82	-187.64	0.84
1	-190.00	-189.20	-184.99	-187.80	0.83
1.25	-188.96	-188.19	-184.45	-186.48	0.83
1.6	-187.21	-186.78	-183.80	-184.93	0.83
2	-185.44	-185.13	-183.22	-184.05	0.83
2.5	-183.69	-183.52	-181.84	-182.19	0.83
3.15	-181.76	-181.54	-179.19	-179.66	0.83
4	-178.28	-178.60	-173.99	-171.92	0.83
5	-177.15	-176.85	-173.15	-173.21	0.83
6.3	-174.67	-174.22	-168.83	-171.01	0.83
8	-171.17	-170.02	-165.36	-166.13	0.83
10	-166.39	-166.90	-162.50	-163.19	0.83
12.5	-155.31	-155.05	-152.75	-152.69	0.84
16	-144.22	-143.13	-144.17	-142.35	0.84
20	-145.34	-141.93	-144.51	-143.10	0.84

3.11 Dynamic Range

Dynamic range is defined as the ratio between the power of the largest and smallest signals that may be output by the sensor.

3.11.1 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).

3.11.2 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.

3.11.3 Analysis

The dynamic range over a given passband is:

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

Where

$$\begin{aligned} \text{signal power} &= (\text{fullscale}/\sqrt{2})^2 \\ \text{noise power} &= (\text{RMS Noise})^2 \end{aligned}$$

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

3.11.4 Result

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

Table 39 Dynamic Range of the T120 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)
T120 Horizon 2029	16.6 mm/s	2.1 nm/s	4.6 nm/s	5.1 nm/s	134.95 dB	128.14 dB	127.24 dB
T120 Horizon 2028	16.6 mm/s	1.5 nm/s	5.9 nm/s	6.0 nm/s	137.87 dB	125.97 dB	125.83 dB
T120 Horizon 0769	16.6 mm/s	1.4 nm/s	7.8 nm/s	7.8 nm/s	138.47 dB	123.55 dB	123.55 dB
T120 Slim PH 2024	16.6 mm/s	2.0 nm/s	6.3 nm/s	7.1 nm/s	135.37 dB	125.41 dB	124.37 dB

The dynamic range values were between 134.95dB – 138.47dB for the vertical axis and 123.55dB – 128.14dB for the horizontal axis. All 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 this evaluation.

3.12 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 voltage signal.

3.12.1 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.

3.12.2 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 68, 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.

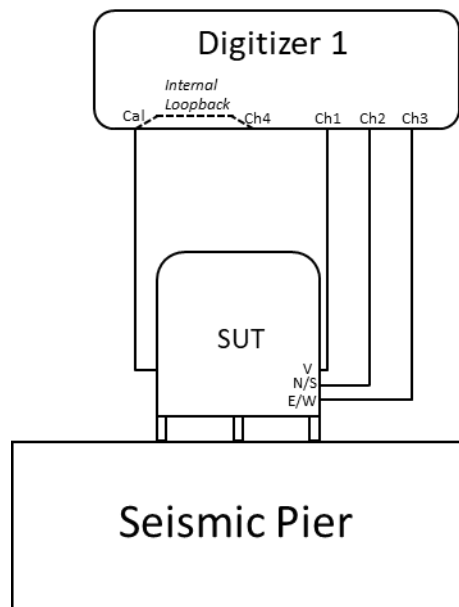


Figure 68 Calibrator Frequency Response Configuration Diagram

Table 40 Calibrator Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Seismic Pier	SNL	Bunker	23C
SUT Digitizer 1	Nanometrics / Centaur	9403	500Hz, 1x gain Port A: Horizon V2 2029 Port B: Horizon V2 2028
SUT Digitizer 2	Nanometrics / Centaur	9404	500Hz, 1x gain Port A: Horizon V1 0769 Port B: Slim PH 2024

3.12.3 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:

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

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:

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

The sensor's response to ground motion is then removed from the relative transfer functions. The nominal ground motion response model provided by the manufacturer is used. These corrected transfer functions can then be directly compared to the manufacturer's specification for the response of the electrical calibration system.

3.12.4 Result

The figure below shows a representative waveform time series for T120 Horizon V2 2029 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 Centaur datalogger, with units of acceleration, and the next three waveforms are the sensor's W, V and U output signals respectively, with units of velocity.

