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2022 MB3a Infrasound Sensor Type Approval Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated an updated version of the MB3a infrasound sensor, designed by CEA and manufactured by SeismoWave. The purpose of this infrasound sensor evaluation is to measure the performance characteristics in such areas as power consumption, sensitivity, full scale, self-noise, dynamic range, response, passband, sensitivity variation due to changes in barometric pressure and temperature, and sensitivity to acceleration. The MB3a infrasound sensors are being evaluated for use in the International Monitoring System (IMS) of the Preparatory Commission to the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

ACKNOWLEDGEMENTS

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ACRONYMS AND TERMS

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

1 INTRODUCTION

The evaluation of the 3 MB3a infrasound sensors, serial numbers 415, 417, and 420, was performed to determine the sensors performance characteristics relative to the manufacturer's specifications and IMS requirements.

Figure 1 MB3a Infrasound Sensors

The MB3a sensor was previously evaluated for approval for use within the IMS (Merchant, 2014). However, several design changes were made to the sensor by designer, CEA, and manufacturer, Seismowave, to improve its performance in operational environments.

The MB3a sensor specifications and IMS application requirements are shown in the figures below.

SEISMO WAVE

KEY FEATURES

TRANSDUCER BLOCK	
Bandwitdth (f -3 db)	Pressure output: 0,01 - 28 Hz Pressure derived output: DC - 28 Hz
BLDR (Band Limited Dynamic Range) [0,02 ; 4 Hz]	117 dB @ f< 1,6 Hz 109 dB @ f= 4 Hz
Self-noise	0,13 mPa/√Hz @ 1 Hz < 10 dB under LNM (Low Noise Model)
Resolution [0,02 ; 4 Hz]	1,75 mPaRMS
MB3a Nominal sensitivity (adjustable gain)	• Pressure output: 20 mV/Pa • Pressure derived output: 2 mV/Pa.s-1 • Calibration output: 6 Pa/V
Auxiliary outputs Temperature sensor Atmospheric pressure Sensor	• [-40 ; +110]°C, 10 mV/°C, ±0,2°C • [150 ; 1150] hPa, 1 mV/Pa • Offset stability: 0,25% full scale / uncertainty: 1,5% full scale
ANALOG HOOD	
Output range	24 V pp
Output type	Differential (symmetric)
Output impedance	2 × 50 Ω
Dynamic range	Output P (Pa) :±min (12000 [Pa/s]/2.π.f[Hz] ; 1200[Pa]) Output dP: ±12000 (Pa/s)
Power requirements	12 V DC (7-20 V) - 300 mW
ENVIRONMENTAL SPECIFICATIONS	
Operating temperature	-20°C to +50°C
Storage temperature	-30°C to +70°C
Seismic sensitivity	< 30 Pa/m.s-2
Sealing	CEI 60529-IP67 (with sealed acoustic inlets)
Shock / Drop	NF EN 60721-3-1, 2M1 (free fall, impact, shock)
Transport	NF EN 60721-3-2, 2M3 (vibration)
EMC	NF EN 55024 classes A & B (immunity) NF EN 55022 class B (emission)
PHYSICAL CHARACTERISTICS	
Weight	3 Kg
Diameter	110 mm
Height	140 mm

Datasheet MB3a V2021.1 2

Figure 2 MB3a Infrasound Sensor Specifications (SeismoWave, V2021.1)

Characteristics	Minimum Requirements
Sensor type	Microbarometer
Number of sensors	Four element array[a]
Geometry	Triangle with a component at the centre
Spacing	Triangle basis: 1 to 3 km[b]
Station location accuracy	$\leq$100 m
Relative sensor location	$\leq$1 m
Measured parameter	Absolute[c] or differential pressure
Passband	0.02 to 4 Hz
Sensor response	Flat to pressure over the passband
Sensor noise	$\leq$18 dB below minimum acoustic noise[d]
Calibration	$\leq$5% in absolute amplitude[e]
State of health	Status data transmitted to the International Data Centre
Sampling rate	$\geq$10 samples per second
Resolution	$\geq$1 count per 1 mPa
Dynamic range	$\geq$108 dB
Timing accuracy	$\leq$1 ms[f]
Standard temperature range	-10°C to $+45^{\circ}$C[g]
Buffer at the station or National Data Centre	$\geq$7 days
Data format	Group of Scientific Experts format
Data frame length	$\leq$30 s
Data transmission	Continuous
Data availability	$\geq$98%
Timely data availability	$\geq$97%
Mission capable array	$\geq$3 elements operational
Acoustic filtering	Noise reduction pipes (site dependent)
Auxiliary data	Meteorological data[h]

[a] In the case of noisy sites or when increased capability is required, the number of components could be increased.
[b] 3 km is the recommended spacing.
[c] Used for daily state of health.
[d] Minimum noise level at 1 Hz: ~5 mPa.
[e] Periodicity: once per year (minimum).
[f] Better than or equal to 1 ms.
[g] Temperature range to be adapted for some specific sites.
[h] Once per minute.

Figure 3 Minimum Requirements for Infrasound Station Specifications (CTBT/WGB/TL-11,17/17/Rev.5)

2 TEST PLAN

2.1 Test Facility

Testing was performed at Sandia National Laboratories' Facility for Acceptance, Calibration and Testing (FACT) located near Albuquerque, New Mexico, USA. The FACT site is at approximately 1830 meters in elevation.

Sandia National Laboratories (SNL), Ground-based Monitoring R&E Department has the capability of evaluating the performance of seismometers, infrasound sensors, preamplifiers, digitizing waveform recorders, and analog-to-digital converters/high-resolution digitizers for geophysical applications.

Tests are based on 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.

Testing was performed within the FACT Site's 1400L infrasound test chamber, seismic calibration table, and thermal chamber.

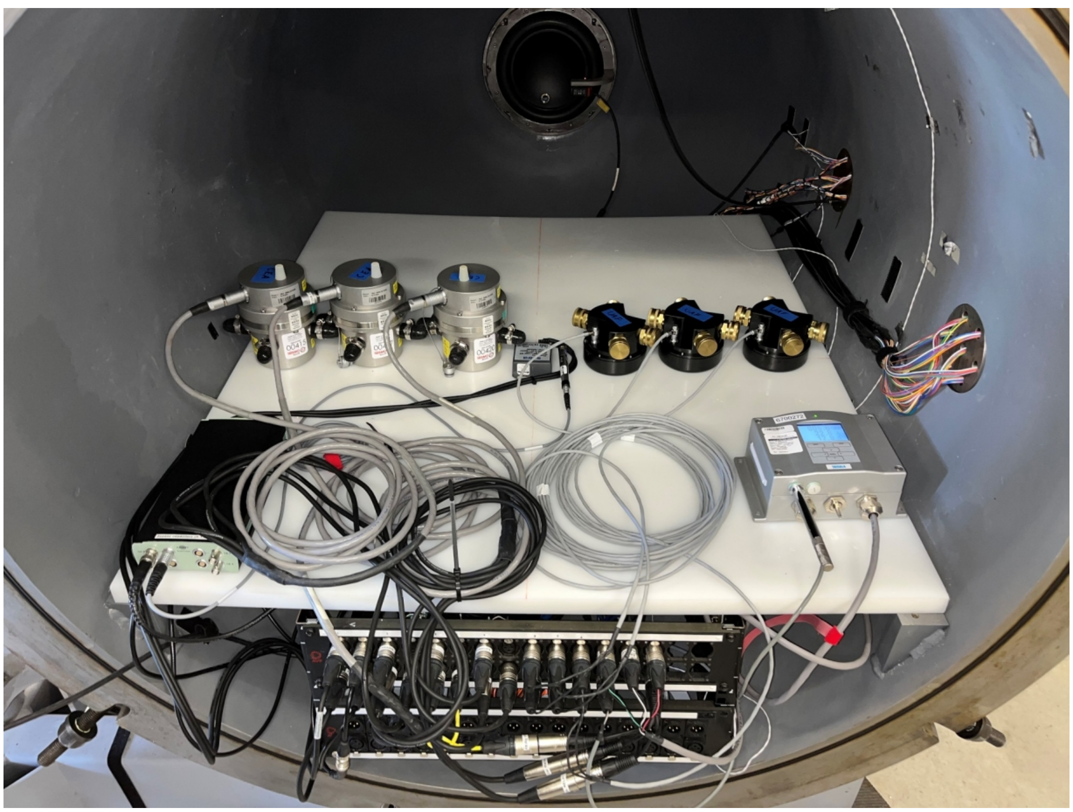

Figure 4 SNL 1400L Infrasound Chamber

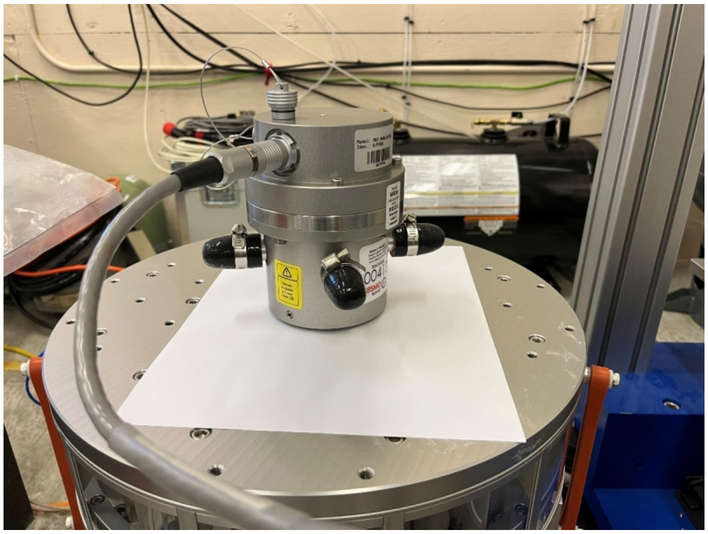

Figure 5 SNL Seismic Calibration Table

Figure 6 SNL Thermal Chamber

The temperature, pressure, and relative humidity was recorded continuously throughout the testing within the testing environment by several calibrated Vaisala PTU-300.

Figure 7 Vaisala PTU300 Temperature, Pressure, and RH within Infrasound Chamber

The sensors were all powered from a laboratory power supply, separate from the data recorder and reference sensors, configured to output 13 V.

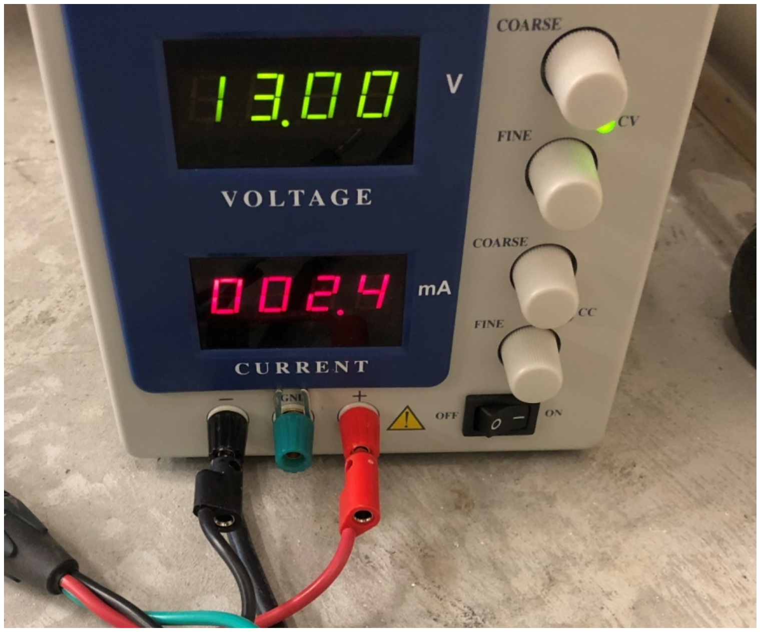

Figure 8 Lab Power Supply

2.2 Scope

The following table lists the tests and resulting evaluations that were performed. The laboratory infrasound portions of the test sequence were performed at controlled conditions at 820 hPa or 1013 hPa static pressures and 23 C temperature. Extended measurements of variability to environmental conditions were made over +/- 50 hPa and -20 C to 50 C.

Table 1 Tests performed

Test
Power Consumption
Sensitivity at 1 Hz and 0.25 Hz
Frequency Response (Tonal, 0.01 – 10 Hz)
Passband
Sensitivity vs power supply voltage
Sensitivity vs input amplitude
Full Scale
Self-Noise
Dynamic Range
Calibrator Frequency Response
Static Temperature Response Variation
Static Pressure Response Variation
Response to Acceleration

2.3 Timeline

Testing was performed at Sandia National Laboratories from February 18 to March 1, 2022:

Table 2 Timeline of Testing

Day	Time (UTC)	Description
February 18, 2022		Adjusted sensors to a 1013 hPa barometric pressure. Setup sensors within infrasound chamber.
February 21, 2022	Afternoon	Pressurized 1400 L chamber to sea level Measured sensor power consumption Measured sensor sensitivity vs power supply voltage
	Overnight	Measured frequency response using discrete tones over 0.01 to 20 Hz at 1013 hPa barometric pressure
February 22, 2022	Morning	Measured limited frequency response over barometric pressures ranging from 963 hPa to 1063 hPa
	Afternoon	Demonstrated MB3a self-calibrator functionality. Reduced chamber pressure to ambient (820 hPa), readjusted MB3a sensors to ambient, and re-installed in infrasound chamber.
	Overnight	Capped sensors and measured sensor self-noise inside sealed chamber
February 23, 2022	Morning	Measured sensor response to vertical acceleration
	Afternoon	Measured sensor frequency response at ambient barometric pressure in infrasound chamber.
	Overnight	Measured sensor linearity using external pressure calibrator.
February 24, 2022		Measured sensor full-scale using external pressure calibrator.
February 25, 2022		Installed sensors in thermal chamber to measure the change in frequency response over -20 C to +50 C
March 1, 2022		Testing completed

2.4 Evaluation Frequencies

The frequency range of the measurements is from 0.01 Hz to 10 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 = -20, -19, …, 16, 10. The nominal center frequency values, in Hz, are:

0.01,	0.0125,	0.016,	0.020,	0.025,	0.0315,	0.040,	0.050,	0.063,	0.08,
0.10,	0.125,	0.16,	0.20,	0.25,	0.315,	0.40,	0.50,	0.63,	0.8,
1.0,	1.25,	1.6,	2.0,	2.5,	3.15,	4.0,	5.0,	6.3,	8.0,
10.0									

3 TEST EVALUATION

3.1 Power Consumption

The Power Consumption test is used to measure the amount of power that an actively powered sensor consumes during its operation.

3.1.1 Measurand

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

3.1.2 Configuration

The digitizer is connected to a power supply, current meter, and voltage meter as shown in the diagram below.

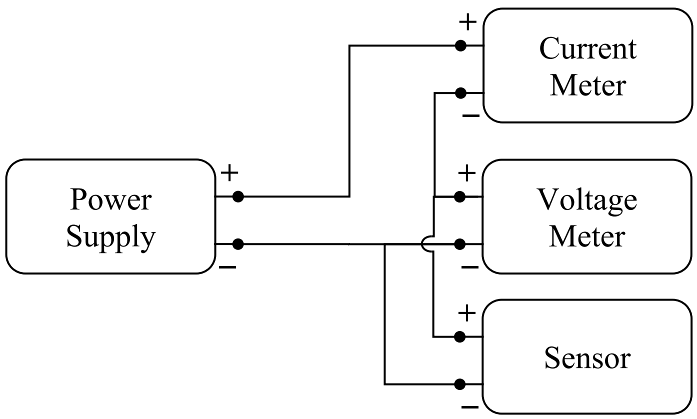

Figure 9 Power Consumption Configuration Diagram

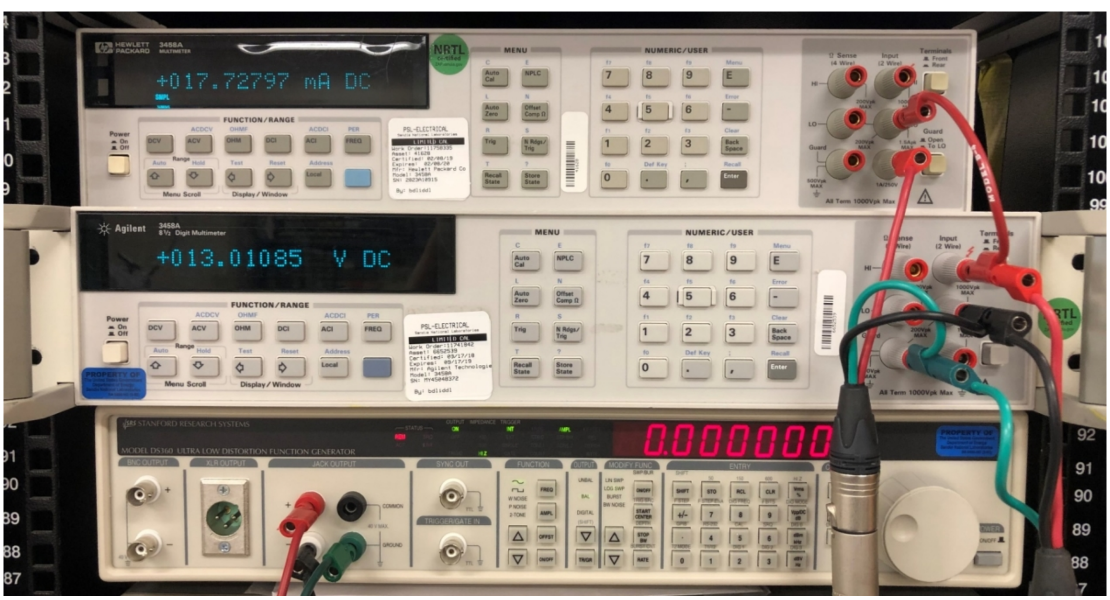

Figure 10 Power Consumption Configuration Picture

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	HP 3458A	2823A10915	DC Voltage Mode
Current Meter	Agilent 3458A	MY45048372	DC Current Mode

The meters used to measure current and voltage 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 voltage and current.