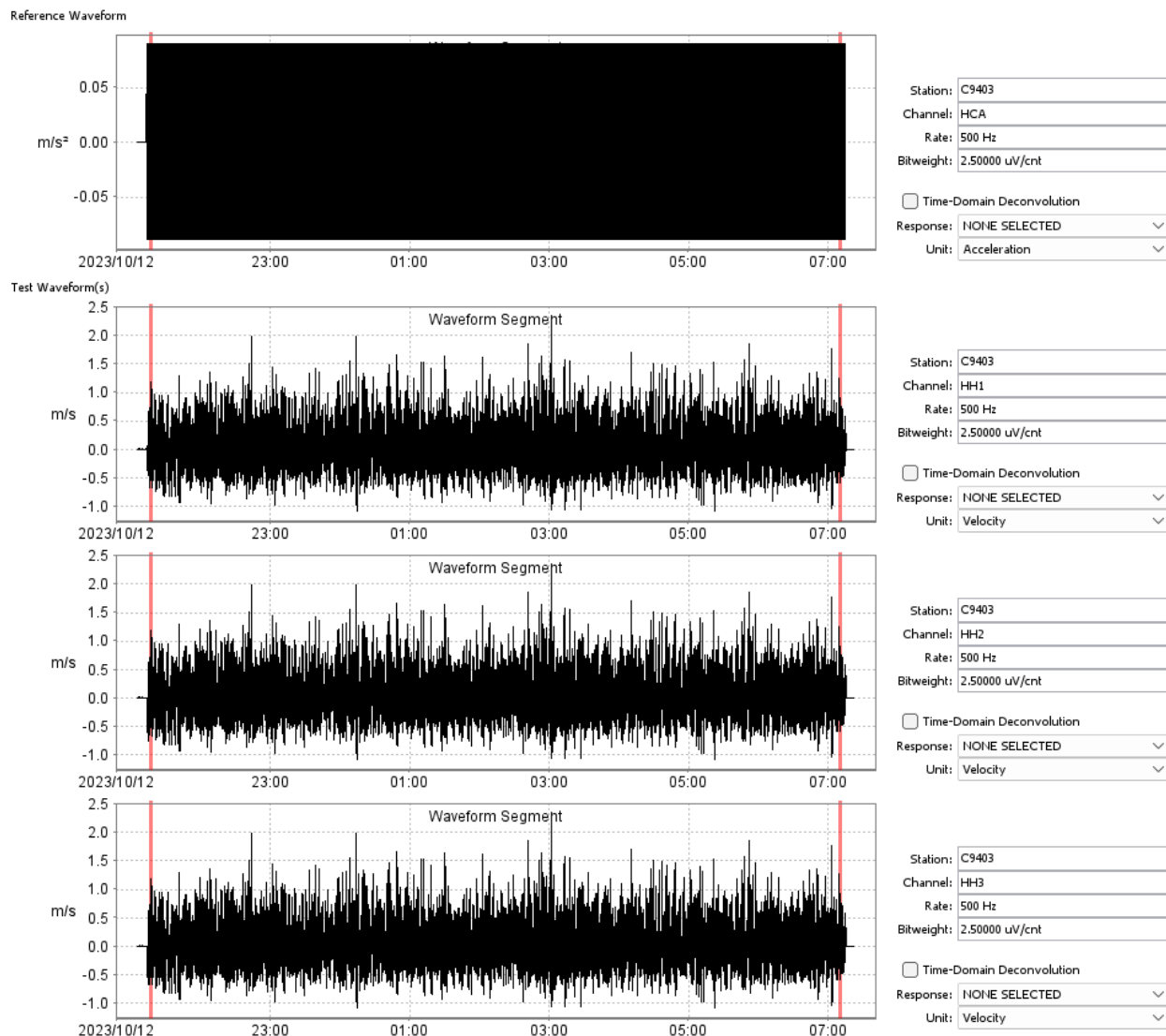


Figure 69 T120 Horizon 2029 Calibrator Frequency Response Time Series

The following plots show the calculated amplitude and phase response of the electrical calibration system for each of the four T120 sensors. Note that the manufacturer provides a frequency independent response specification for the T120 Horizon V2 sensors as well as the T120 Slim PH sensor. The T120 Horizon V1 has a frequency dependent specification.