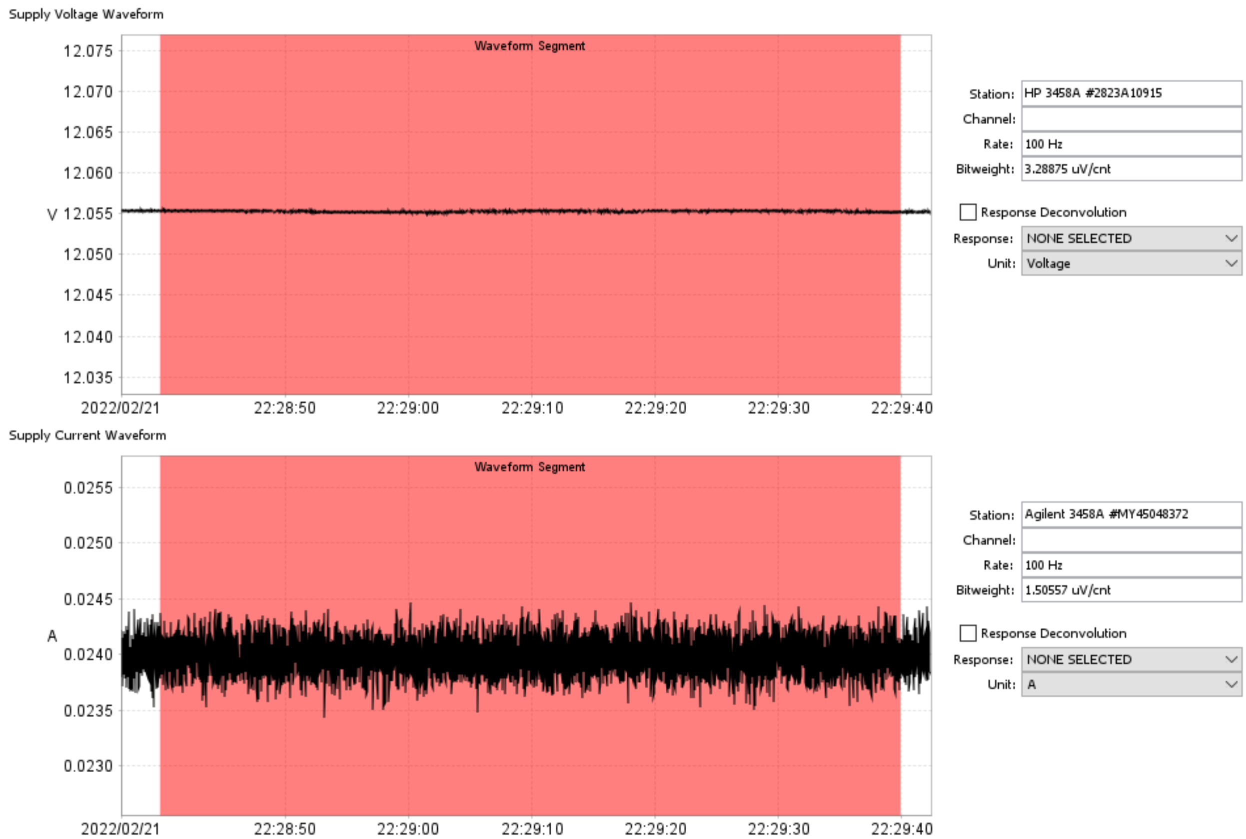

Figure 11 Power Consumption Voltage and Current Time Series

The resulting voltage, current, and power consumption levels are shown in the table below.

Table 4 Power Consumption Results

	Supply Voltage	Supply Voltage Standard Deviation	Supply Current	Supply Current Standard Deviation	Power	Power Standard Deviation
MB3a #415	12.06 V	0.08 mV	23.99 mA	0.15 mA	0.2891 W	1.82 mW
MB3a #417	12.06 V	3.25 mV	23.64 mA	0.23 mA	0.2850 W	2.88 mW
MB3a #420	12.06 V	0.10 mV	24.13 mA	0.26 mA	0.2909 W	3.19 mW

The MB3a infrasound sensors were observed to consume approximately 0.29 W of power at a 12 V supply. These results are consistent with the 0.3 W of consumption mentioned in the manufacturer's datasheet.

3.2 Sensitivity

The sensitivity of a sensor is defined to be the ratio between the change in the output voltage and the corresponding change in the quantity being measured.

3.2.1 Measurand

The quantity being measured is the sensor's sensitivity in V/Pa and degrees at a reference frequency.

3.2.2 Configuration

The infrasound sensor under test and a reference sensor with known response characteristics are placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in temperature or pressure and provide air coupling between the sensor inlets.

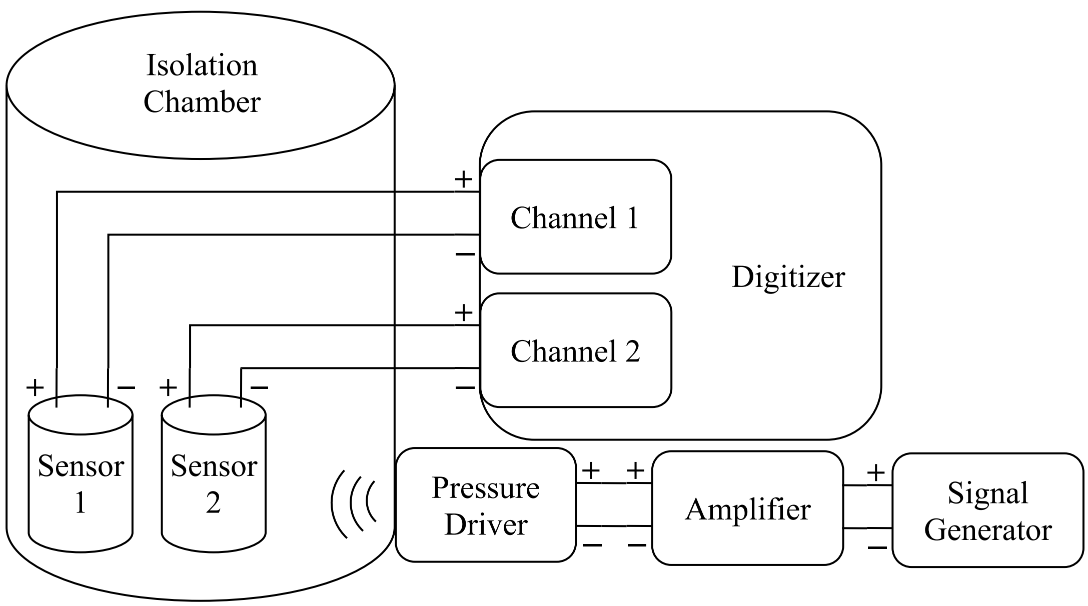

Figure 12 Sensitivity Configuration Diagram

A pressure driver is attached the isolation chamber. The pressure driver is driven with a sinusoid from a signal generator and amplifier. The pressure driver serves to generate a pressure wave with characteristics defined by the signal generator. This pressure wave is recorded by both the reference sensor and the sensor under test.

Table 5 Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	3085404	2.115 mV/Pa at 1 Hz, 1013 hPa, 23 C, >= 0.5 Hz
Reference Sensor	Setra 278	7632595	0.0832926 mV/Pa, 1013 hPa, 23 C, < 0.5 Hz
Infrasound Chamber	SNL	1400 L Chamber	1013 hPa, 23 C
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	0.25 Hz and 1 Hz, 0.4 Vp sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A

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

3.2.3 Analysis

A minimum of 10 cycles, or 10 seconds at 1 Hz, is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f/2 to f*2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in Volts to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

$$V_{test} \sin(2\, pi\, f_{test}\, t + \theta_{test}) + V_{dc\, test}$$

The sensor amplitude sensitivity in Volts / Pascal is computed:

$$Sensitivity = \frac{V_{test}}{P_{ref}}$$

The sensor phase sensitivity in degrees is computed:

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

Measurements were averaged over 4 different times with 10 iterations each time, for a total of 40 iterations.

3.2.4 Result

The figure below shows a representative waveform time series for the recording made on the reference sensor and sensors under test. The window regions bounded by the colored lines indicate the segment of data used for analysis.

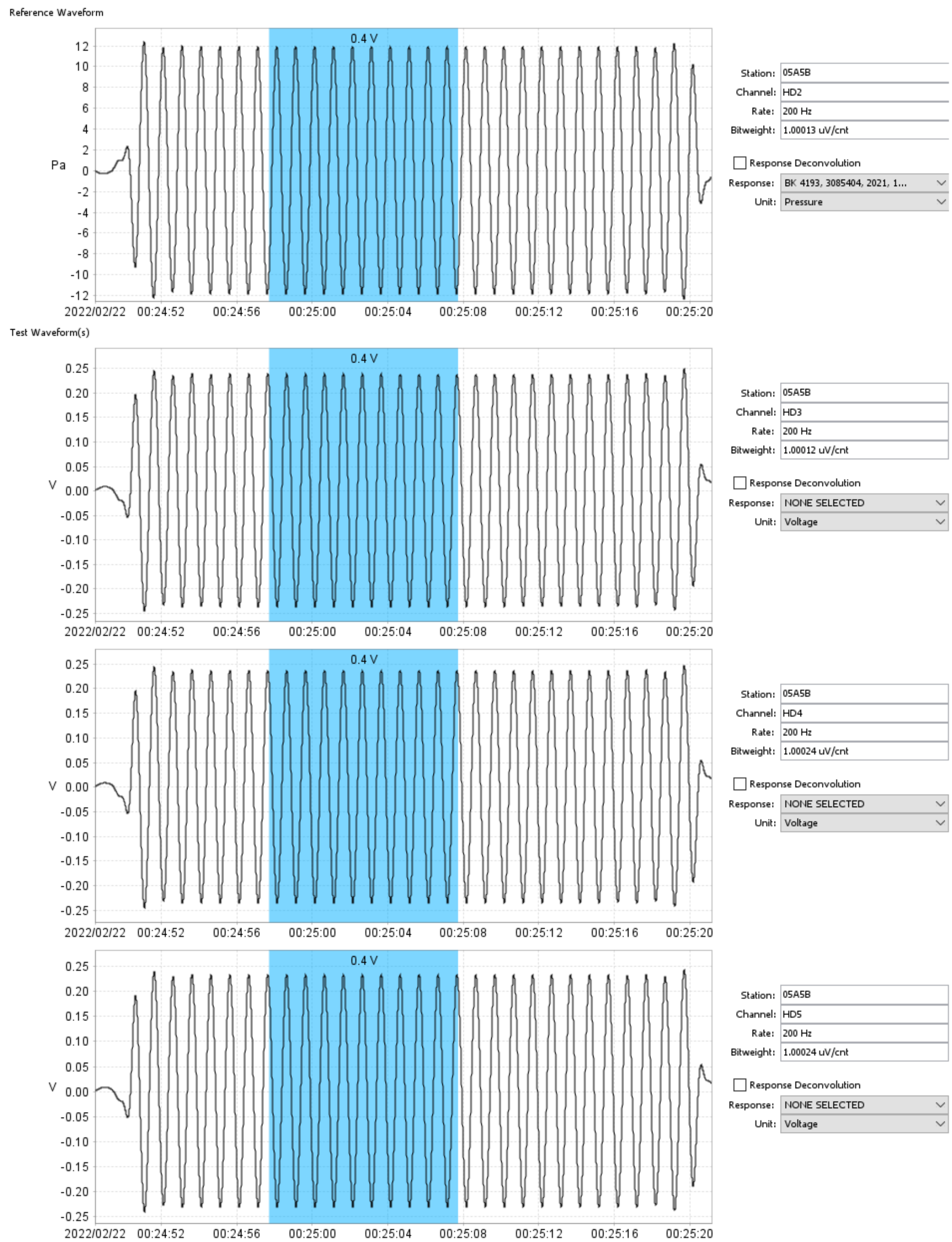

Figure 13 Sensitivity Time Series

The top waveform is the reference, with the unit of Pascals of pressure, and the remaining waveforms are from the sensors under test, with units in Volts.

The following table contains the nominal value, estimated combined measurement uncertainty, and computed result for each of the sensors under test. The sensitivities were tested at a dynamic pressure amplitude of approximately 12 Pa.

Table 6 Sensitivity at 1 Hz

	Amplitude	Phase
Nominal	20.00 mV/Pa	-1.18 deg
Uncertainty (k=2)	+/- 0.92%	+/- 0.31 deg
MB3a #415	19.97 mV/Pa	-1.57 deg
MB3a #417	19.81 mV/Pa	-1.60 deg
MB3a #420	19.53 mV/Pa	-1.55 deg

Table 7 Sensitivity at 0.25 Hz

	Amplitude	Phase
Nominal	19.99 mV/Pa	1.87 deg
Uncertainty (k=2)	+/- 1.04%	+/- 1.04 deg
MB3a #415	19.88 mV/Pa	1.98 deg
MB3a #417	19.72 mV/Pa	1.99 deg
MB3a #420	19.44 mV/Pa	1.98 deg

The measured sensitivities were all close to the nominal value, within 2.4% and 0.4 degrees at 1 Hz and within 2.75% and 0.1 degrees at 0.25 Hz. The differences from the nominal amplitude sensitivity are greater than the estimated uncertainty, indicating that these sensors amplitude sensitivity is slightly lower than nominal. However, the phase differences are within the estimated uncertainty, indicating that they closely match the nominal phase

3.3 Frequency Response

The sensor frequency response is defined as being the linear time-invariant (LTI) change in the sensor output signal amplitude and phase relative to an input pressure signal.

3.3.1 Measurand

Response including the amplitude expressed in dB relative to the reference frequency and the phase expressed in degrees over the defined frequencies.

3.3.2 Configuration

The infrasound sensor under test and a reference sensor with known response characteristics are placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in temperature or pressure and provide air coupling between the sensor inlets.

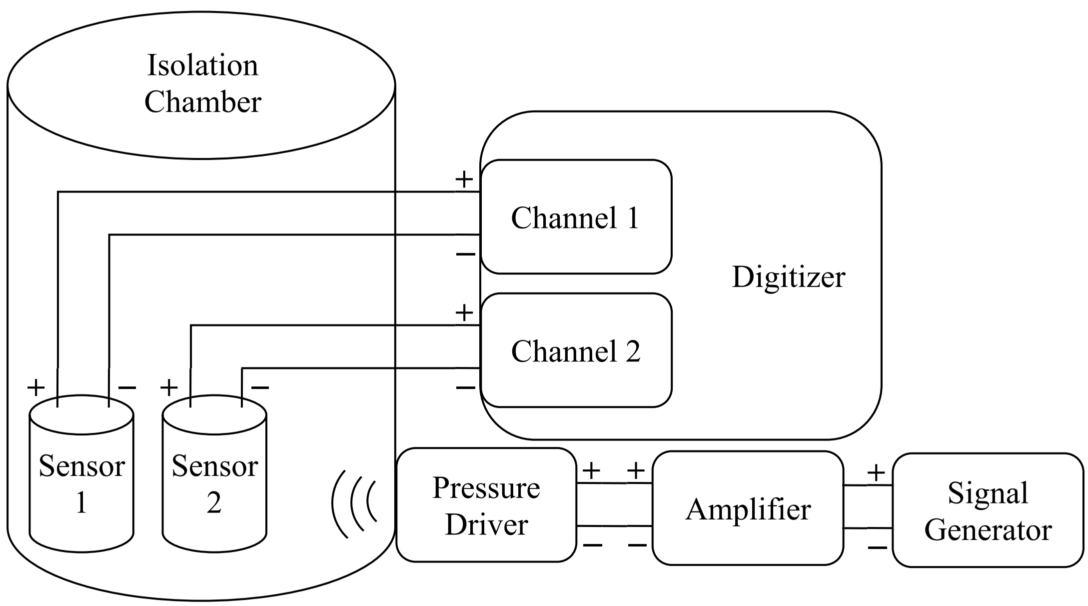

Figure 14 Frequency Response Configuration Diagram

A pressure driver is attached to an inlet port on the isolation chamber. The pressure driver is driven with a sinusoid from a signal generator. The pressure driver serves to generate a pressure wave with characteristics defined by the signal generator. This pressure wave is recorded by both the reference sensor and the sensor under test.

Table 8 Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	3085404	2.115 mV/Pa at 1 Hz, 1013 hPa, 23 C, >= 0.5 Hz
Reference Sensor	Setra 278	7632595	0.0832926 mV/Pa, 1013 hPa, 23 C, < 0.5 Hz
Infrasound Chamber	SNL	1400 L Chamber	1013 hPa, 23 C
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	0.01 Hz – 10 Hz, 0.4 Vp sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A

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

The Setra 278 was used as the reference for frequencies below 0.5 Hz and the B&K 4193 microphone was used as the reference for frequencies at 0.5 Hz and above. Combined, the two references span the 0.01 to 10 Hz evaluation passband.

This test was performed with a set of tones that span the evaluation frequencies in a randomized order.

3.3.3 Analysis

For the tonal analysis, a minimum of 10 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f/2 to f*2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in volts to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

$$V_{test} \sin(2\, pi\, f_{test}\, t + \theta_{test}) + V_{dc\, test}$$

The sensor amplitude sensitivity in Volts / Pascal is computed:

$$Sensitivity = \frac{V_{test}}{P_{ref}}$$

The sensor phase sensitivity in degrees is computed:

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

Measurements of amplitude and phase sensitivity versus frequency were averaged over 4 measurements at different time periods.

As a final step, 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.

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

3.3.4 Result

The figure below shows a representative waveform time series for the tonal recording made on the reference sensor and a sensor under test. The window regions bounded by the colored lines indicate the segment of data used for analysis.

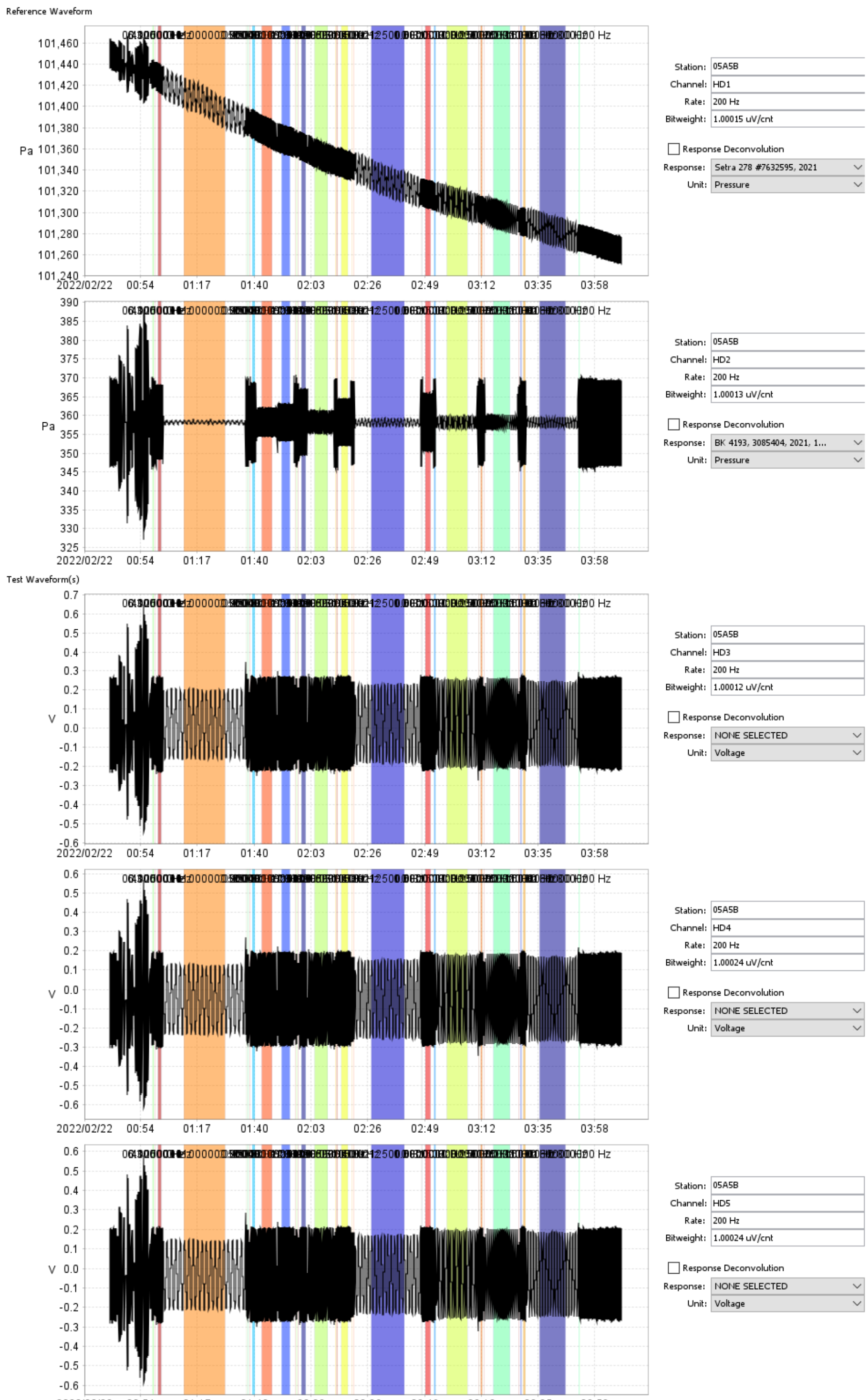

Figure 15 Frequency Response Time Series

The top two waveforms are the references, with the unit of Pascals of pressure, and the remaining waveforms are from the sensors under test, with units in Volts. Note that the order of the frequencies was randomized to prevent any environmental changes in time from being correlated with signal frequency.

The following plots show the amplitude and phase responses that were measured.

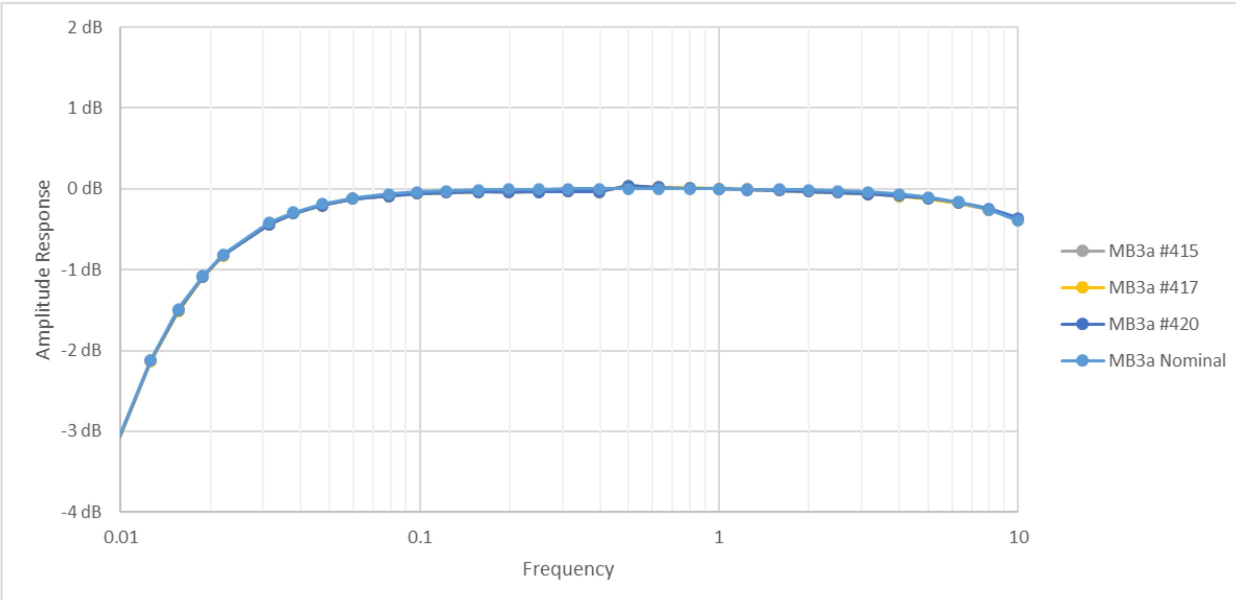

Figure 16 Amplitude Response

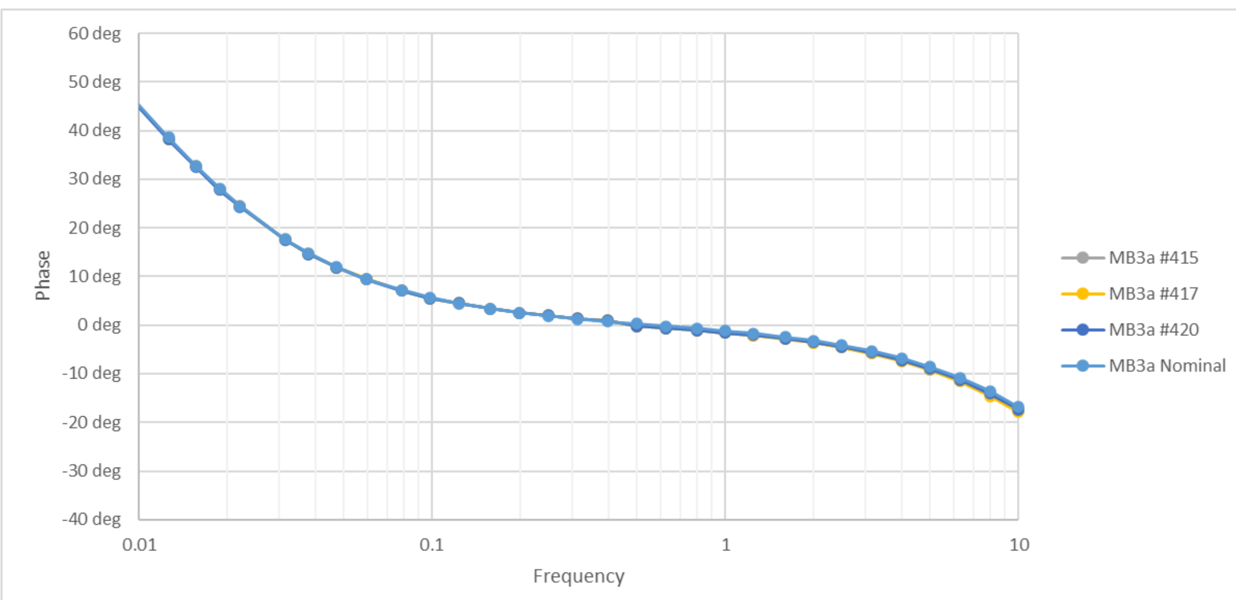

Figure 17 Phase Response

The amplitude and phase responses correspond well with the nominal model provided by CEA. A slight transition in the amplitude response is observable at 0.5 Hz where we switched between the Setra and B&K 4193 references.   However, this change is well within the combined measurement uncertainty.

Over the 0.02 Hz to 4 Hz infrasound passband, all three sensors were consistent with the nominal model to within +/- 0.04 dB (0.5 %) and +/- 0.5 degrees, within the range of the combined measurement uncertainty.

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

Table 9 Amplitude Response

Frequency	MB3a #415	MB3a #417	MB3a #420	Nominal	Uncertainty (k=2)
0.0094 Hz	-3.28 dB	-3.29 dB	-3.28 dB	-3.28 dB	0.067 dB
0.0126 Hz	-2.12 dB	-2.13 dB	-2.12 dB	-2.12 dB	0.067 dB
0.0156 Hz	-1.51 dB	-1.52 dB	-1.51 dB	-1.48 dB	0.067 dB
0.0188 Hz	-1.09 dB	-1.09 dB	-1.08 dB	-1.08 dB	0.067 dB
0.0220 Hz	-0.82 dB	-0.83 dB	-0.82 dB	-0.81 dB	0.067 dB
0.0314 Hz	-0.44 dB	-0.44 dB	-0.44 dB	-0.41 dB	0.067 dB
0.0378 Hz	-0.30 dB	-0.30 dB	-0.30 dB	-0.29 dB	0.067 dB
0.0472 Hz	-0.21 dB	-0.21 dB	-0.21 dB	-0.19 dB	0.067 dB
0.0598 Hz	-0.12 dB	-0.12 dB	-0.12 dB	-0.11 dB	0.067 dB
0.0789 Hz	-0.09 dB	-0.09 dB	-0.09 dB	-0.06 dB	0.070 dB
0.0978 Hz	-0.05 dB	-0.05 dB	-0.06 dB	-0.04 dB	0.072 dB
0.1231 Hz	-0.05 dB	-0.05 dB	-0.05 dB	-0.02 dB	0.072 dB
0.1577 Hz	-0.04 dB	-0.04 dB	-0.04 dB	-0.01 dB	0.078 dB
0.199 Hz	-0.04 dB	-0.04 dB	-0.04 dB	-0.01 dB	0.084 dB
0.249 Hz	-0.03 dB	-0.03 dB	-0.03 dB	0.00 dB	0.090 dB
0.312 Hz	-0.03 dB	-0.03 dB	-0.03 dB	0.00 dB	0.097 dB
0.40 Hz	-0.04 dB	-0.04 dB	-0.04 dB	0.00 dB	0.101 dB
0.50 Hz	0.04 dB	0.04 dB	0.04 dB	0.00 dB	0.080 dB
0.63 Hz	0.02 dB	0.02 dB	0.02 dB	0.00 dB	0.080 dB
0.80 Hz	0.01 dB	0.01 dB	0.01 dB	0.00 dB	0.080 dB
1.00 Hz	0.00 dB	0.00 dB	0.00 dB	0.00 dB	0.080 dB
1.25 Hz	-0.01 dB	-0.01 dB	-0.01 dB	0.00 dB	0.080 dB
1.60 Hz	-0.02 dB	-0.02 dB	-0.02 dB	-0.01 dB	0.080 dB
2.00 Hz	-0.03 dB	-0.03 dB	-0.03 dB	-0.01 dB	0.080 dB
2.50 Hz	-0.04 dB	-0.04 dB	-0.04 dB	-0.02 dB	0.080 dB
3.15 Hz	-0.06 dB	-0.06 dB	-0.06 dB	-0.04 dB	0.080 dB
4.00 Hz	-0.09 dB	-0.09 dB	-0.09 dB	-0.06 dB	0.080 dB
5.00 Hz	-0.12 dB	-0.12 dB	-0.12 dB	-0.10 dB	0.080 dB
6.30 Hz	-0.17 dB	-0.17 dB	-0.17 dB	-0.16 dB	0.080 dB
8.00 Hz	-0.25 dB	-0.26 dB	-0.24 dB	-0.26 dB	0.080 dB
10.00 Hz	-0.38 dB	-0.39 dB	-0.36 dB	-0.39 dB	0.080 dB

Table 10 Phase Response

Frequency	MB3a #415	MB3a #417	MB3a #420	Nominal	Uncertainty (k=2)
0.0094 Hz	46.64 deg	46.71 deg	46.59 deg	46.91 deg	6.71 deg
0.0126 Hz	38.24 deg	38.32 deg	38.21 deg	38.58 deg	5.26 deg
0.0156 Hz	32.62 deg	32.70 deg	32.59 deg	32.71 deg	4.32 deg
0.0188 Hz	27.82 deg	27.89 deg	27.80 deg	28.11 deg	3.63 deg
0.0220 Hz	24.37 deg	24.42 deg	24.34 deg	24.53 deg	3.29 deg
0.0314 Hz	17.56 deg	17.60 deg	17.54 deg	17.68 deg	2.68 deg
0.0378 Hz	14.61 deg	14.65 deg	14.59 deg	14.83 deg	2.22 deg
0.0472 Hz	11.80 deg	11.83 deg	11.79 deg	11.95 deg	1.95 deg
0.0598 Hz	9.43 deg	9.45 deg	9.42 deg	9.43 deg	1.52 deg
0.0789 Hz	7.05 deg	7.06 deg	7.04 deg	7.12 deg	1.48 deg
0.0978 Hz	5.45 deg	5.47 deg	5.45 deg	5.69 deg	1.37 deg
0.1231 Hz	4.53 deg	4.54 deg	4.53 deg	4.46 deg	1.32 deg
0.1577 Hz	3.39 deg	3.40 deg	3.39 deg	3.37 deg	1.14 deg
0.199 Hz	2.49 deg	2.49 deg	2.49 deg	2.54 deg	0.94 deg
0.249 Hz	2.03 deg	2.03 deg	2.03 deg	1.87 deg	1.04 deg
0.312 Hz	1.38 deg	1.37 deg	1.38 deg	1.30 deg	0.94 deg
0.40 Hz	0.91 deg	0.90 deg	0.91 deg	0.75 deg	1.06 deg
0.50 Hz	-0.21 deg	-0.22 deg	-0.20 deg	0.28 deg	0.33 deg
0.63 Hz	-0.66 deg	-0.67 deg	-0.65 deg	-0.18 deg	0.30 deg
0.80 Hz	-1.10 deg	-1.13 deg	-1.09 deg	-0.68 deg	0.31 deg
1.00 Hz	-1.57 deg	-1.60 deg	-1.55 deg	-1.18 deg	0.31 deg
1.25 Hz	-2.10 deg	-2.13 deg	-2.07 deg	-1.73 deg	0.31 deg
1.60 Hz	-2.79 deg	-2.84 deg	-2.75 deg	-2.44 deg	0.31 deg
2.00 Hz	-3.59 deg	-3.65 deg	-3.54 deg	-3.21 deg	0.32 deg
2.50 Hz	-4.53 deg	-4.60 deg	-4.45 deg	-4.13 deg	0.33 deg
3.15 Hz	-5.75 deg	-5.83 deg	-5.65 deg	-5.32 deg	0.34 deg
4.00 Hz	-7.31 deg	-7.42 deg	-7.19 deg	-6.81 deg	0.36 deg
5.00 Hz	-9.11 deg	-9.25 deg	-8.96 deg	-8.58 deg	0.39 deg
6.30 Hz	-11.41 deg	-11.59 deg	-11.23 deg	-10.76 deg	0.43 deg
8.00 Hz	-14.34 deg	-14.57 deg	-14.11 deg	-13.55 deg	0.49 deg
10.00 Hz	-17.65 deg	-17.93 deg	-17.37 deg	-16.78 deg	0.57 deg

3.4 Passband

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

3.4.1 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 half, the measured sensitivity at 1Hz.

3.4.2 Configuration

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

3.4.3 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.

3.4.4 Result

The following table contains the passband limits of the MB3a sensors.

Table 11 Passband

	Lower Limit	Upper Limit
MB3a #415	0.0101 Hz	> 10 Hz
MB3a #417	0.0101 Hz	> 10 Hz
MB3a #420	0.0101 Hz	> 10 Hz

All the MB3a sensors had a lower passband limit at 0.0101 Hz. Their upper limit was above the 10 Hz range over which the frequency response was evaluated. These results are consistent with the specifications from the manufacturer and cover the minimum requirement IMS passband of 0.02 to 4 Hz.

3.5 Sensitivity vs power supply voltage

The sensitivity vs power supply voltage is measured as an indicator of linearity with respect to power supply voltage. The pressure sensitivity values are measured at a calibration frequency across several increments of the power supply voltage.

3.5.1 Measurand

The quantity being measured is the change in sensitivity versus input pressure, expressed as a percent in amplitude and degrees difference in phase.

3.5.2 Configuration

The infrasound sensor under test and a reference sensor with known response characteristics are placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in temperature or pressure and provide air coupling between the sensor inlets.

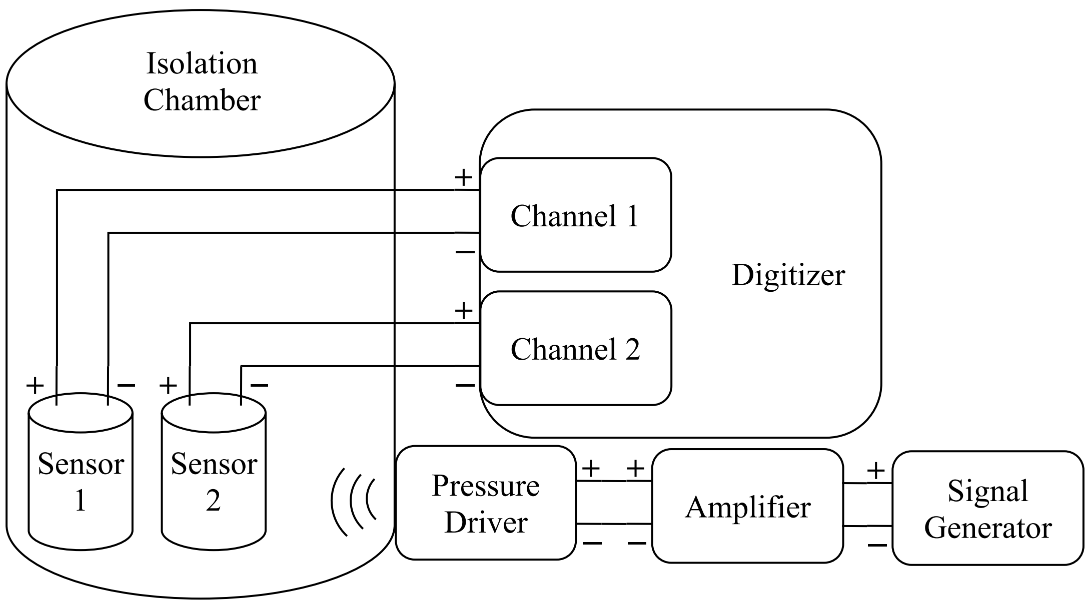

Figure 18 Sensitivity vs Input Amplitude Configuration Diagram

A pressure driver is attached to the isolation chamber. The pressure driver is driven with a sinusoid from a signal generator and amplifier. The pressure driver serves to generate a pressure wave with characteristics defined by the signal generator. This pressure wave is recorded by both the reference sensor and the sensor under test.

The power supply voltage is incremented from 9 V to 20 V in 1 V increments, with a minimum of a 5-minute pause at each voltage level to allow the sensor electronics to stabilize. Note that the digitizer and reference sensors are powered off a separate power supply maintaining a stable voltage throughout.

Table 12 Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	3085404	2.115 mV/Pa at 1 Hz, 1013 hPa, 23 C
Infrasound Chamber	SNL	1400 L Chamber	1013 hPa, 23 C
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	1 Hz, 0.4 Vp sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Power Supply	Protek DC Power Supply 3003B	N/A	9 V – 20 V, in 1 V increments
Pressure Driver	JL Audio 10w7ae	N/A	N/A

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

3.5.3 Analysis

A minimum of 10 cycles, or 10 seconds at 1 Hz, is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f/2 to f*2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in Volts to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

The sensor amplitude sensitivity in Volts / Pascal is computed:

$$S_{amp} = \frac{V_{test}}{P_{ref}}$$

The sensor phase sensitivity in degrees is computed:

$$S_{phase} = \theta_{test} - \theta_{ref}$$

The change in sensitivity, expressed as a percentage in amplitude and degrees in phase, at each amplitude level are computed relative to a reference measurement:

$$Change\ S_{amp}(Ampl) = 100 * \frac{(S_{amp}(Ampl) - S_{amp}(Ref\ Ampl))}{S_{amp}(Ref\ Ampl)}$$

$$Change\ S_{phase}(Ampl) = S_{phase}(Ampl) - S_{phase}(Ref\ Ampl)$$

3.5.4 Result

The following charts represents the changes in amplitude and phase sensitivity, relative to the measurement at 12 V, that were observed across the power supply voltage ranges.