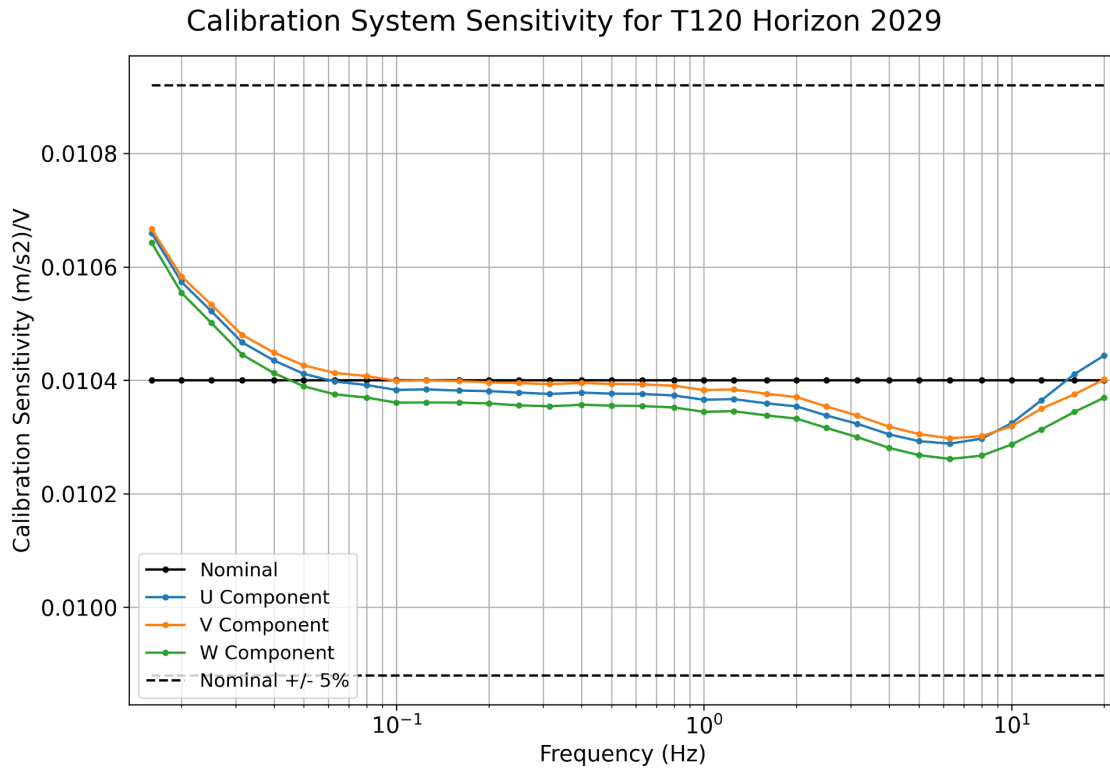


Figure 70 T120 Horizon V2 2029 Calibrator Amplitude Response

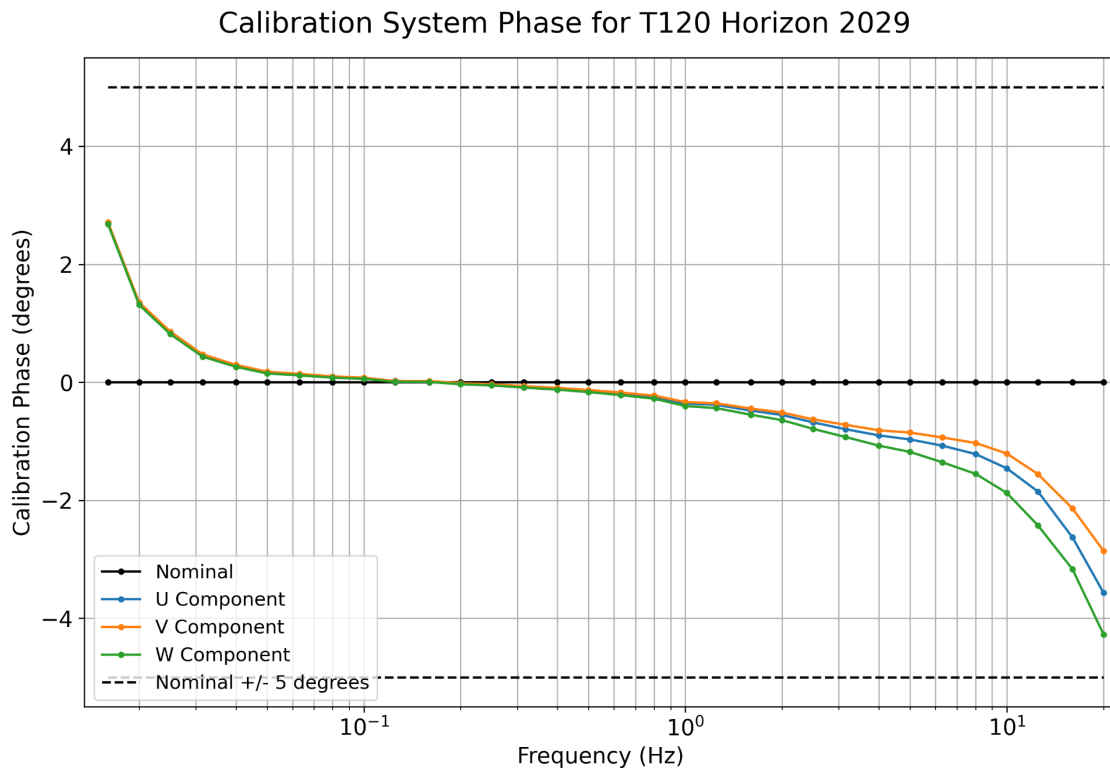


Figure 71 T120 Horizon V2 2029 Calibrator Phase Response

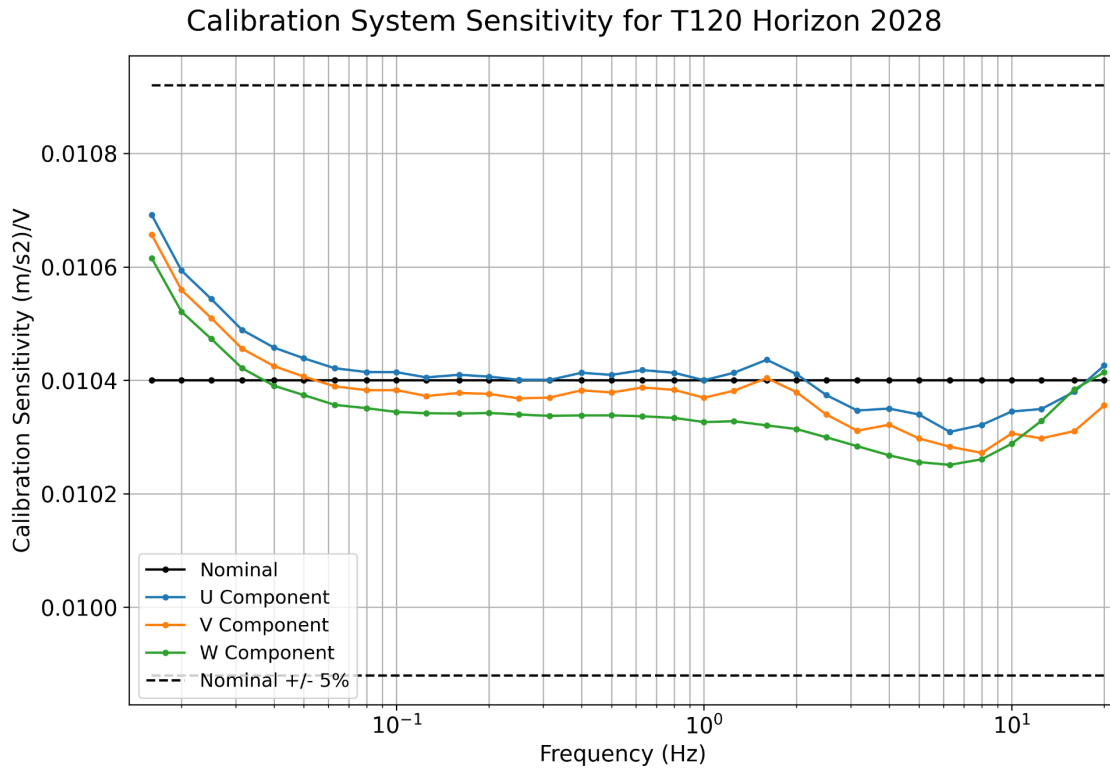


Figure 72 T120 Horizon V2 2028 Calibrator Amplitude Response

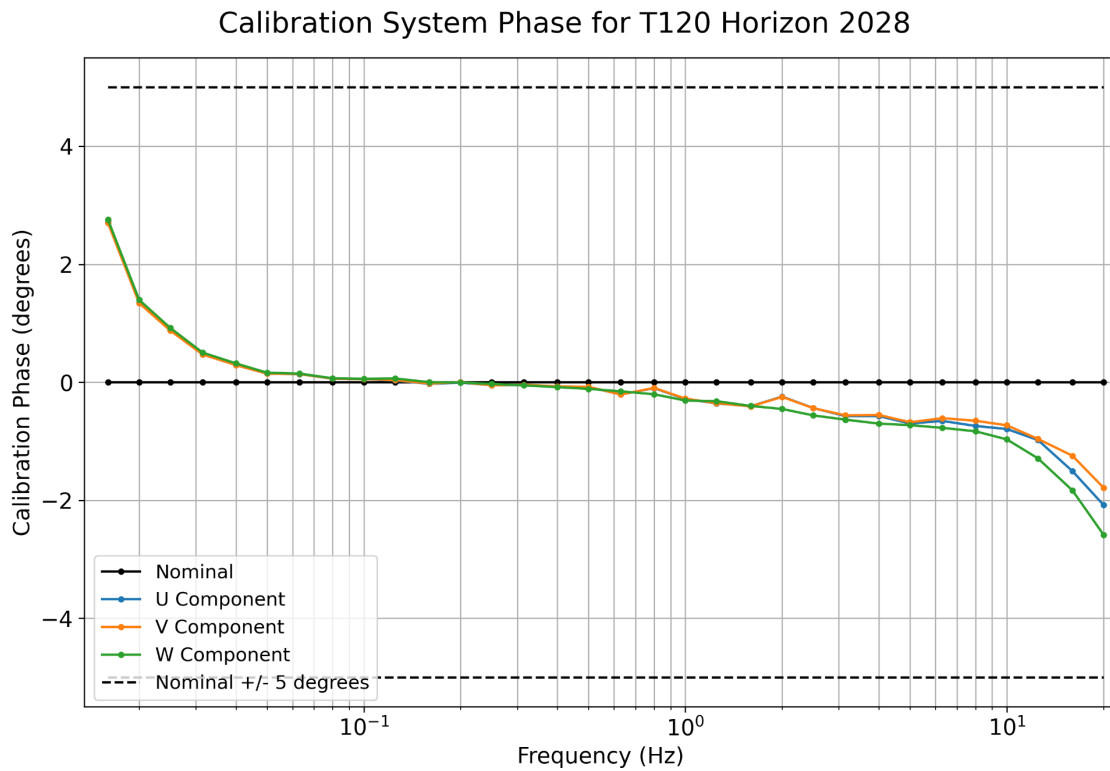


Figure 73 T120 Horizon V2 2028 Calibrator Phase Response

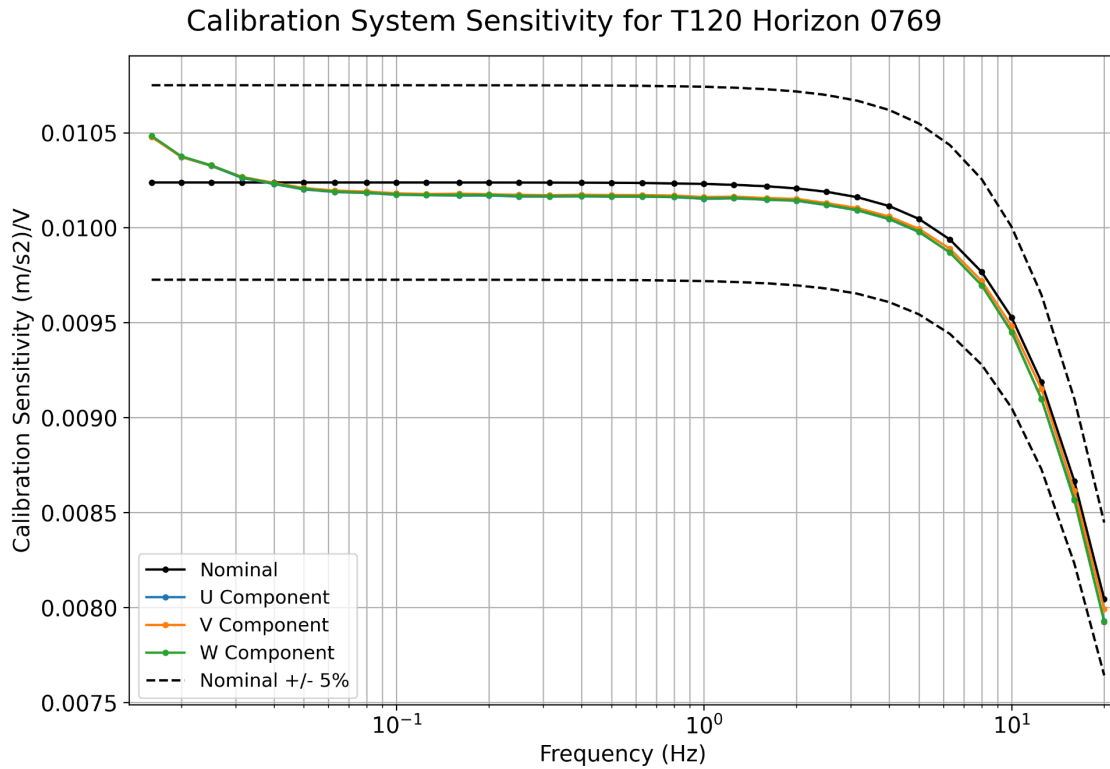


Figure 74 T120 Horizon V1 0769 Calibrator Amplitude Response

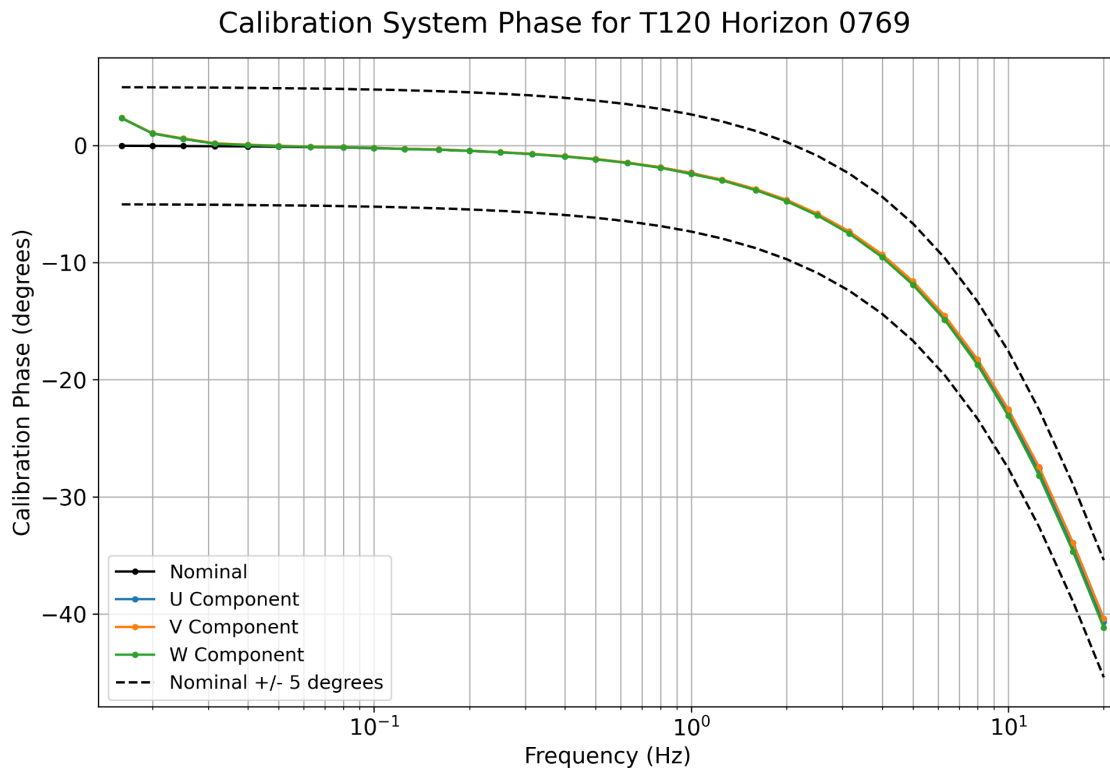


Figure 75 T120 Horizon V1 0769 Calibrator Phase Response

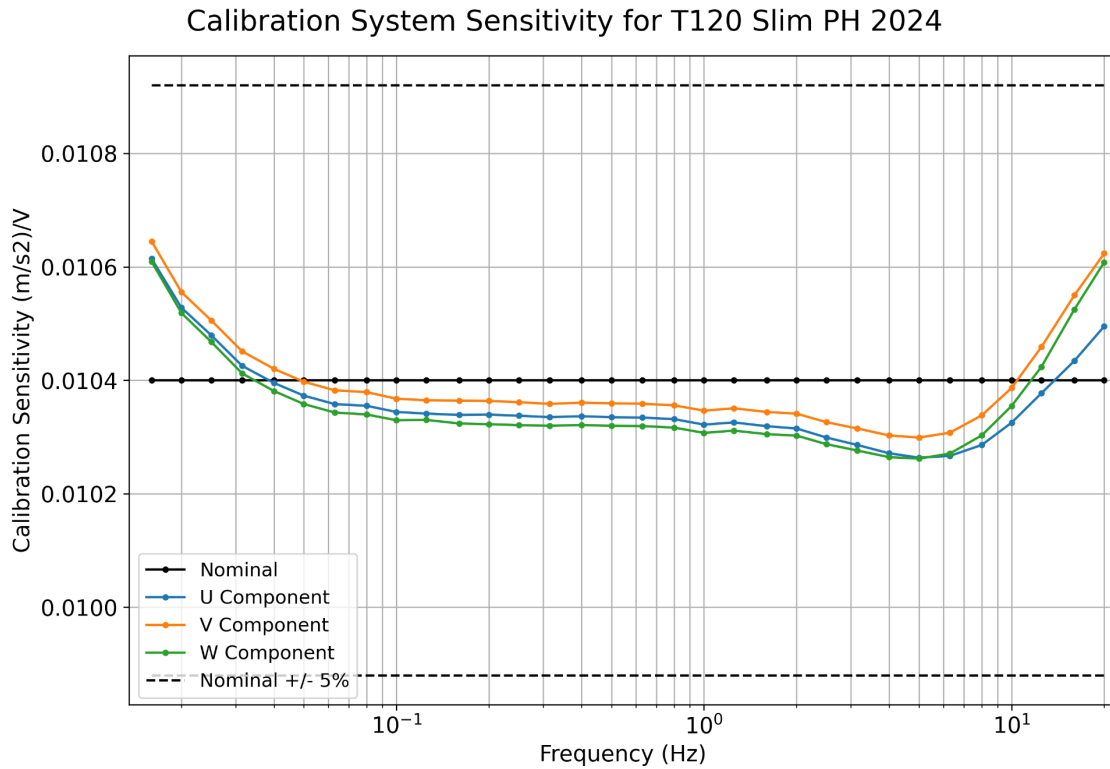


Figure 76 T120 Slim PH 2024 Calibrator Amplitude Response

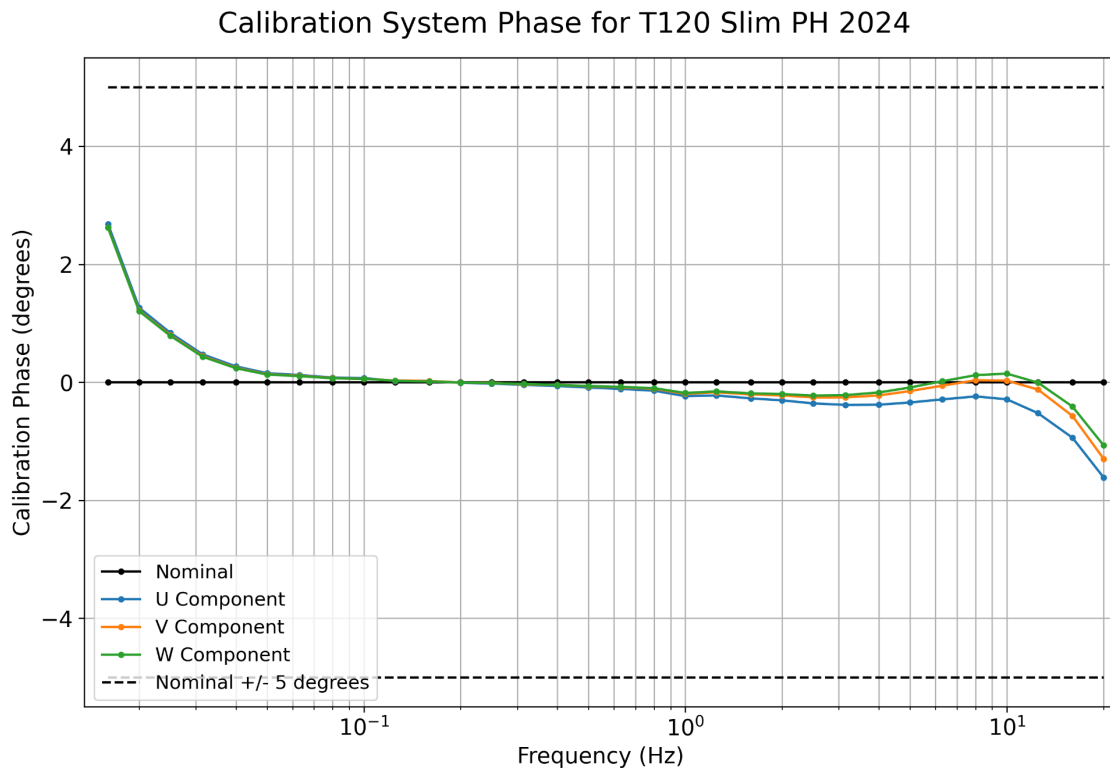


Figure 77 T120 Slim PH 2024 Calibrator Phase Response

The measured calibration system response of all four T120 Horizon sensors are all within 5% and 5 degrees of the nominal amplitude and phase response across the entire evaluated frequency range of 0.02Hz-20Hz. The T120 Horizon V1, 0769, does not have a flat calibrator response with respect to frequency but it appears that the frequency response of the system is well modeled by the manufacturer. The following tables contains the values used to generate the above plots.