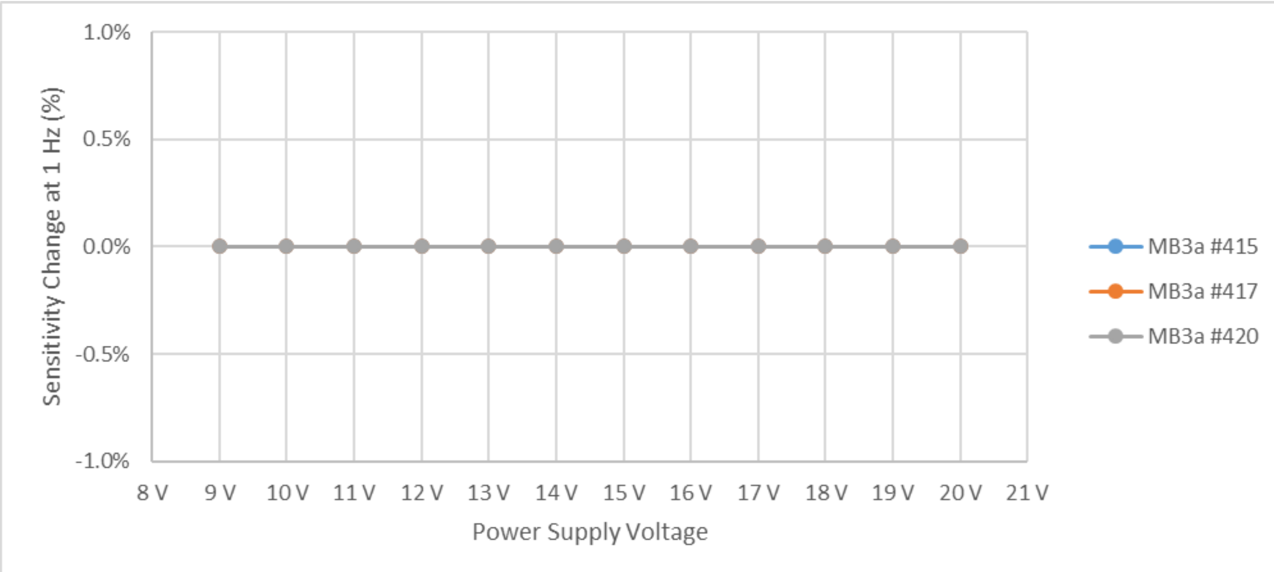

Figure 19 Amplitude vs Power Supply Voltage

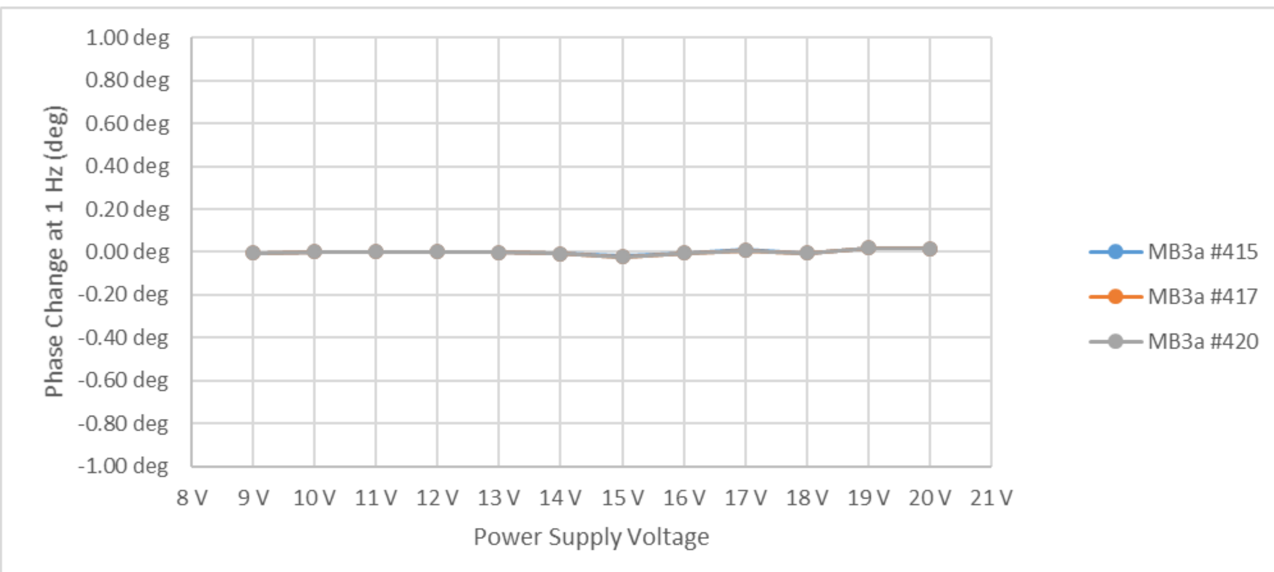

Figure 20 Phase vs Power Supply Voltage

We observe that there is no significant variation in the amplitude or phase sensitivity due to changes in the power supply voltage across 9 V to 20 V.

The following tables contains the values used to generate the above plots. The combined relative measurement uncertainties at 1 Hz are 0.3 % and 0.1 degrees.

Table 13 Change in Amplitude vs Power Supply Voltage

Power Supply Voltage	MB3a #415	MB3a #417	MB3a #420
9 V	0.00%	0.00%	0.00%
10 V	0.00%	0.00%	0.00%
11 V	0.00%	0.00%	0.00%
12 V	0.00%	0.00%	0.00%
13 V	0.00%	0.00%	0.00%
14 V	0.00%	0.00%	0.00%
15 V	0.00%	0.00%	0.00%
16 V	0.00%	0.00%	0.00%
17 V	0.00%	0.00%	0.00%
18 V	0.00%	0.00%	0.00%
19 V	0.00%	0.00%	0.00%
20 V	0.00%	0.00%	0.00%

Table 14 Change in Phase vs Power Supply Voltage

Power Supply Voltage	MB3a #415	MB3a #417	MB3a #420
9 V	0.00 deg	-0.01 deg	-0.01 deg
10 V	0.00 deg	0.00 deg	0.00 deg
11 V	0.00 deg	0.00 deg	0.00 deg
12 V	0.00 deg	0.00 deg	0.00 deg
13 V	0.00 deg	0.00 deg	0.00 deg
14 V	-0.01 deg	-0.01 deg	-0.01 deg
15 V	-0.02 deg	-0.02 deg	-0.02 deg
16 V	0.00 deg	-0.01 deg	-0.01 deg
17 V	0.01 deg	0.01 deg	0.01 deg
18 V	0.00 deg	-0.01 deg	-0.01 deg
19 V	0.02 deg	0.02 deg	0.02 deg
20 V	0.02 deg	0.02 deg	0.02 deg

3.6 Sensitivity vs input amplitude

The sensitivity vs input amplitude is measured as an indicator of linearity with respect to amplitude. The pressure sensitivity values are measured at a calibration frequency across several increments of dynamic input pressure amplitude.

3.6.1 Measurand

The quantity being measured is the change in sensitivity versus input pressure, expressed as a percent in amplitude and degrees difference in phase.

3.6.2 Configuration

The infrasound sensor under test and a reference sensor with known response characteristics are placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in temperature or pressure and provide air coupling between the sensor inlets.

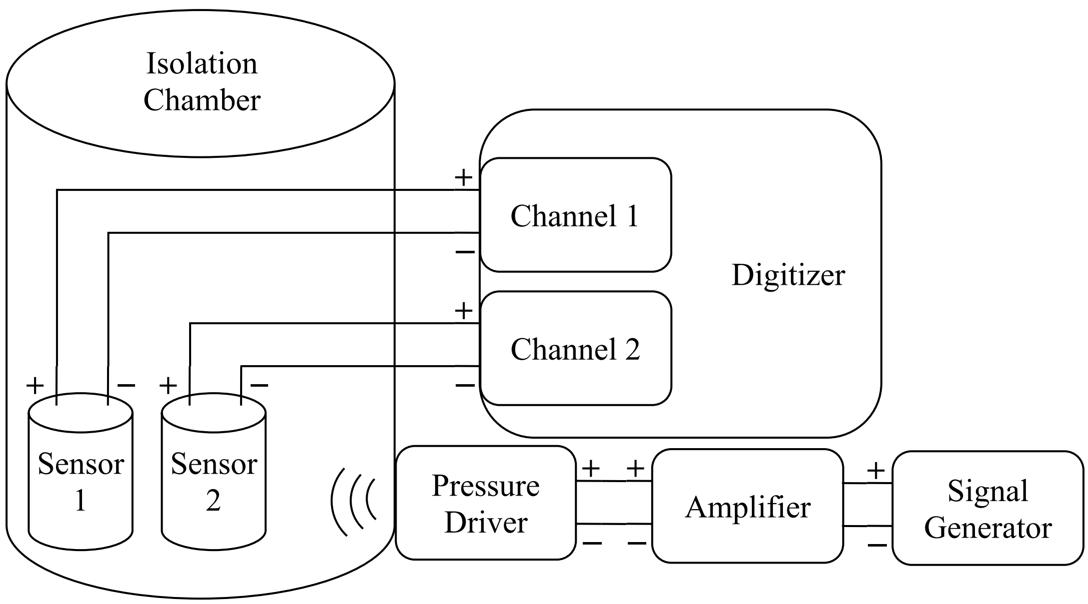

Figure 21 Sensitivity vs Input Amplitude Configuration Diagram

A pressure driver is attached to the isolation chamber. The pressure driver is driven with a sinusoid from a signal generator and amplifier. The pressure driver serves to generate a pressure wave with characteristics defined by the signal generator. This pressure wave is recorded by both the reference sensor and the sensor under test.

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

Table 15 Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	3085404	2.115 mV/Pa at 1 Hz, 1013 hPa, 23 C, >= 0.5 Hz
Infrasound Chamber	SNL	1400 L Chamber	1013 hPa, 23 C
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	0.25 Hz and 1 Hz, 0.4 Vp sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A

3.6.3 Analysis

A minimum of 10 cycles, or 10 seconds at 1 Hz, is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f/2 to f*2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in Volts to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

The sensor amplitude sensitivity in Volts / Pascal is computed:

$$S_{amp} = \frac{V_{test}}{P_{ref}}$$

The sensor phase sensitivity in degrees is computed:

$$S_{phase} = \theta_{test} - \theta_{ref}$$

Measurements of amplitude and phase sensitivity were averaged over 4 measurements at different time periods.

The change in sensitivity, expressed as a percentage in amplitude and degrees in phase, at each amplitude level are computed relative to a reference amplitude level:

$$Change\ S_{amp}(Ampl) = 100 * \frac{(S_{amp}(Ampl) - S_{amp}(Ref\ Ampl))}{S_{amp}(Ref\ Ampl)}$$

$$Change\ S_{phase}(Ampl) = S_{phase}(Ampl) - S_{phase}(Ref\ Ampl)$$

3.6.4 Result

The figure below shows a representative waveform time series for the recording made on the reference sensor and sensors under test. The window regions bounded by the colored lines indicate the segment of data used for analysis.

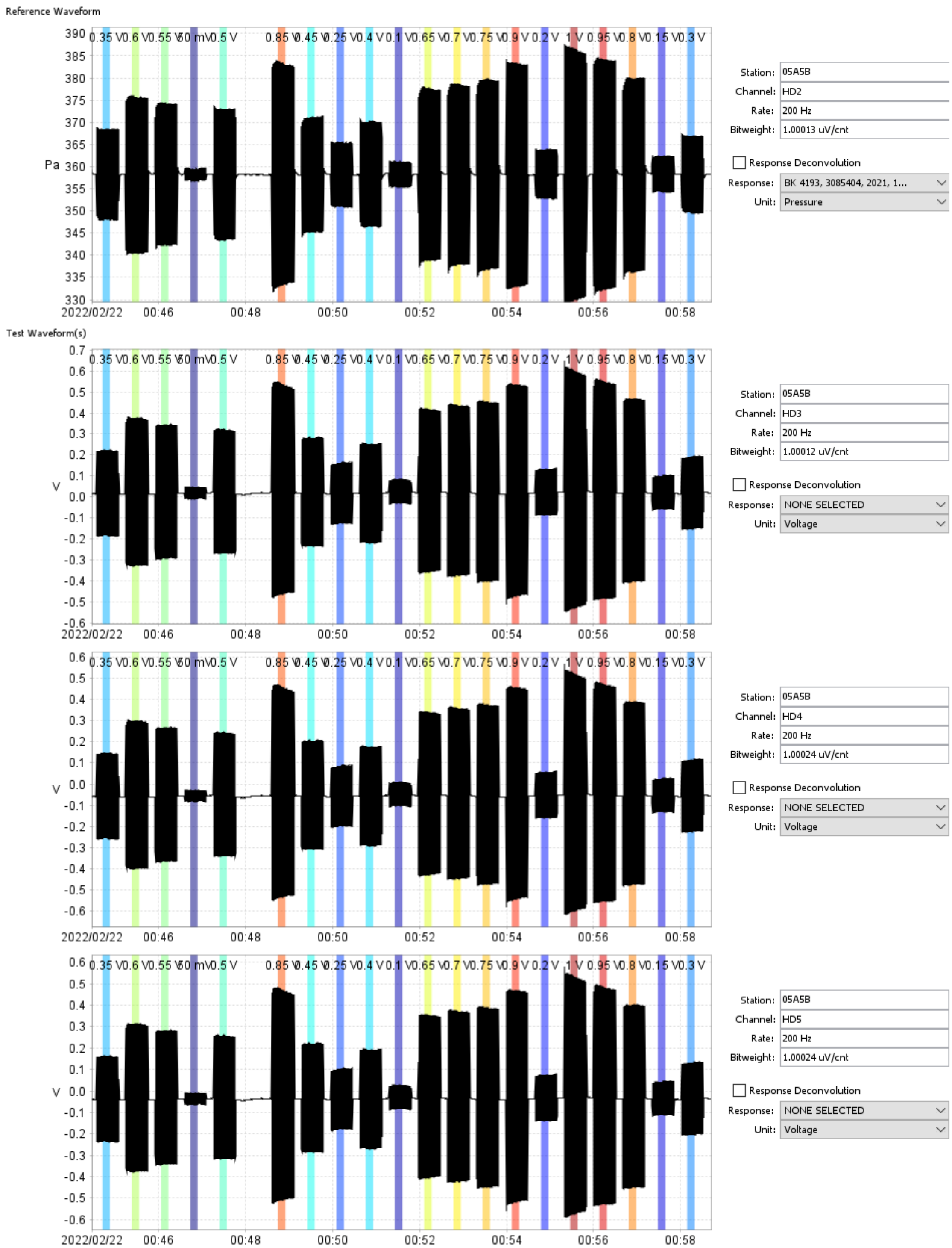

Figure 22 Sensitivity vs Input Amplitude Time Series

The top waveform is the reference, with the unit of Pascals of pressure, and the remaining waveforms are from the sensors under test, with units in Volts. Note that the order of the amplitude steps was randomized to prevent any environmental changes in time from being correlated with input amplitude.

The following charts represent the changes in amplitude and phase sensitivity, relative to the measurement at 10 Pa, that were observed across the input amplitude range.

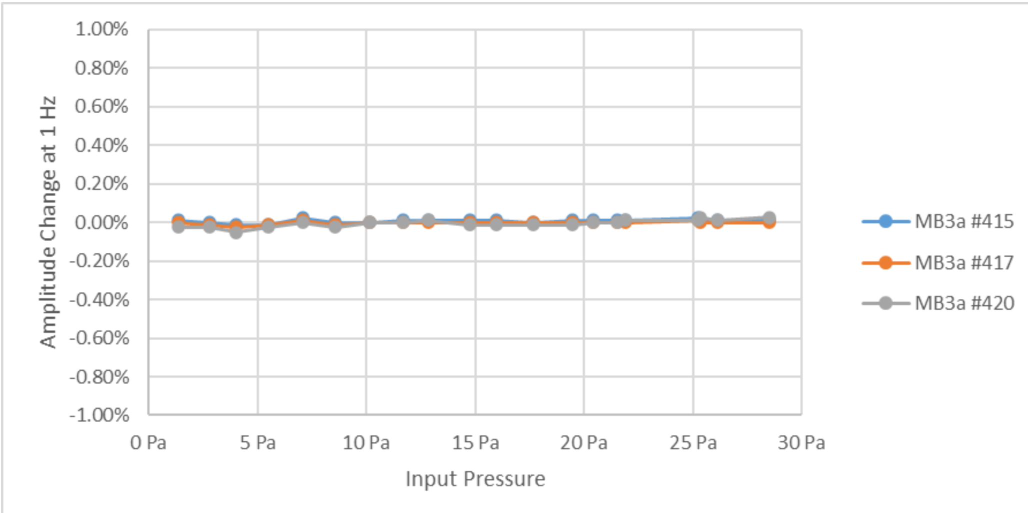

Figure 23 Amplitude Sensitivity vs Input Amplitude

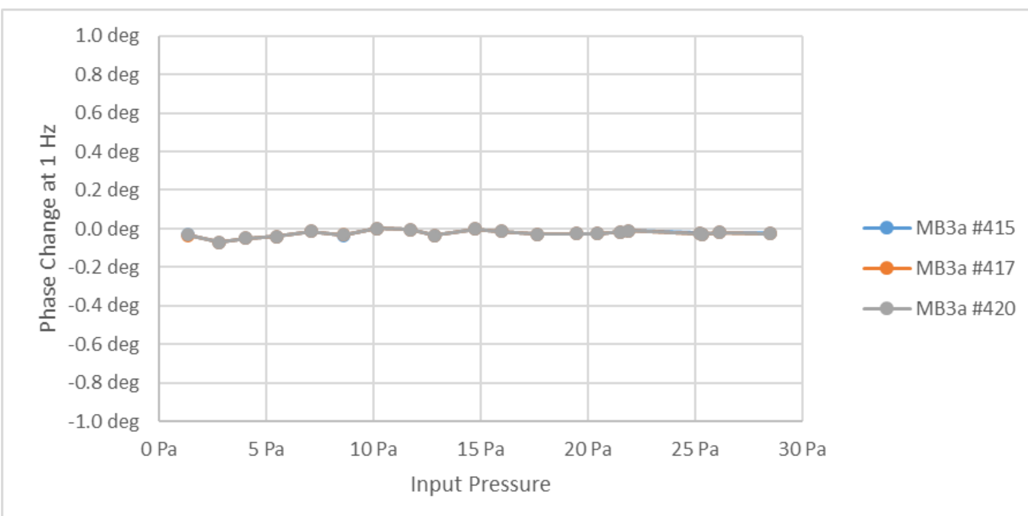

Figure 24 Phase Sensitivity vs Input Amplitude

We observe that there is no consistent change in the amplitude or phase sensitivity with respect to dynamic input pressure. The sensors under test all demonstrated the same sensitivity from 1 Pa to 28 Pa. These values are less than the combined relative measurements uncertainties at 1 Hz of 0.3 % and 0.1 degrees.

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

Table 16 Change in Amplitude vs Input Amplitude

Input Amplitude	MB3a #415	MB3a #417	MB3a #420
1.34 Pa	0.01%	0.00%	-0.03%
2.80 Pa	0.00%	-0.01%	-0.03%
4.02 Pa	-0.01%	-0.03%	-0.05%
5.47 Pa	-0.01%	-0.01%	-0.03%
7.07 Pa	0.03%	0.01%	0.00%
8.58 Pa	0.00%	-0.01%	-0.03%
10.16 Pa	0.00%	0.00%	0.00%
11.70 Pa	0.01%	0.00%	0.00%
12.83 Pa	0.01%	0.00%	0.01%
14.73 Pa	0.01%	0.00%	-0.01%
15.96 Pa	0.01%	0.00%	-0.01%
17.65 Pa	0.00%	0.00%	-0.01%
19.47 Pa	0.01%	0.00%	-0.01%
20.43 Pa	0.01%	0.00%	0.00%
21.52 Pa	0.01%	0.00%	0.00%
21.89 Pa	0.01%	0.00%	0.01%
25.21 Pa	0.03%	0.01%	0.01%
25.34 Pa	0.01%	0.00%	0.03%
26.11 Pa	0.01%	0.00%	0.01%
28.53 Pa	0.01%	0.00%	0.03%

Table 17 Change in Phase vs Input Amplitude

Input Amplitude	MB3a #415	MB3a #417	MB3a #420
1.34 Pa	-0.03 deg	-0.03 deg	-0.03 deg
2.80 Pa	-0.07 deg	-0.07 deg	-0.07 deg
4.02 Pa	-0.05 deg	-0.05 deg	-0.05 deg
5.47 Pa	-0.04 deg	-0.04 deg	-0.04 deg
7.07 Pa	-0.01 deg	-0.01 deg	-0.01 deg
8.58 Pa	-0.03 deg	-0.03 deg	-0.03 deg
10.16 Pa	0.00 deg	0.00 deg	0.00 deg
11.70 Pa	0.00 deg	0.00 deg	0.00 deg
12.83 Pa	-0.03 deg	-0.03 deg	-0.03 deg
14.73 Pa	0.00 deg	0.00 deg	0.00 deg
15.96 Pa	-0.01 deg	-0.01 deg	-0.01 deg
17.65 Pa	-0.03 deg	-0.03 deg	-0.03 deg
19.47 Pa	-0.02 deg	-0.02 deg	-0.02 deg
20.43 Pa	-0.03 deg	-0.03 deg	-0.02 deg
21.52 Pa	-0.02 deg	-0.02 deg	-0.02 deg
21.89 Pa	-0.01 deg	-0.01 deg	-0.01 deg
25.21 Pa	-0.02 deg	-0.02 deg	-0.03 deg
25.34 Pa	-0.03 deg	-0.03 deg	-0.03 deg
26.11 Pa	-0.02 deg	-0.02 deg	-0.02 deg
28.53 Pa	-0.02 deg	-0.02 deg	-0.02 deg

3.7 Full Scale

The full scale of a sensor is defined to be the maximum pressure amplitude that a sensor is capable of recording without clipping.