Table 41 T120 Horizon 2029 Calibrator Amplitude Response

Frequency (Hz)	U Component		V Component		W Component		Nominal	
	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)
0.016	0.0107	2.6999	0.0107	2.7097	0.0106	2.6801	0.0104	0.0000
0.02	0.0106	1.3352	0.0106	1.3534	0.0106	1.3122	0.0104	0.0000
0.025	0.0105	0.8377	0.0105	0.8591	0.0105	0.8161	0.0104	0.0000
0.0315	0.0105	0.4525	0.0105	0.4737	0.0104	0.4350	0.0104	0.0000
0.04	0.0104	0.2754	0.0104	0.2960	0.0104	0.2617	0.0104	0.0000
0.05	0.0104	0.1614	0.0104	0.1793	0.0104	0.1498	0.0104	0.0000
0.063	0.0104	0.1267	0.0104	0.1426	0.0104	0.1174	0.0104	0.0000
0.08	0.0104	0.0849	0.0104	0.1005	0.0104	0.0782	0.0104	0.0000
0.1	0.0104	0.0631	0.0104	0.0778	0.0104	0.0583	0.0104	0.0000
0.125	0.0104	0.0241	0.0104	0.0212	0.0104	0.0073	0.0104	0.0000
0.16	0.0104	0.0063	0.0104	0.0208	0.0104	0.0054	0.0104	0.0000
0.2	0.0104	-0.0167	0.0104	-0.0157	0.0104	-0.0343	0.0104	0.0000
0.25	0.0104	-0.0429	0.0104	-0.0334	0.0104	-0.0532	0.0104	0.0000
0.315	0.0104	-0.0749	0.0104	-0.0647	0.0104	-0.0905	0.0104	0.0000