3.7.1 Measurand

The quantity being measured is the sensor's maximum pressure amplitude in Pascals (Pa).

3.7.2 Configuration

The pressure driver in the infrasound chamber that is used in other portions of the infrasound sensor testing does not have the capability to generate pressure amplitudes sufficient to clip the sensors under test. Therefore, an external linearity calibrator with a smaller manifold volume is used instead. The infrasound sensor under test is connected via a small volume manifold to a piston that generates a dynamic pressure, as shown in the configuration diagram below.

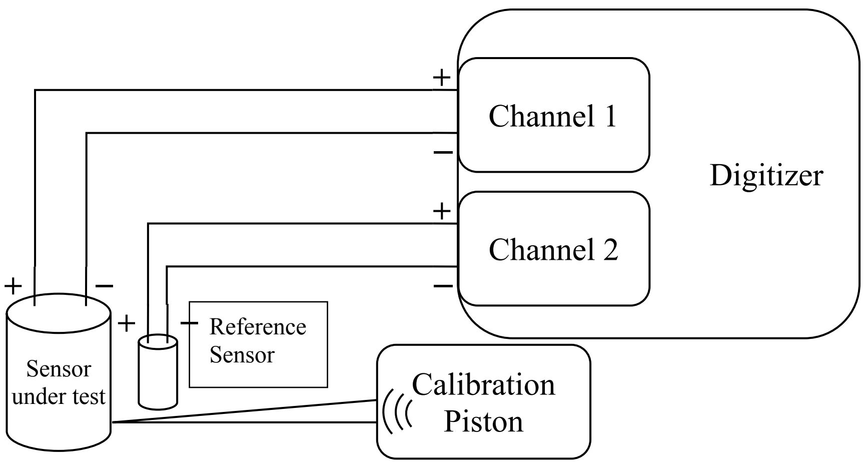

Figure 25 Full Scale Configuration Diagram

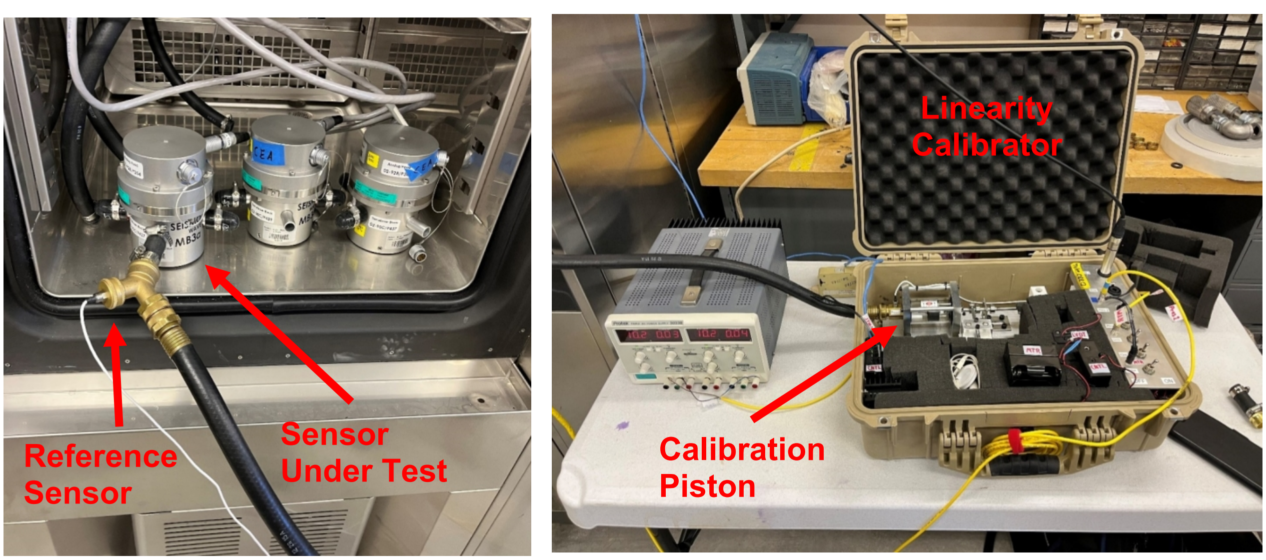

Figure 26 Full Scale Configuration Picture

Table 18 Full Scale Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	Kulite XCS-190S-5D	N/A	0.856900 mV/Pa
Infrasound Chamber	N/A	N/A	815 hPa, +/- 5 hPa 22 C, +/- 2 C 20 % Rh, +/- 5 % Rh
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	PSU Linearity Calibrator	N/A	1 Hz, 0.05 to 2 mm piston displacement
Pressure Driver	PSU Linearity Calibrator	N/A	N/A

The amplitude of the sinusoidal tone is increased in steps until the sensor full-scale is reached.

As the infrasound sensor is expected to generate nearly 20 V peak output, which is close to the maximum input of the testbed digitizer, a signal attenuator with a measured 8.65x of attenuation was placed in-line between the sensor and data recorder.

Figure 27 Full Scale Signal Attenuator

The use of an attenuator should scale the maximum 20 V output of the sensor down to approximately 2.3 V. This was done to ensure that we would be observing the full-scale output of the sensor and not the digitizer clipping. The effect of the attenuator was accounted for in the digitizer bit weight to scale the waveform time series.

The dynamic pressure being generated by the external calibrator was increased until it exceeded the sensor full-scale, and clipping was observed.

3.7.3 Analysis

The minimum and maximum pressure outputs are observed in the time series of the sensor under test.

3.7.4 Result

The figure below shows a representative waveform time series for each of the sensors under test.

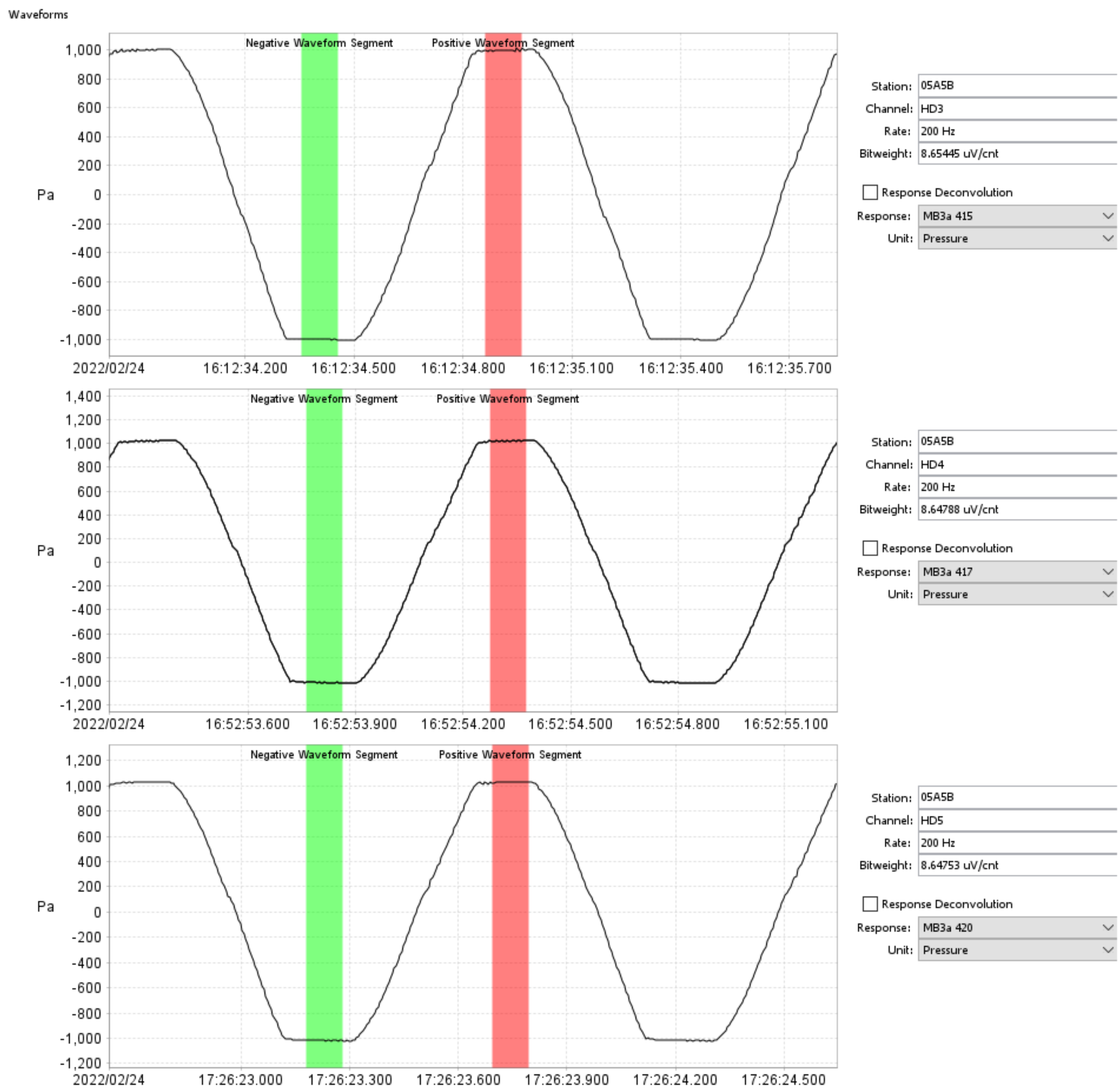

Figure 28 Full Scale Time Series

The positive and negative clip levels are clearly visible where the sensor output does not increase any further.

The following table contains the minimum and maximum pressure levels that were observed in the output of each of the sensors under test while the dynamic pressure was being generated.

Table 19 Full Scale Observed Pressure

	Minimum	Maximum
MB3a #415	-1,006.8 Pa	1,010.1 Pa
MB3a #417	-1,021.6 Pa	1,023.0 Pa
MB3a #420	-1,024.6 Pa	1,027.2 Pa

From the MB3a datasheet, the peak-to-peak full scale is specified as:

$$Full\ Scale_{pp} = \min\left(1200; \frac{12000}{2 * pi * f}\right)$$

So, at 1 Hz, the full scale would be expected to be approximately 1910 Pa peak-to-peak, or +/- 955 Pa peak. All the MB3a sensors were observed to have a full-scale limit that exceeds the datasheet specification.

3.8 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 Pa^2/Hz.

3.8.1 Measurand

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

3.8.2 Configuration

The infrasound sensors under test are placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in temperature or pressure. In addition, the sensors were capped to further attenuate any input signal and to eliminate any noise from convective air currents within the chamber.

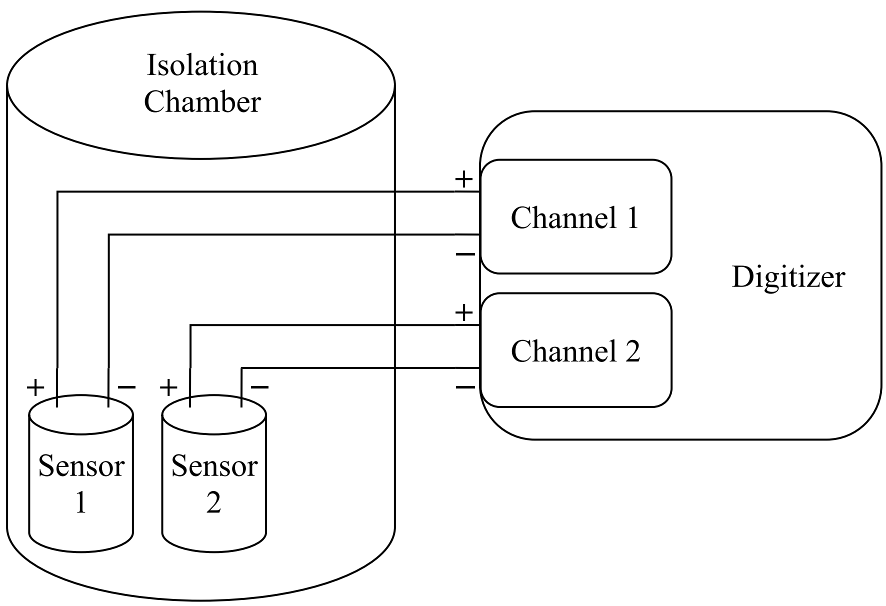

Figure 29 Self-Noise Configuration Diagram

Table 20 Self-Noise Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Digitizer	Guralp Affinity	405A5B	40 Hz, 8x gain, 5 Vpp
Infrasound Chamber	SNL	1400 L Chamber	808 hPa, 22.9 C, 16 % RH

As the sensor inlets must be capped before placing the sensors inside of the sealed isolation chamber, this test must be performed at a local barometric pressure of 820 hPa. Prior to initiating this test, the MB3a sensors were re-centered for a barometric pressure in an ambient environment of 809 hPa, 22.2 C, and 18 % RH. The sensor sensitivity and frequency response were reconfirmed at the ambient barometric pressure inside of the infrasound chamber prior capping the sensors for the self-noise evaluation.

In addition, due to the combination of the MB3a's 20 mV/Pa sensitivity and low self-noise, the digitizer gain was temporarily changed to 8x to better resolve the sensor self-noise. At the same time as the measurement of sensor self-noise, one of the unused digitizer channels was shorted with a 100-ohm resistor to confirm the digitizer self-noise levels.

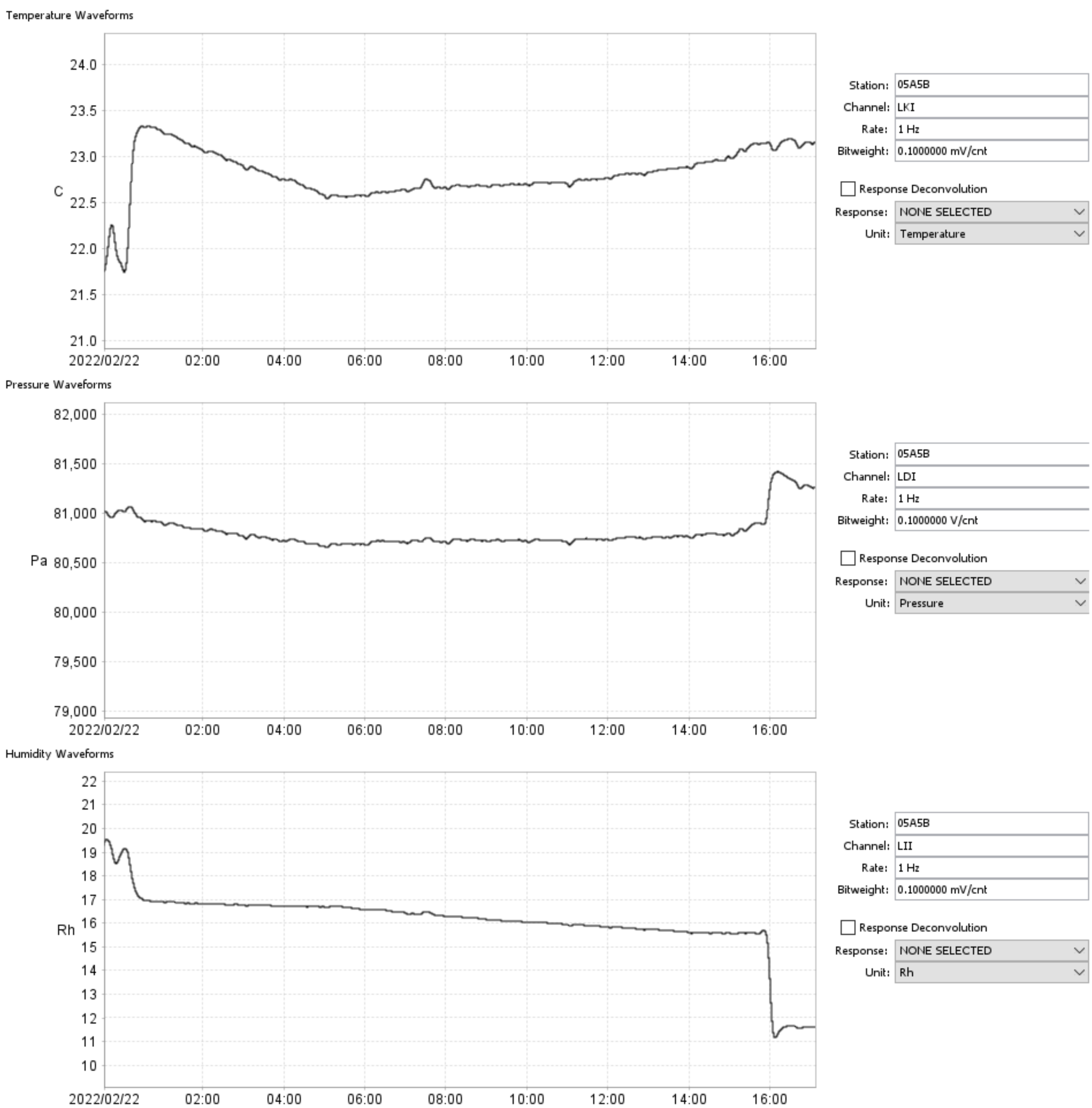

Figure 30 Self-Noise Environmental Conditions

The self-noise measurement was taken on February 22, 2022 from the time period of 08:00 to 16:00 UTC. Environmental conditions over the period of self-noise, as shown in Figure 30, show the recorded temperature, pressure, and relative humidity were 22.9 C +/- 0.2 C, 808 hPa, +/- 1 hPa, and 16 % RH, +/- 0.5%.

3.8.3 Analysis

The measured sensitivities are applied to the collected data:

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

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 pass-band of 0.01 Hz. The resulting 95% confidence interval was determined to be 0.74 dB.

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

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

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

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

3.8.4 Result

The figures below show the waveform time series for the recording made on a sensor under test. The window regions bounded by the red lines indicate the segment of data used for analysis.

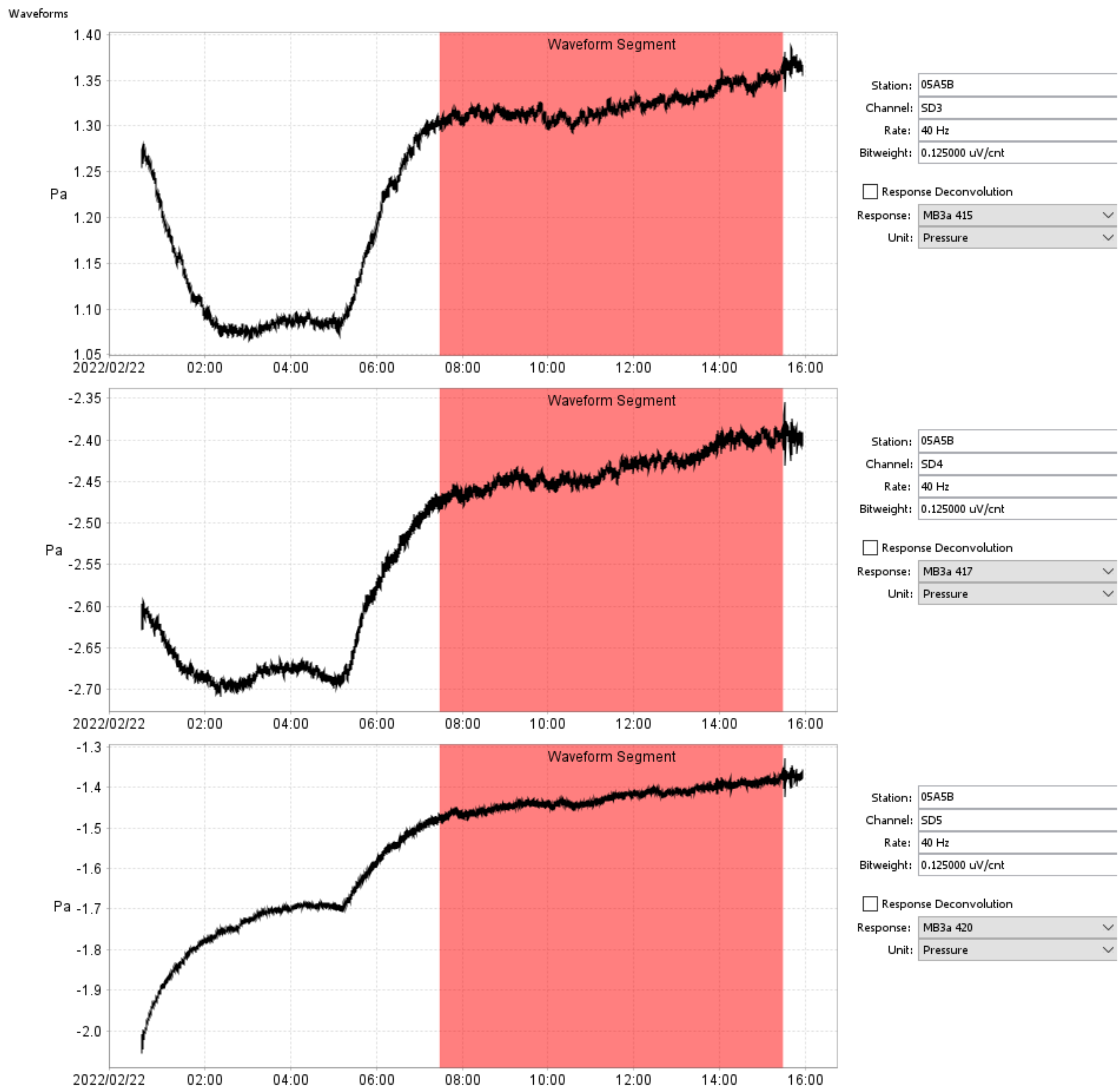

Figure 31 Self-Noise Time Series

The self-noise data was collected during the overnight period while conditions were stable and quiet. An 8-hour window of time was selected when environmental conditions were most stable to obtain the best measurement of the sensor self-noise.

The power spectra plot below shows the self-noise spectra corresponding to the time series. The respective self-noise spectra are plotted alongside the New Low Noise Model (Marty, 2021) in green, the IMS Minimum Requirement in blue, and the expected MB3a noise model provided by

CEA in magenta. The noise floor of the digitizer used in the testbed, converted to Pascal using the nominal sensor response, is plotted in red to confirm that the digitizer is sufficiently below the estimate of sensor self-noise.

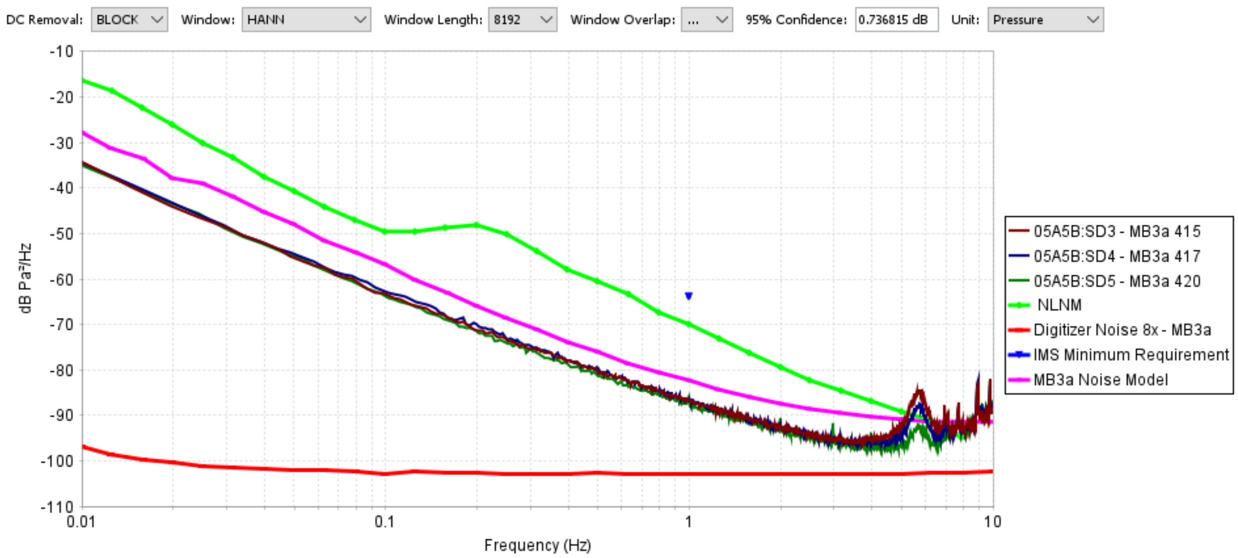

Figure 32 Self-Noise Power Spectra

The MB3a self-noise levels were all below the low-noise model across the IMS passband of 0.02 to 4 Hz. In addition, the self-noise at 1 Hz is less than -86 dB, well below the IMS requirement of being below -64 dB. At frequencies above 4 Hz, there was some elevated noise on the sensor output. This high frequency noise is believed to be due to ambient vibration due to wind conditions during the overnight period.

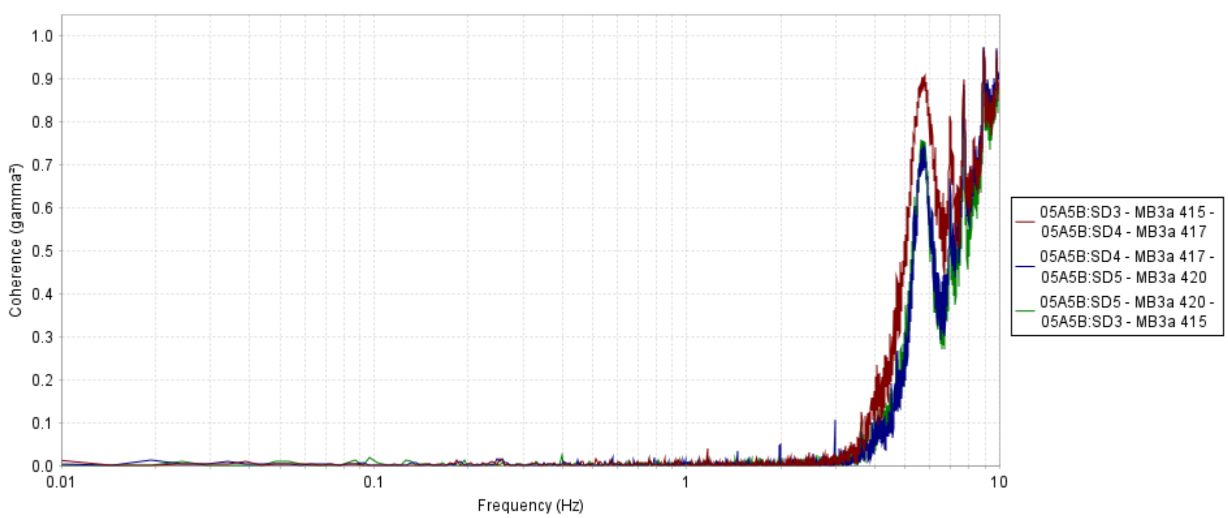

Figure 33 Self-Noise Coherence

The spectral coherence was also calculated between each pair of sensors, shown in Figure 33. There was no measurable coherence at frequencies below 4 Hz. Above 4 Hz, the observed increases in the power spectra believed to be due to vibration resulted in some coherence between the sensor outputs.   Applying a 3-channel coherence removal (Sleeman, 2006) resulted in the incoherent power spectra shown in Figure 34.

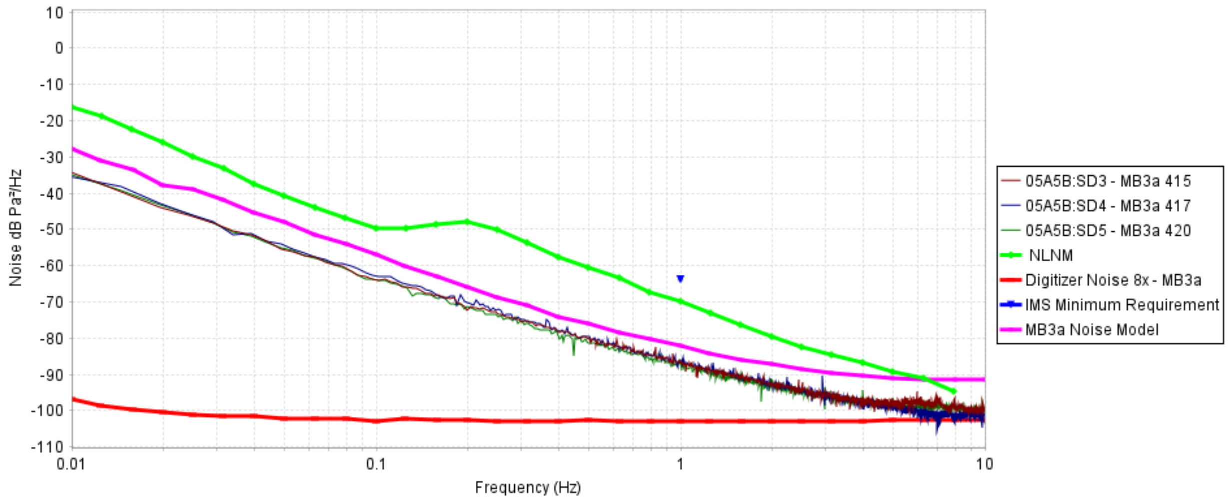

Figure 34 Self-Noise Incoherent Spectra

Removing the coherent portions of the power spectra resulted in an improved estimate of the sensor self-noise above 4 Hz and did not result in any significant change below 4 Hz.

The following table contains the integrated RMS self-noise levels over the 0.02 – 4 Hz application passband.

Table 21 Self Noise RMS

Sensor	0.02 Hz – 4.0 Hz
MB3a #415	0.613 mPa rms
MB3a #417	0.638 mPa rms
MB3a #420	0.617 mPa rms

The RMS noise power over 0.02 to 4 Hz IMS passband was below 0.64 mPa rms, which is lower than the MB3a datasheet specification of 1.75 mPa rms.

The following table contains incoherent self-noise levels in dB relative to 1 Pa^2/Hz. The total combined uncertainty estimate for the PSD is included as well.

Table 22 Self-Noise Power Spectra

Frequency	MB3a #415	MB3a #417	MB3a #420	Uncertainty (k=2)
0.0100 Hz	-34.35 dB	-35.64 dB	-35.02 dB	5.20 dB
0.0125 Hz	-37.36 dB	-37.17 dB	-37.49 dB	4.64 dB
0.0160 Hz	-41.24 dB	-39.76 dB	-40.77 dB	4.38 dB
0.0200 Hz	-44.28 dB	-43.43 dB	-43.70 dB	4.13 dB
0.0250 Hz	-46.66 dB	-46.32 dB	-46.14 dB	3.87 dB
0.0315 Hz	-49.41 dB	-49.67 dB	-49.69 dB	3.62 dB
0.0400 Hz	-52.13 dB	-51.76 dB	-52.48 dB	3.36 dB
0.0500 Hz	-55.81 dB	-54.66 dB	-55.40 dB	3.11 dB
0.0630 Hz	-57.81 dB	-57.62 dB	-58.23 dB	2.86 dB
0.0800 Hz	-60.75 dB	-59.82 dB	-61.16 dB	2.61 dB
0.100 Hz	-63.97 dB	-62.74 dB	-63.96 dB	2.30 dB
0.125 Hz	-66.10 dB	-65.19 dB	-66.33 dB	2.07 dB
0.160 Hz	-68.43 dB	-68.47 dB	-68.81 dB	1.95 dB
0.200 Hz	-71.47 dB	-70.25 dB	-71.95 dB	1.79 dB
0.250 Hz	-73.06 dB	-72.38 dB	-73.77 dB	1.63 dB
0.315 Hz	-75.69 dB	-75.26 dB	-76.45 dB	1.48 dB
0.40 Hz	-78.27 dB	-77.80 dB	-79.34 dB	1.33 dB
0.50 Hz	-80.25 dB	-79.92 dB	-81.46 dB	1.27 dB
0.63 Hz	-82.54 dB	-82.60 dB	-83.51 dB	1.08 dB
0.80 Hz	-84.77 dB	-84.89 dB	-85.82 dB	0.91 dB
1.00 Hz	-86.84 dB	-86.83 dB	-87.65 dB	0.80 dB
1.25 Hz	-88.98 dB	-88.92 dB	-89.72 dB	0.81 dB
1.60 Hz	-90.97 dB	-90.97 dB	-91.72 dB	0.85 dB
2.00 Hz	-92.88 dB	-92.83 dB	-93.59 dB	0.93 dB
2.50 Hz	-94.47 dB	-94.47 dB	-95.10 dB	1.03 dB
3.15 Hz	-95.99 dB	-96.13 dB	-96.54 dB	1.11 dB
4.00 Hz	-97.52 dB	-97.69 dB	-97.95 dB	1.04 dB
5.00 Hz	-98.11 dB	-99.08 dB	-98.87 dB	0.84 dB
6.30 Hz	-98.11 dB	-100.70 dB	-99.16 dB	0.82 dB
8.00 Hz	-99.23 dB	-101.34 dB	-99.47 dB	0.83 dB
10.00 Hz	-99.78 dB	-101.72 dB	-99.76 dB	1.40 dB

3.9 Dynamic Range

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

3.9.1 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).

3.9.2 Configuration

There is no test configuration for the dynamic range test. The full-scale value used for the largest signal comes from the evaluated sensor full-scale determined in section 3.7 Full Scale. The value for the smallest signal comes from the evaluated sensor self-noise determined in section 3.8 Self-Noise.

3.9.3 Analysis

The dynamic range over a given pass-band is:

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

Where

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

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

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

3.9.4 Result

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

Table 23 Dynamic Range

	Full Scale (Peak)	RMS Noise (0.02 Hz – 4 Hz)	Dynamic Range (0.02 – 4 Hz)
MB3a #415	1,010.1 Pa	0.613 mPa rms	121.33 dB
MB3a #417	1,023.0 Pa	0.638 mPa rms	121.09 dB
MB3a #420	1,027.2 Pa	0.617 mPa rms	121.42 dB

The MB3a dynamic range was determined to be greater than 121 dB. This exceeds the MB3a specification of 117 dB as well as the IMS minimum requirement of 108 dB.

3.10 Calibrator Frequency Response

The calibrator frequency response is defined as being the linear time-invariant (LTI) change in the induced pressure into the sensor sensing element relative to an input volage signal.

3.10.1 Measurand

Response including the amplitude expressed in Pa/V and the phase expressed in degrees over the defined frequencies.

3.10.2 Configuration

The infrasound sensor under test is placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in temperature or pressure.

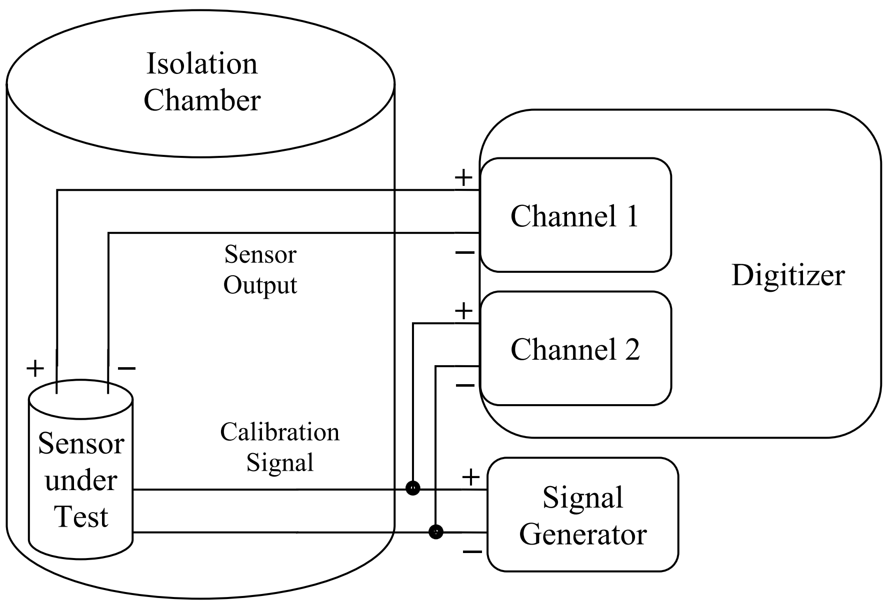

Figure 35 Calibrator Frequency Response Configuration Diagram

The sensor inlets are open to the interior of the infrasound chamber and a calibration enable line and a voltage signal line connected to the sensor under test to command its calibrator.

A signal generator is command to generate a sinusoidal voltage signal with a defined amplitude and frequency. The voltage signal causes the sensor calibrator to generate an induced signal in the sensor output. The calibration input voltage and the sensor output are both recorded by a digitizer. The sensor output is treated as the reference, converting the voltage output to pressure using the MB3a pole-zero model and the measured sensitivity at 1 Hz. to determine the frequency response characteristics of the calibrator.

Table 24 Calibrator Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	MB3a, SUT	#415, #417, and #420	N/A
Infrasound Chamber	SNL	1400 L Chamber	1013 hPa, 23 C
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	0.01 Hz – 10 Hz, 1.6 Vp sinusoid

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

This test was performed with a set of tones that span the evaluation frequencies in a randomized order.

3.10.3 Analysis

For the tonal analysis, a minimum of 10 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f/2 to f*2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in volts to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

$$V_{test} \sin(2\, pi\, f_{test}\, t + \theta_{test}) + V_{dc\, test}$$

The sensor amplitude sensitivity in Pascal / Volts is computed:

$$Sensitivity = \frac{P_{ref}}{V_{test}}$$

The sensor phase sensitivity in degrees is computed:

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

3.10.4 Result

The figure below shows a representative waveform time series for the tonal recording made on the sensor under test output as the reference and the voltage signal input to the calibrator. The window regions bounded by the colored lines indicate the segment of data used for analysis.