0.4	0.0104	-0.1077	0.0104	-0.0961	0.0104	-0.1245	0.0104	0.0000
0.5	0.0104	-0.1442	0.0104	-0.1310	0.0104	-0.1667	0.0104	0.0000
0.63	0.0104	-0.1899	0.0104	-0.1737	0.0104	-0.2167	0.0104	0.0000
0.8	0.0104	-0.2444	0.0104	-0.2255	0.0104	-0.2781	0.0104	0.0000
1	0.0104	-0.3589	0.0104	-0.3360	0.0103	-0.4016	0.0104	0.0000
1.25	0.0104	-0.3832	0.0104	-0.3562	0.0103	-0.4382	0.0104	0.0000
1.6	0.0104	-0.4799	0.0104	-0.4456	0.0103	-0.5505	0.0104	0.0000
2	0.0104	-0.5548	0.0104	-0.5121	0.0103	-0.6416	0.0104	0.0000
2.5	0.0103	-0.6802	0.0104	-0.6289	0.0103	-0.7900	0.0104	0.0000
3.15	0.0103	-0.7945	0.0103	-0.7202	0.0103	-0.9274	0.0104	0.0000
4	0.0103	-0.9001	0.0103	-0.8138	0.0103	-1.0732	0.0104	0.0000
5	0.0103	-0.9682	0.0103	-0.8521	0.0103	-1.1800	0.0104	0.0000
6.3	0.0103	-1.0742	0.0103	-0.9344	0.0103	-1.3557	0.0104	0.0000
8	0.0103	-1.2165	0.0103	-1.0287	0.0103	-1.5519	0.0104	0.0000
10	0.0103	-1.4585	0.0103	-1.2073	0.0103	-1.8758	0.0104	0.0000
12.5	0.0104	-1.8513	0.0104	-1.5558	0.0103	-2.4257	0.0104	0.0000
16	0.0104	-2.6275	0.0104	-2.1375	0.0103	-3.1672	0.0104	0.0000
20	0.0104	-3.5678	0.0104	-2.8572	0.0104	-4.2731	0.0104	0.0000