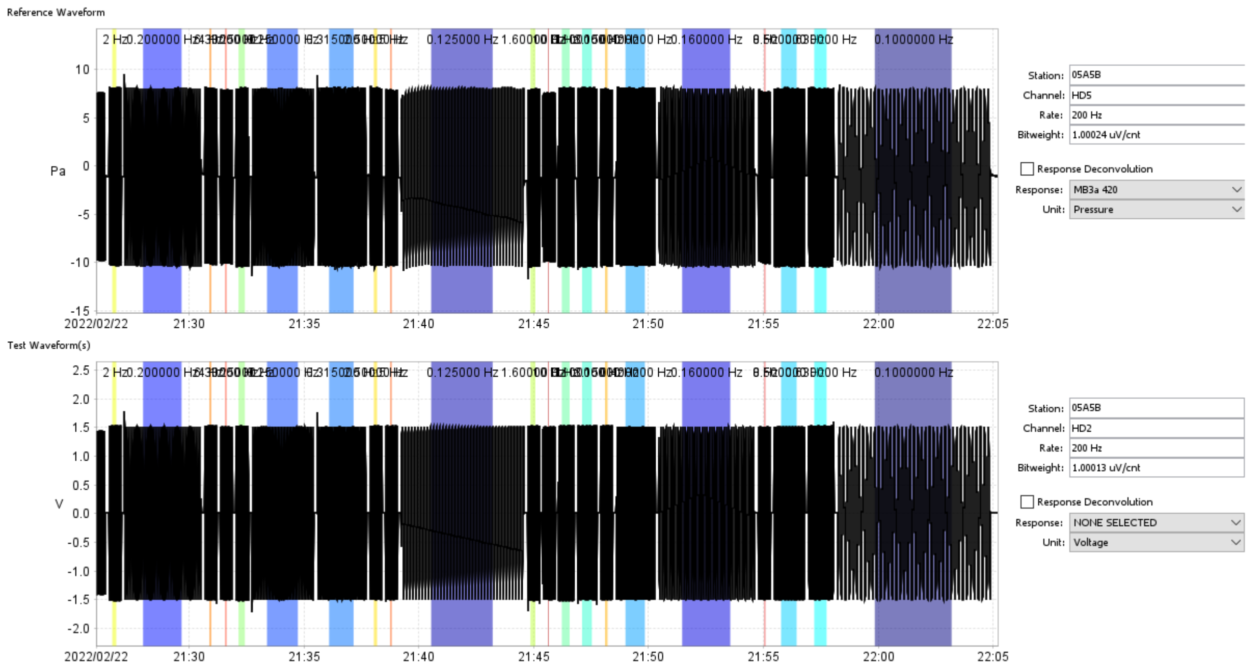

Figure 36 Calibrator Frequency Response Time Series

The top waveform is the output of the sensor under test as the reference, with the unit of Pascals of pressure, and the bottom waveform is the input signal to the sensor calibrator, with units in Volts. Note that the order of the frequencies was randomized to prevent any non-causal environmental changes in time from being correlated with signal frequency.

The following plots show the amplitude and phase responses that were measured.

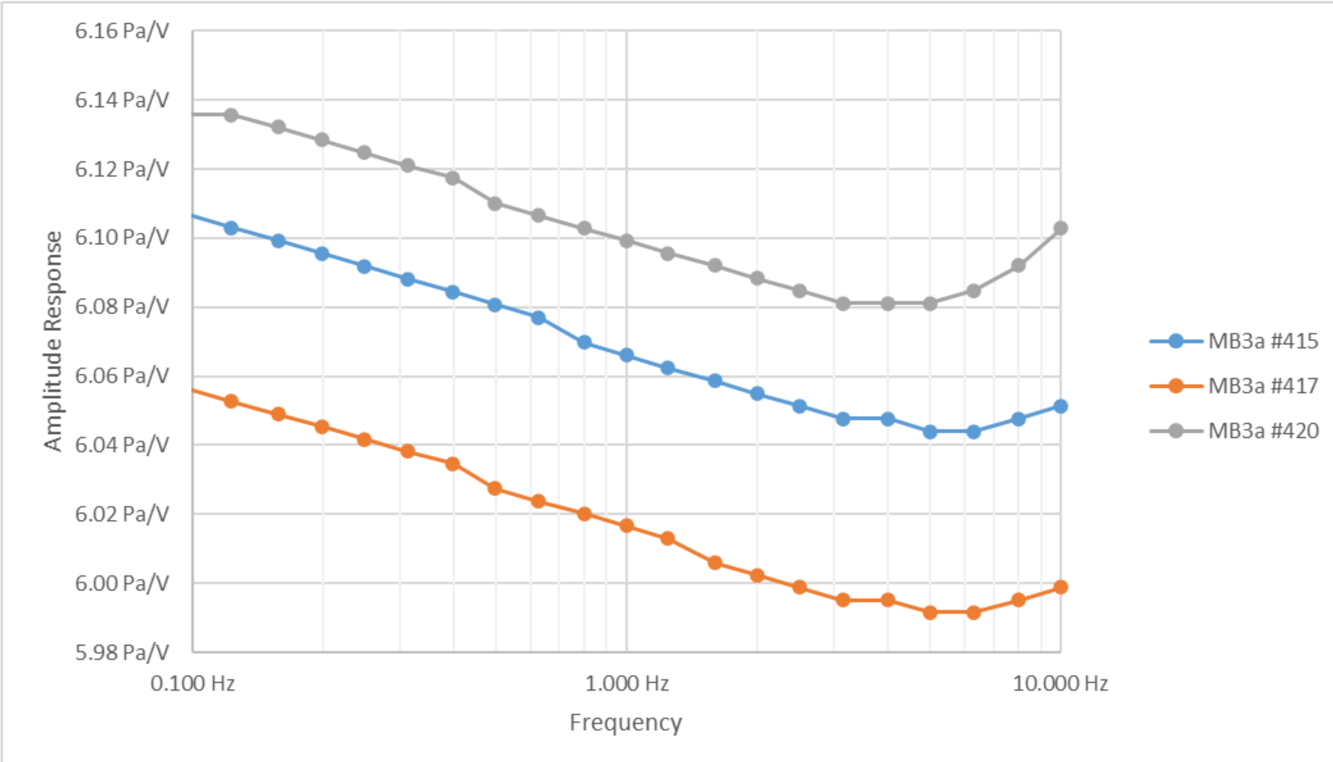

Figure 37 Calibrator Amplitude Response

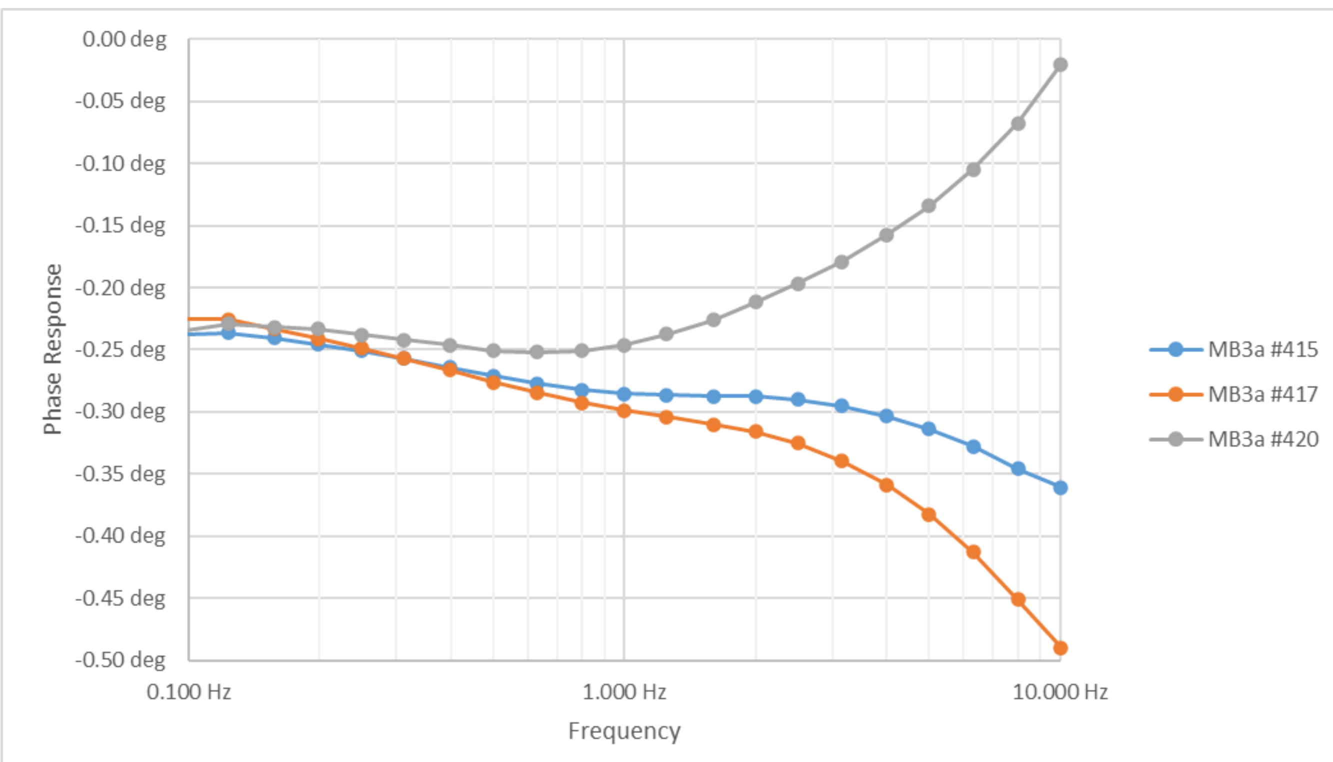

Figure 38 Calibrator Phase Response

The calibrator amplitude responses were all within 2% of the nominal 6 Pa/V.   Each individual amplitude response varied by only 1% over the 0.1 Hz to 10 Hz passband.

The calibrator phase responses were all within 0.5 degrees of the nominal 0 degrees. Each individual phase response varied by only 0.25 degrees over the 0.1 Hz to 10 Hz passband.

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

Table 25 Calibrator Amplitude Response

Frequency	MB3a #415	MB3a #417	MB3a #420	Nominal
0.098 Hz	6.11 Pa/V	6.06 Pa/V	6.14 Pa/V	6 Pa/V
0.123 Hz	6.10 Pa/V	6.05 Pa/V	6.14 Pa/V	6 Pa/V
0.158 Hz	6.10 Pa/V	6.05 Pa/V	6.13 Pa/V	6 Pa/V
0.199 Hz	6.10 Pa/V	6.05 Pa/V	6.13 Pa/V	6 Pa/V
0.249 Hz	6.09 Pa/V	6.04 Pa/V	6.12 Pa/V	6 Pa/V
0.312 Hz	6.09 Pa/V	6.04 Pa/V	6.12 Pa/V	6 Pa/V
0.398 Hz	6.08 Pa/V	6.03 Pa/V	6.12 Pa/V	6 Pa/V
0.499 Hz	6.08 Pa/V	6.03 Pa/V	6.11 Pa/V	6 Pa/V
0.628 Hz	6.08 Pa/V	6.02 Pa/V	6.11 Pa/V	6 Pa/V
0.799 Hz	6.07 Pa/V	6.02 Pa/V	6.10 Pa/V	6 Pa/V
0.998 Hz	6.07 Pa/V	6.02 Pa/V	6.10 Pa/V	6 Pa/V
1.247 Hz	6.06 Pa/V	6.01 Pa/V	6.10 Pa/V	6 Pa/V
1.598 Hz	6.06 Pa/V	6.01 Pa/V	6.09 Pa/V	6 Pa/V
1.999 Hz	6.06 Pa/V	6.00 Pa/V	6.09 Pa/V	6 Pa/V
2.497 Hz	6.05 Pa/V	6.00 Pa/V	6.08 Pa/V	6 Pa/V
3.148 Hz	6.05 Pa/V	6.00 Pa/V	6.08 Pa/V	6 Pa/V
3.997 Hz	6.05 Pa/V	6.00 Pa/V	6.08 Pa/V	6 Pa/V
4.998 Hz	6.04 Pa/V	5.99 Pa/V	6.08 Pa/V	6 Pa/V
6.299 Hz	6.04 Pa/V	5.99 Pa/V	6.08 Pa/V	6 Pa/V
7.998 Hz	6.05 Pa/V	6.00 Pa/V	6.09 Pa/V	6 Pa/V
10.000 Hz	6.05 Pa/V	6.00 Pa/V	6.10 Pa/V	6 Pa/V

Table 26 Calibrator Phase Response

Frequency	MB3a #415	MB3a #417	MB3a #420	Nominal
0.098 Hz	-0.24 deg	-0.23 deg	-0.23 deg	0 deg
0.123 Hz	-0.24 deg	-0.23 deg	-0.23 deg	0 deg
0.158 Hz	-0.24 deg	-0.23 deg	-0.23 deg	0 deg
0.199 Hz	-0.25 deg	-0.24 deg	-0.23 deg	0 deg
0.249 Hz	-0.25 deg	-0.25 deg	-0.24 deg	0 deg
0.312 Hz	-0.26 deg	-0.26 deg	-0.24 deg	0 deg
0.398 Hz	-0.26 deg	-0.27 deg	-0.25 deg	0 deg
0.499 Hz	-0.27 deg	-0.28 deg	-0.25 deg	0 deg
0.628 Hz	-0.28 deg	-0.28 deg	-0.25 deg	0 deg
0.799 Hz	-0.28 deg	-0.29 deg	-0.25 deg	0 deg
0.998 Hz	-0.29 deg	-0.30 deg	-0.25 deg	0 deg
1.247 Hz	-0.29 deg	-0.30 deg	-0.24 deg	0 deg
1.598 Hz	-0.29 deg	-0.31 deg	-0.23 deg	0 deg
1.999 Hz	-0.29 deg	-0.32 deg	-0.21 deg	0 deg
2.497 Hz	-0.29 deg	-0.33 deg	-0.20 deg	0 deg
3.148 Hz	-0.30 deg	-0.34 deg	-0.18 deg	0 deg
3.997 Hz	-0.30 deg	-0.36 deg	-0.16 deg	0 deg
4.998 Hz	-0.31 deg	-0.38 deg	-0.13 deg	0 deg
6.299 Hz	-0.33 deg	-0.41 deg	-0.10 deg	0 deg
7.998 Hz	-0.35 deg	-0.45 deg	-0.07 deg	0 deg
10.000 Hz	-0.36 deg	-0.49 deg	-0.02 deg	0 deg

3.11 Static Temperature Response Variation

The response variation with static temperature is defined as being the observable change in sensor frequency response as the ambient static temperature is varied. The purpose of this test is to confirm that the sensor response will be sufficiently stable when the sensor is deployed in an environment where the temperature will vary over time from when the sensor was first installed.

3.11.1 Measurand

The measured quantity is the change in frequency response, expressed as a percent change in amplitude and degrees difference in phase, as a function of temperature.

3.11.2 Configuration

The infrasound sensors under test are placed inside of a thermal chamber that is used to control the temperature of the sensors. A reference sensor with known performance characteristics is outside of the thermal chamber where it is maintained at room ambient conditions, near 23 C, and not impacted by the temperature inside of the thermal chamber. A signal generator, amplifier, and pressure driver external to the thermal chamber generates a pressure signal inside of an equalization volume that is also connected to both the reference sensor and the sensors under test via a manifold. The diagram below represents this configuration:

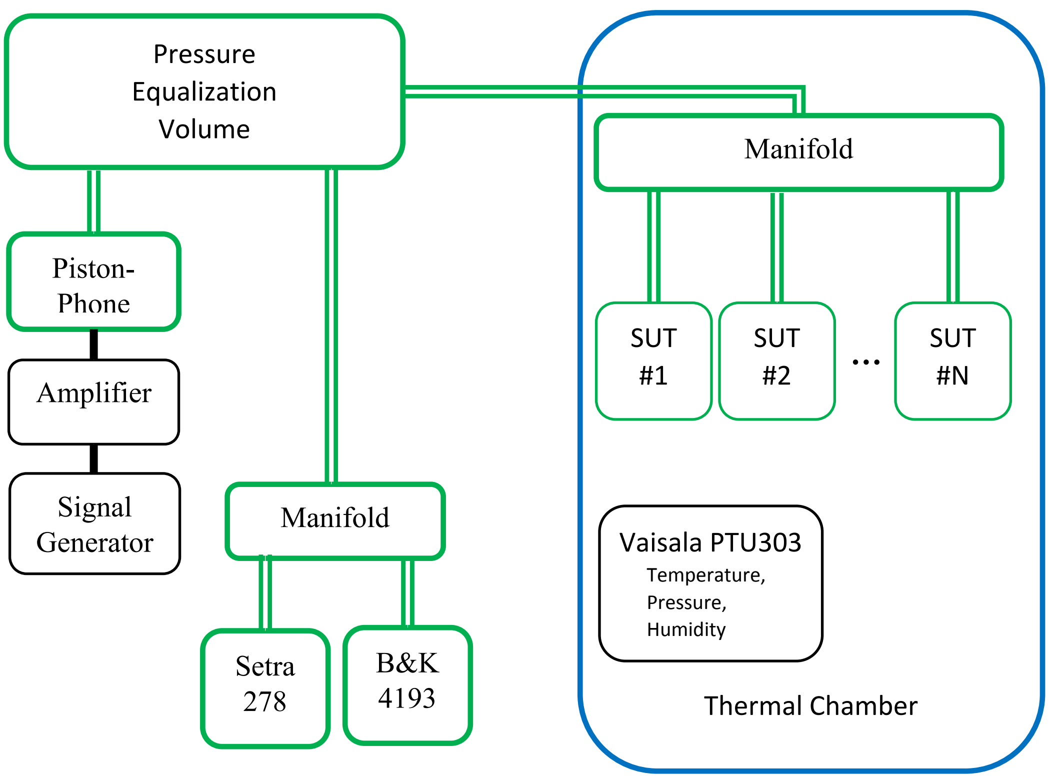

Figure 39 Static Temperature Response Configuration Diagram

In the configuration diagram shown in Figure 39, the blue line representing the perimeter of the temperature chamber indicates that all the instruments within the chamber are maintained at the controlled temperature levels. The green lines representing the piston-phone, equalization volume, manifolds, and sensors indicate that air-tight connections are made between those instruments so that generated pressure signal is transmitted to all the sensors.