Table 42 T120 Horizon 2028 Calibrator Amplitude Response

Frequency (Hz)	U Component		V Component		W Component		Nominal	
	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)
0.016	0.0107	2.7176	0.0107	2.6993	0.0106	2.7564	0.0104	0.0000
0.02	0.0106	1.3527	0.0106	1.3419	0.0105	1.3966	0.0104	0.0000
0.025	0.0105	0.8823	0.0105	0.8764	0.0105	0.9209	0.0104	0.0000
0.0315	0.0105	0.4741	0.0105	0.4716	0.0104	0.5038	0.0104	0.0000
0.04	0.0105	0.2929	0.0104	0.2921	0.0104	0.3205	0.0104	0.0000
0.05	0.0104	0.1463	0.0104	0.1466	0.0104	0.1622	0.0104	0.0000
0.063	0.0104	0.1387	0.0104	0.1399	0.0104	0.1480	0.0104	0.0000
0.08	0.0104	0.0625	0.0104	0.0630	0.0104	0.0677	0.0104	0.0000
0.1	0.0104	0.0535	0.0104	0.0536	0.0103	0.0591	0.0104	0.0000
0.125	0.0104	0.0301	0.0104	0.0380	0.0103	0.0649	0.0104	0.0000
0.16	0.0104	-0.0264	0.0104	-0.0214	0.0103	0.0015	0.0104	0.0000
0.2	0.0104	-0.0062	0.0104	0.0027	0.0103	-0.0024	0.0104	0.0000
0.25	0.0104	-0.0492	0.0104	-0.0509	0.0103	-0.0275	0.0104	0.0000
0.315	0.0104	-0.0449	0.0104	-0.0408	0.0103	-0.0527	0.0104	0.0000
0.4	0.0104	-0.0720	0.0104	-0.0699	0.0103	-0.0821	0.0104	0.0000
0.5	0.0104	-0.0810	0.0104	-0.0767	0.0103	-0.1117	0.0104	0.0000
0.63	0.0104	-0.2058	0.0104	-0.2080	0.0103	-0.1532	0.0104	0.0000
0.8	0.0104	-0.1000	0.0104	-0.0949	0.0103	-0.2031	0.0104	0.0000
1	0.0104	-0.2822	0.0104	-0.2765	0.0103	-0.3089	0.0104	0.0000
1.25	0.0104	-0.3580	0.0104	-0.3547	0.0103	-0.3196	0.0104	0.0000
1.6	0.0104	-0.4047	0.0104	-0.4081	0.0103	-0.4013	0.0104	0.0000
2	0.0104	-0.2420	0.0104	-0.2478	0.0103	-0.4521	0.0104	0.0000
2.5	0.0104	-0.4366	0.0103	-0.4383	0.0103	-0.5613	0.0104	0.0000
3.15	0.0103	-0.5726	0.0103	-0.5600	0.0103	-0.6336	0.0104	0.0000
4	0.0104	-0.5723	0.0103	-0.5534	0.0103	-0.7001	0.0104	0.0000
5	0.0103	-0.6993	0.0103	-0.6771	0.0103	-0.7267	0.0104	0.0000
6.3	0.0103	-0.6549	0.0103	-0.6078	0.0103	-0.7719	0.0104	0.0000
8	0.0103	-0.7402	0.0103	-0.6521	0.0103	-0.8310	0.0104	0.0000
10	0.0103	-0.7918	0.0103	-0.7293	0.0103	-0.9674	0.0104	0.0000
12.5	0.0103	-0.9791	0.0103	-0.9601	0.0103	-1.2901	0.0104	0.0000
16	0.0104	-1.5057	0.0103	-1.2452	0.0104	-1.8322	0.0104	0.0000
20	0.0104	-2.0799	0.0104	-1.7870	0.0104	-2.5849	0.0104	0.0000

Table 43 T120 Horizon 0769 Calibrator Amplitude Response

	U Component		V Component		W Component		Nominal	
Frequency (Hz)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)
0.016	0.0105	2.3140	0.0105	2.3447	0.0105	2.3221	0.0102	-0.0378
0.02	0.0104	1.0092	0.0104	1.0450	0.0104	1.0118	0.0102	-0.0473
0.025	0.0103	0.5493	0.0103	0.5924	0.0103	0.5529	0.0102	-0.0591
0.0315	0.0103	0.1415	0.0103	0.1786	0.0103	0.1392	0.0102	-0.0744
0.04	0.0102	0.0259	0.0102	0.0567	0.0102	0.0254	0.0102	-0.0945
0.05	0.0102	-0.0607	0.0102	-0.0355	0.0102	-0.0635	0.0102	-0.1182
0.063	0.0102	-0.1294	0.0102	-0.1075	0.0102	-0.1325	0.0102	-0.1489
0.08	0.0102	-0.1629	0.0102	-0.1435	0.0102	-0.1642	0.0102	-0.1891
0.1	0.0102	-0.2245	0.0102	-0.2093	0.0102	-0.2283	0.0102	-0.2363
0.125	0.0102	-0.3134	0.0102	-0.2999	0.0102	-0.3206	0.0102	-0.2954
0.16	0.0102	-0.3650	0.0102	-0.3480	0.0102	-0.3648	0.0102	-0.3781
0.2	0.0102	-0.4691	0.0102	-0.4556	0.0102	-0.4715	0.0102	-0.4727
0.25	0.0102	-0.5823	0.0102	-0.5749	0.0102	-0.5988	0.0102	-0.5908
0.315	0.0102	-0.7413	0.0102	-0.7257	0.0102	-0.7514	0.0102	-0.7444
0.4	0.0102	-0.9458	0.0102	-0.9283	0.0102	-0.9575	0.0102	-0.9453
0.5	0.0102	-1.1832	0.0102	-1.1629	0.0102	-1.1985	0.0102	-1.1815
0.63	0.0102	-1.4905	0.0102	-1.4647	0.0102	-1.5077	0.0102	-1.4886
0.8	0.0102	-1.8923	0.0102	-1.8626	0.0102	-1.9146	0.0102	-1.8901
1	0.0102	-2.4218	0.0102	-2.3875	0.0102	-2.4507	0.0102	-2.3622
1.25	0.0102	-2.9605	0.0102	-2.9155	0.0102	-2.9951	0.0102	-2.9519
1.6	0.0101	-3.7889	0.0102	-3.7337	0.0101	-3.8332	0.0102	-3.7766
2	0.0101	-4.7184	0.0102	-4.6508	0.0101	-4.7745	0.0102	-4.7174
2.5	0.0101	-5.9157	0.0101	-5.8332	0.0101	-5.9861	0.0102	-5.8903
3.15	0.0101	-7.4478	0.0101	-7.3459	0.0101	-7.5371	0.0102	-7.4086
4	0.0100	-9.4347	0.0101	-9.3080	0.0100	-9.5514	0.0101	-9.3803
5	0.0100	-11.7402	0.0100	-11.5992	0.0100	-11.9010	0.0100	-11.6752
6.3	0.0099	-14.7211	0.0099	-14.5466	0.0099	-14.8974	0.0099	-14.6098
8	0.0097	-18.5041	0.0097	-18.2769	0.0097	-18.7362	0.0098	-18.3470
10	0.0095	-22.7707	0.0095	-22.5334	0.0094	-23.0890	0.0095	-22.5729
12.5	0.0091	-27.8073	0.0092	-27.4584	0.0091	-28.1829	0.0092	-27.5614
16	0.0086	-34.2692	0.0086	-33.9506	0.0086	-34.6845	0.0087	-33.9543
20	0.0079	-40.6869	0.0080	-40.4050	0.0079	-41.1867	0.0080	-40.4111

Table 44 T120 Slim PH 2024 Calibrator Amplitude Response

Frequency (Hz)	U Component		V Component		W Component		Nominal	
	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)	Amplitude ((m/s ²)/V)	Phase (deg)
0.016	0.0106	2.6822	0.0106	2.6242	0.0106	2.6187	0.0104	0.0000
0.02	0.0105	1.2637	0.0106	1.2156	0.0105	1.2047	0.0104	0.0000
0.025	0.0105	0.8380	0.0105	0.8008	0.0105	0.7881	0.0104	0.0000
0.0315	0.0104	0.4740	0.0105	0.4447	0.0104	0.4341	0.0104	0.0000
0.04	0.0104	0.2690	0.0104	0.2457	0.0104	0.2383	0.0104	0.0000
0.05	0.0104	0.1549	0.0104	0.1369	0.0104	0.1312	0.0104	0.0000
0.063	0.0104	0.1240	0.0104	0.1103	0.0103	0.1048	0.0104	0.0000
0.08	0.0104	0.0795	0.0104	0.0712	0.0103	0.0675	0.0104	0.0000
0.1	0.0103	0.0714	0.0104	0.0575	0.0103	0.0585	0.0104	0.0000
0.125	0.0103	0.0221	0.0104	0.0299	0.0103	0.0260	0.0104	0.0000
0.16	0.0103	0.0226	0.0104	0.0216	0.0103	0.0131	0.0104	0.0000
0.2	0.0103	-0.0089	0.0104	-0.0047	0.0103	-0.0041	0.0104	0.0000
0.25	0.0103	-0.0215	0.0104	-0.0097	0.0103	-0.0132	0.0104	0.0000
0.315	0.0103	-0.0433	0.0104	-0.0340	0.0103	-0.0273	0.0104	0.0000
0.4	0.0103	-0.0627	0.0104	-0.0447	0.0103	-0.0446	0.0104	0.0000
0.5	0.0103	-0.0891	0.0104	-0.0677	0.0103	-0.0628	0.0104	0.0000
0.63	0.0103	-0.1122	0.0104	-0.0844	0.0103	-0.0778	0.0104	0.0000
0.8	0.0103	-0.1426	0.0104	-0.1100	0.0103	-0.1000	0.0104	0.0000
1	0.0103	-0.2346	0.0103	-0.1952	0.0103	-0.1813	0.0104	0.0000
1.25	0.0103	-0.2232	0.0104	-0.1696	0.0103	-0.1541	0.0104	0.0000
1.6	0.0103	-0.2729	0.0103	-0.2063	0.0103	-0.1883	0.0104	0.0000
2	0.0103	-0.3058	0.0103	-0.2221	0.0103	-0.1988	0.0104	0.0000
2.5	0.0103	-0.3578	0.0103	-0.2566	0.0103	-0.2251	0.0104	0.0000
3.15	0.0103	-0.3836	0.0103	-0.2552	0.0103	-0.2168	0.0104	0.0000
4	0.0103	-0.3800	0.0103	-0.2229	0.0103	-0.1725	0.0104	0.0000
5	0.0103	-0.3422	0.0103	-0.1486	0.0103	-0.0882	0.0104	0.0000
6.3	0.0103	-0.2893	0.0103	-0.0572	0.0103	0.0181	0.0104	0.0000
8	0.0103	-0.2394	0.0103	0.0341	0.0103	0.1211	0.0104	0.0000
10	0.0103	-0.2883	0.0104	0.0280	0.0104	0.1468	0.0104	0.0000
12.5	0.0104	-0.5232	0.0105	-0.1228	0.0104	-0.0061	0.0104	0.0000
16	0.0104	-0.9394	0.0105	-0.5700	0.0105	-0.4110	0.0104	0.0000
20	0.0105	-1.6129	0.0106	-1.2964	0.0106	-1.0689	0.0104	0.0000

3.13 Sensor Control Line Functionality

The T120 seismometers have several control lines that were exercised throughout the testing. These include the 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 mass re-center control line was exercised throughout the testing but special attention was paid to its functionality during the Power Consumption section. Here, the functionality of these control lines is summarized, and any identified issues are highlighted.

3.13.1 Measurand

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

3.13.2 Configuration

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

3.13.3 Analysis

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

3.13.4 Result

Table 36 summarizes the control line observations made during the evaluation.

Table 45 Summary of Control Line Functionality Verification

Sensor	Mass Recenter at 9.5V	Mass Recenter at 12V	Mass Recenter at 30V	UVW Mode Control	Calibration Enable Control
T120 Horizon 2029	Yes	Yes	Yes	Yes	Yes
T120 Horizon 2028	Yes	Yes	Yes	Yes	Yes
T120 Horizon 0769	Yes	Yes	Yes	Yes	Yes
T120 Slim BH 2024	Yes	Yes	Yes	Yes	Yes

All T120 sensors demonstrated correct control line functionality for mass re-centering, UVW Mode, and calibration enable.

4 SUMMARY

Power Consumption

The T120 Horizon sensors consumed between 0.22W to 0.49W at 12V. The T120 Slim PH sensor consumed 0.22W at 12V. The manufacturer's specification is that the T120 Horizon V2 and T120 Slim PH sensors should nominally consume 0.23W. The specification for the T120 Horizon V1 is that it nominally consumed 0.49W. All sensors were consistent with these specifications.

The sensors were fully functional when operated at input voltages of 9.5V, 12V and 30V.

Primary Sensitivity

The T120 sensors were found to have sensitivity values that were consistent with the manufacturer's specifications of a 1Hz sensitivity of 1202.5 V/(m/s) and a 1Hz phase shift of 0.5 degrees.

Primary Frequency Response

The frequency response of the T120 sensors was evaluated from 0.5Hz-20Hz for the vertical axis. For the horizontal axes the three T120 Horizon sensors' response was evaluated from 0.1Hz-20Hz while the response of the T120 Slim Posthole was evaluated from 0.1Hz to 7Hz. The measured phase response for all sensors was well within ± 5 degrees of the nominal phase response for all three axes. The measured amplitude response for all sensors was also within $\pm 5\%$ of the nominal model for all evaluated frequencies.

Comparison Sensitivity

The T120 sensors were found to have comparison sensitivity values that were consistent with the manufacturer's specifications of a 1Hz sensitivity of 1202.5 V/(m/s) and a 1Hz phase shift of 0.5 degrees.

Comparison Frequency Response

The comparison frequency response of the T120 sensors was similar to the primary frequency response although the sensors were evaluated over a wider range of frequencies from 0.02Hz to 20Hz. All sensors closely tracked the nominal response model. At the highest evaluation frequency of 20Hz some of the T120 Horizon sensors deviated slightly more than 5% from the nominal response. The T120 Slim Posthole sensor also tracked the nominal response model but showed substantially more variability in its measured amplitude response. This is likely due to the lower coherency between it and the reference STS-2 seismometer caused by non-idealities in the installation of the T120 Slim Posthole in a simulation borehole.

Passband

The T120 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 T120 sensors at 1Hz and 10Hz did not change as the power supply voltage was changed from 9.0V to 30.0V.

Sensitivity vs Input Amplitude

The response of the T120 sensors from 1Hz to 10Hz did not change as the amplitude of the velocity signal increased from 10% to 98% of the full-scale value.

Full Scale

When the T120 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 7Hz. Above 7Hz the horizontal axes of T120 Horizon V1 0769 and T120 Slim PH 2024 had elevated distortion levels which may indicate they were closer to exceeding their input rating than the Horizon V2 sensors. However, all sensors still had an amplitude and phase response that closely matched the nominal values indicating that all operated correctly at 98% of their clip level.

Self-Noise

The measured self-noise level of the vertical axis of the T120 sensors was generally below the New Low Noise Model (NLNM) from 0.02Hz to 1Hz. T120 Horizon V2 2029 had higher vertical axis noise than the other sensors at low frequencies. For the horizontal axes, the self-noise of the sensor was at or below the NLNM from 0.5Hz to 3Hz.

It is likely that the test location and non-idealities in the installation of the sensors resulted in higher noise levels and made it challenging to match the manufacture's self-noise specifications across the entire evaluation frequency range.

Dynamic Range

The measured dynamic ranges of the T120 sensors were all greater than 123.55dB which exceeds the IMS requirements of greater than 120dB. Actual seismometer dynamic range is expected to be higher than evaluated, due to the over-estimation of self-noise. The lower self-noise estimates of the vertical axes resulted in higher dynamic ranges for the vertical axes than the horizontal axes.

Calibrator Frequency Response

The calibrator frequency response of the T120s closely matched the manufacturer's specifications for all evaluated frequencies.

Sensor Control Line Functionality

The recenter, calibration enable, and UVW mode control lines of all sensors functioned correctly.

References

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APPENDIX A: TEST REFERENCES

CS18 Shake Table Specifications

CS18P Seismic Calibration System for Seismic Sensors



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 vertical	Expanded Measurement Uncertainty ²⁾ Amount ³⁾ / Phase ¹⁾	Working Range (peak value)		
from	to			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/s ²	25 Hz .. 120 Hz: 40 m/s ²
> 10 Hz	160 Hz	20 kg	1.5 % / 1.5°			120 Hz .. 400 Hz: 40 m/s ² .. 25 m/s ²
> 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/s ²	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/s ²	25 Hz .. 120 Hz: 40 m/s ²
> 10 Hz	160 Hz	20 kg	1.5 % / 1.5°			120 Hz .. 400 Hz: 40 m/s ² .. 25 m/s ²
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 78 SPEKTRA CS18P Specifications

Nominal Response Model for T120 Horizon V1, V2 and T120 Slim Posthole Sensors

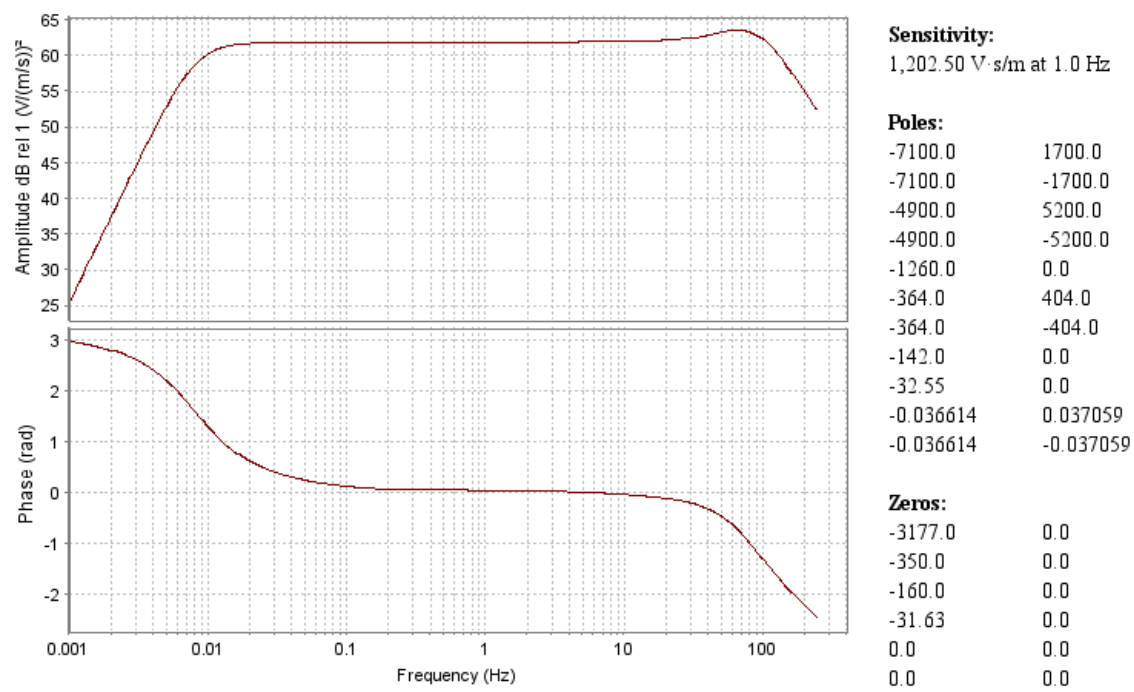


Figure 79 Nominal Response Model for T120 Sensors

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

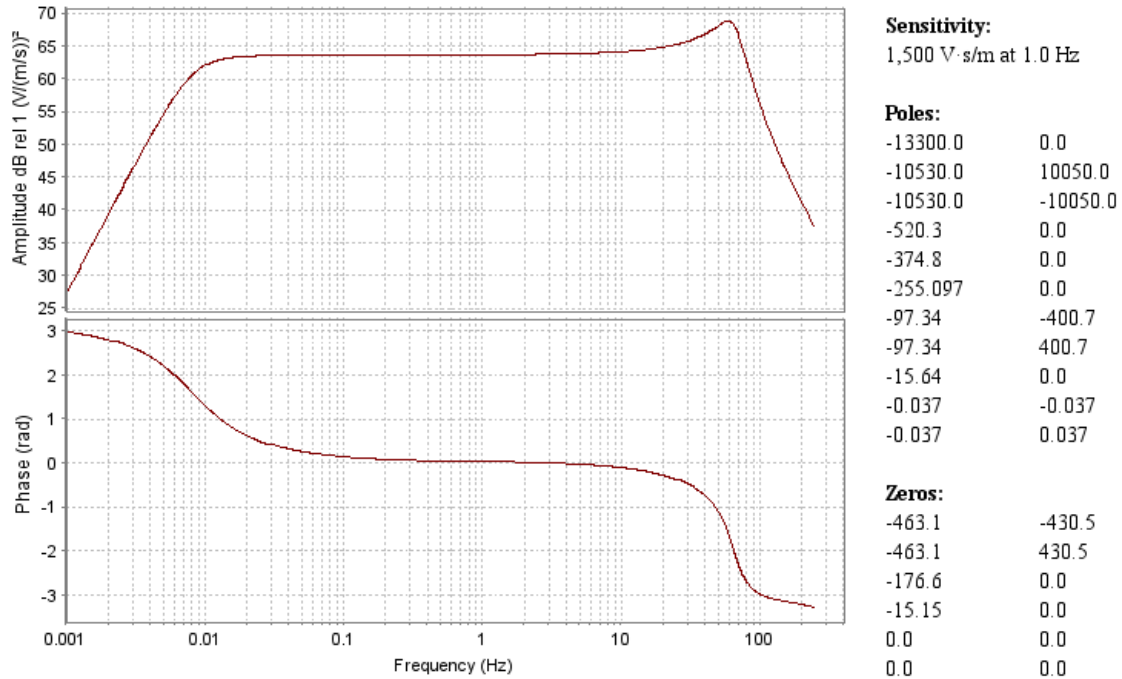


Figure 80 Nominal Response Model for STS-2 Generation 3

Table 46 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

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