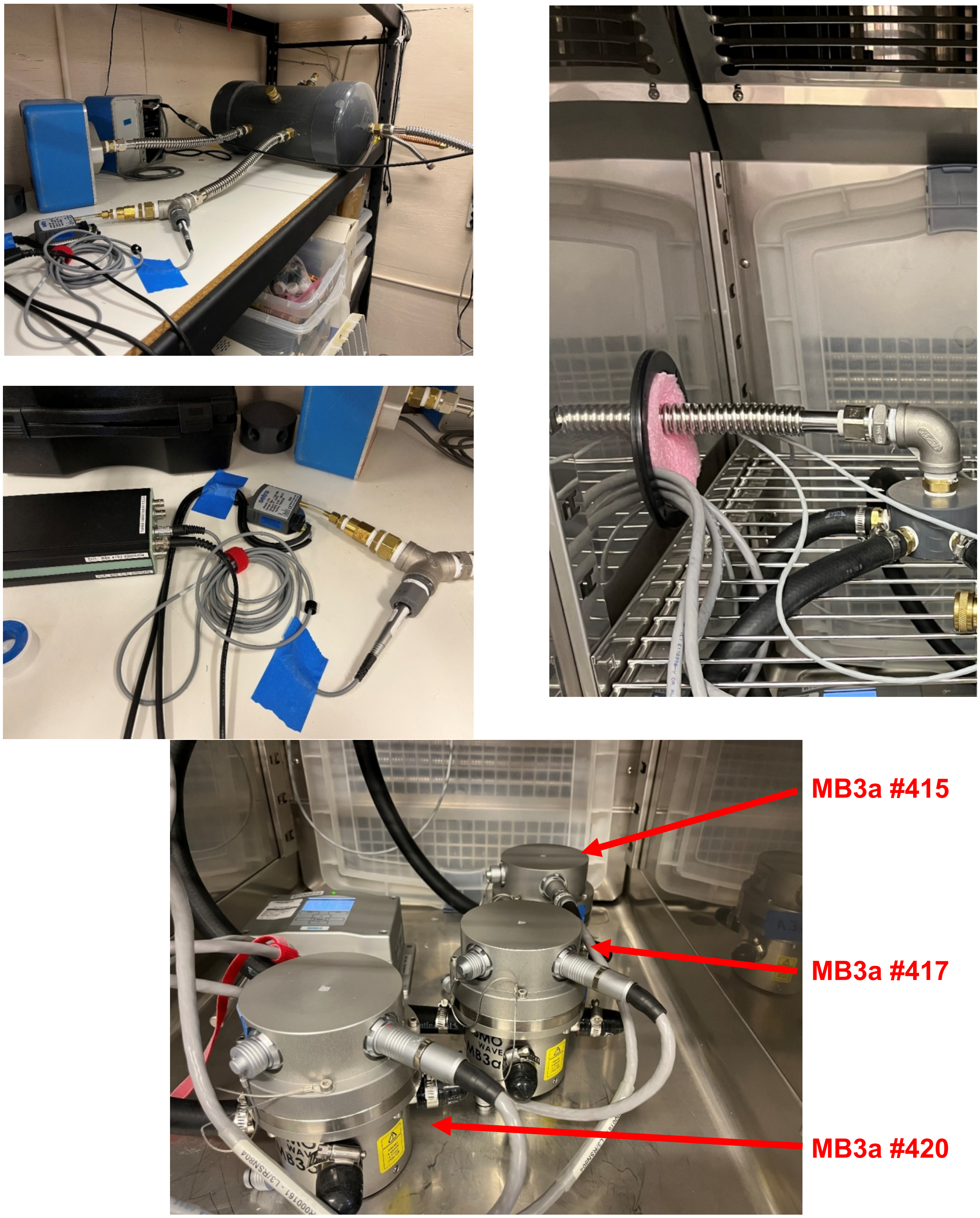

Figure 40 Static Temperature Response Configuration Picture

Note that in Figure 40 a plastic lid was placed between the sensors under test and the thermal chamber air blower to prevent conditioned air from directly hitting the sensor under test.

This configuration is not suitable for absolute measurements of sensitivity as variations in the pipe diameter and length are expected to result in attenuation and harmonics, depending on the frequency, that will prevent the sensor under test and reference sensor from observing a common signal. Placing a reference sensor on the same manifold as the sensors under test within the temperature chamber would also be problematic as the reference sensor would be subjected to changing temperature conditions.

However, we do expect that the test system is highly repeatable, such that in repeated measurements we can expect to get the same relative pressure amplitude levels at each of the sensors, regardless of the temperature within the chamber. Therefore, with this system it is possible to make measurements of how much the sensitivity changes from a baseline configuration as the temperature of the sensor under test is changed.

Table 27 Static Temperature Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	3085404	2.115 mV/Pa at 1 Hz, 820 hPa, 23 C
Reference Sensor	Setra 278	7632595	0.0832926 mV/Pa, 820 hPa, 23 C
Thermal Chamber	ESPEC	N/A	-20 C to 50 C, 10 C steps
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	0.1 Hz – 10 Hz, 0.5 V sinusoid
Voltage Amplifier	APS Dynamics Model 300	#3114	N/A
Pressure Driver	APS Dynamics Model 300	#3114	N/A
Environmental Monitor (inside chamber)	Vaisala PTU300	J3040003	Ambient Temperature, Pressure, and Humidity
Environmental Monitor (outside chamber)	Vaisala PTU300	D1050016	Ambient Temperature, Pressure, and Humidity

The thermal chamber is programmed to iterate through temperature cycles from 20 C, down to -20 C, up to 50 C, and then back down to 20 C in 10 C steps. Comparing the results at both increasing and decreasing temperature levels provides confidence that the sensors have adequately equilibrated to the temperature level before the measurements were made.

At each 10 C temperature step, the thermal chamber maintains the programmed temperature for 4 hours for the sensors for fully equilibrate. After 4 hours of equilibration, a series of pressure tones at discrete frequencies spanning 0.1 Hz to 10 Hz are generated to measure the sensitivity of the sensor under test relative to the reference sensor. The calibration tones are generated with sufficient amplitude to obtain the desired signal to noise ratio while the temperature chamber is operating.

A recording of the static pressure, temperature, and humidity was made of ambient conditions within the temperature chamber, shown below.

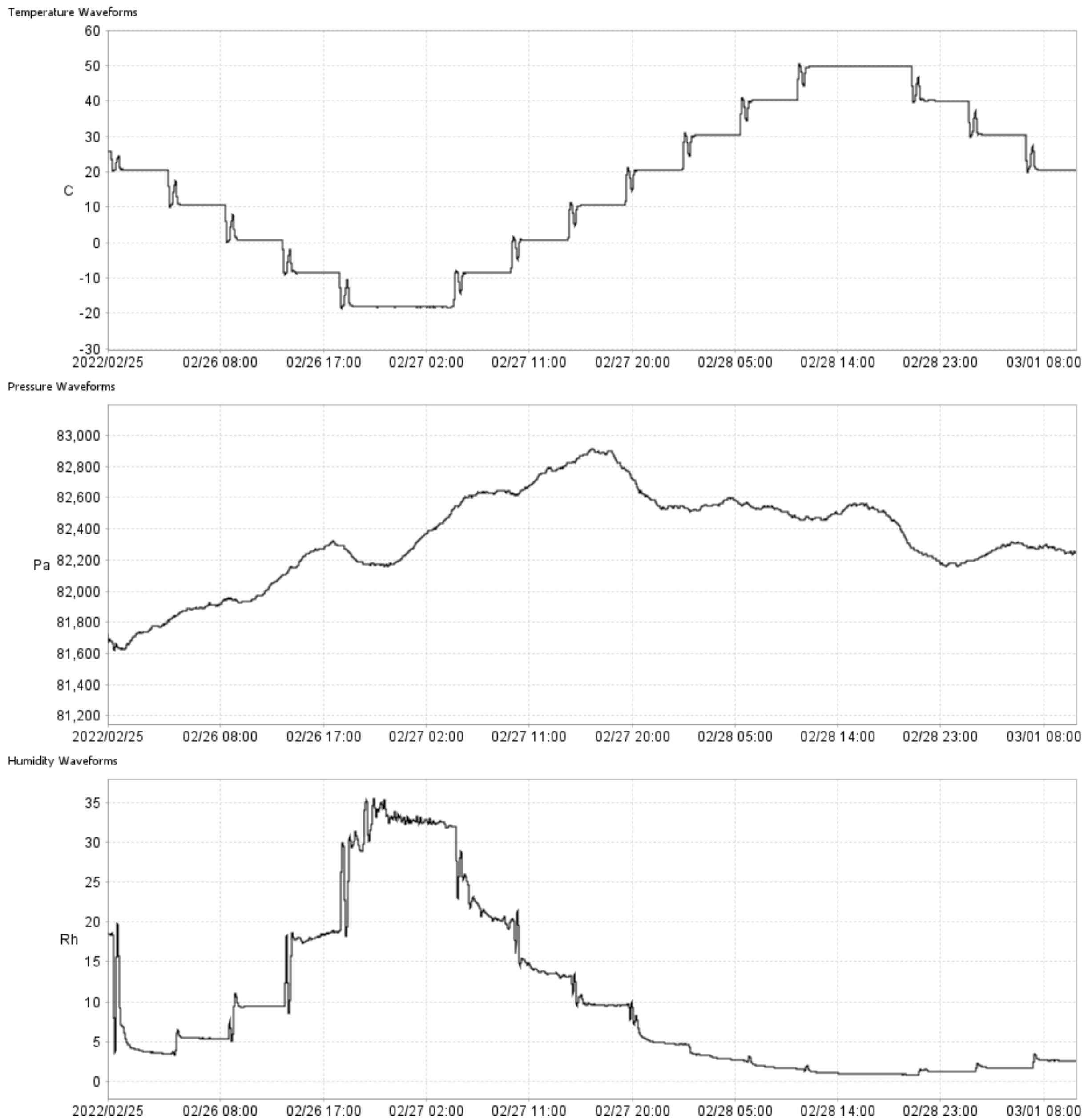

Figure 41 Environmental Conditions Inside Chamber During Temperature Testing

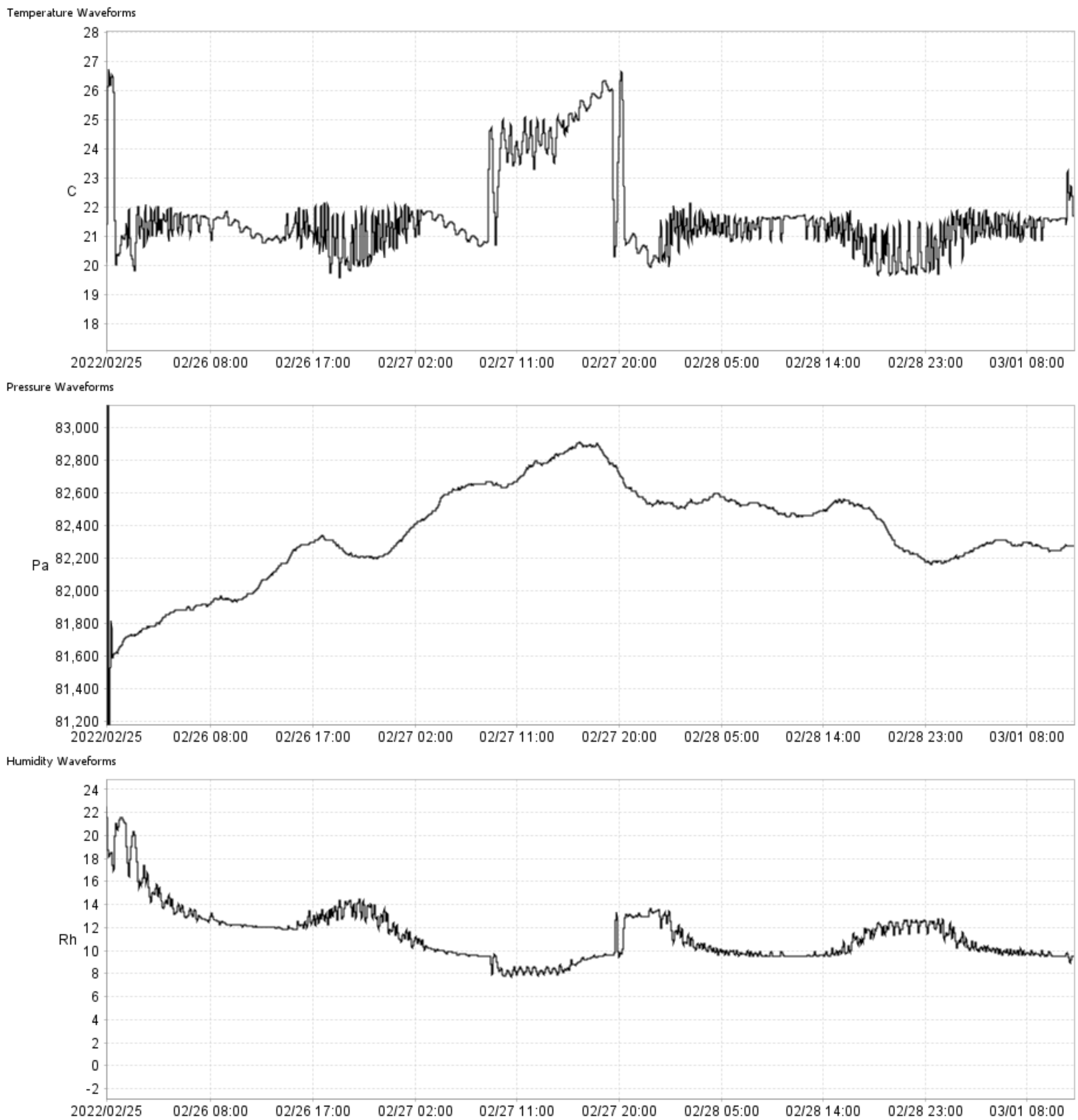

Figure 42 Environmental Conditions Outside Chamber During Temperature Testing

In addition, continuous measurement of the static pressure within the manifold was made with the reference Setra 278, shown below:

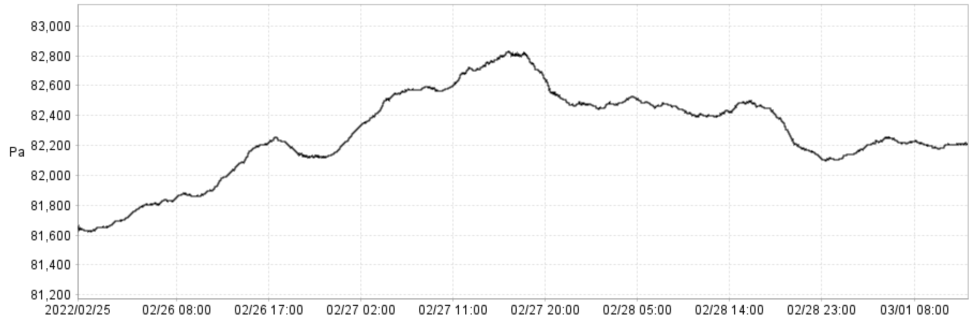

Figure 43 Static Pressure Within Manifold During Temperature Testing

As can be seen, the static pressure throughout the period of testing is 822 hPa within +/- 6 hPa. The temperature outside of the chamber was 23 C, +/- 3 C during the temperature testing. These environmental variations that impact the reference sensor are accounted for in the combined uncertainty model.

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

3.11.3 Analysis

For the tonal analysis, a minimum of 10 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f / 2 to f * 2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in volts to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

$$V_{test} \sin(2\, pi\, f_{test}\, t + \theta_{test}) + V_{dc\, test}$$

The sensor amplitude sensitivity in Volts / Pascal is computed:

$$S_{amp} = \frac{V_{test}}{P_{ref}}$$

The sensor phase sensitivity in degrees is computed:

$$S_{phase} = \theta_{test} - \theta_{ref}$$

Measurements of amplitude and phase sensitivity were averaged over 4 measurements at different time periods.

The change in sensitivity, expressed as a percentage in amplitude and degrees in phase, at each temperature are computed relative to a reference temperature level:

$$Change\ S_{amp}(Temp) = 100 * \frac{(S_{amp}(Temp) - S_{amp}(Ref\ Temp))}{S_{amp}(Ref\ Temp)}$$

$$Change\ S_{phase}(Temp) = S_{phase}(Temp) - S_{phase}(Ref\ Temp)$$

3.11.4 Result

The figure below shows a representative waveform time series for the tonal recording made on the reference sensor and sensors under test. The window regions bounded by the colored lines indicate the segment of data used for analysis.

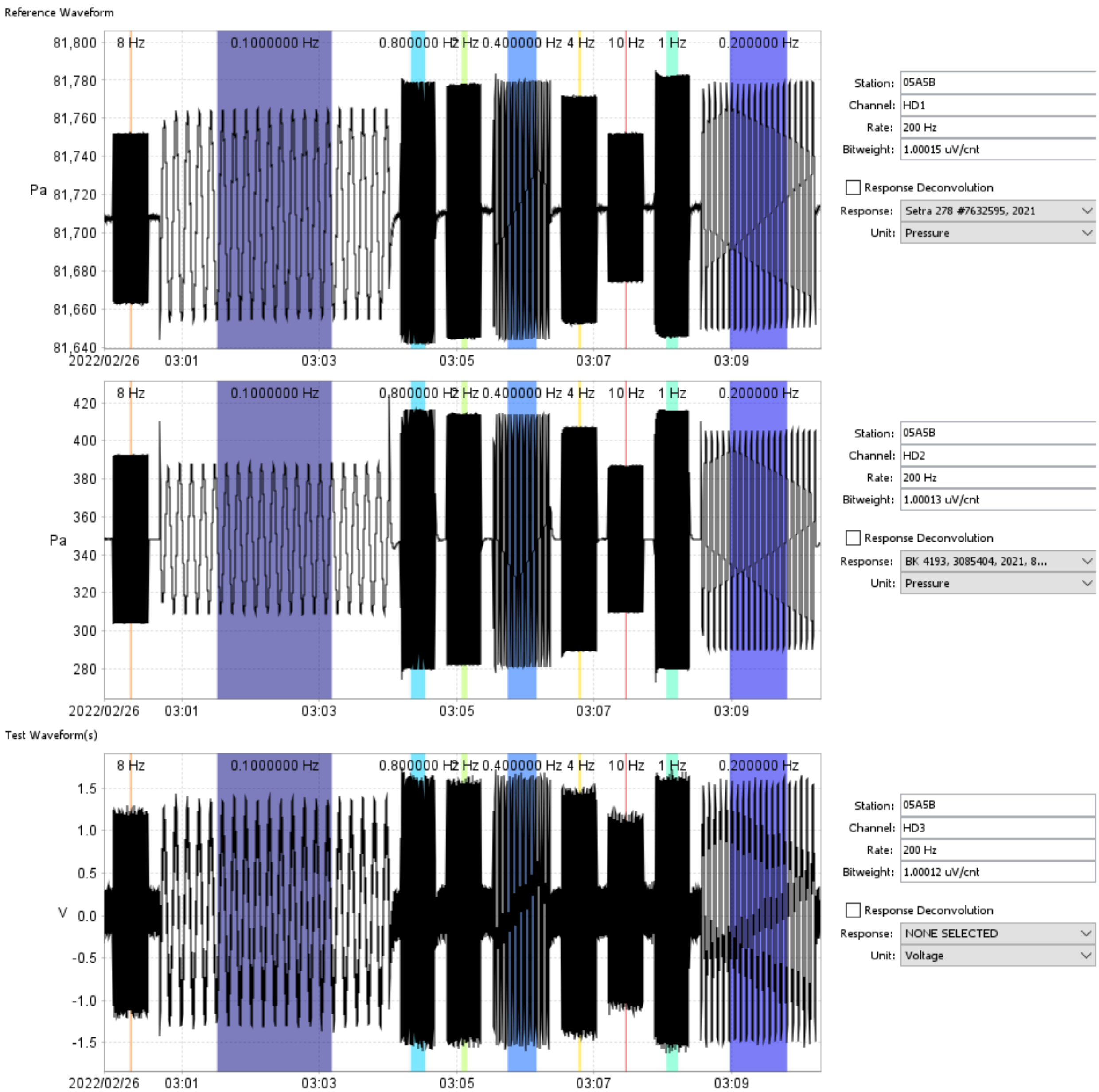

Figure 44 Static Temperature Response Waveforms

The top two waveforms are the references, with the unit of Pascals of pressure, and the remaining waveforms are from the sensors under test, with units in Volts. Only a single waveform from a sensor under test is shown.

The plots of the change in amplitude sensitivity at the various steps over -20 C to +50 C, in both positive and negative directions, are shown below for each of the sensors evaluated. The percent change at each frequency and temperature level is computed relative to a similar measurement made at that frequency just before the temperature chamber sequence was started.

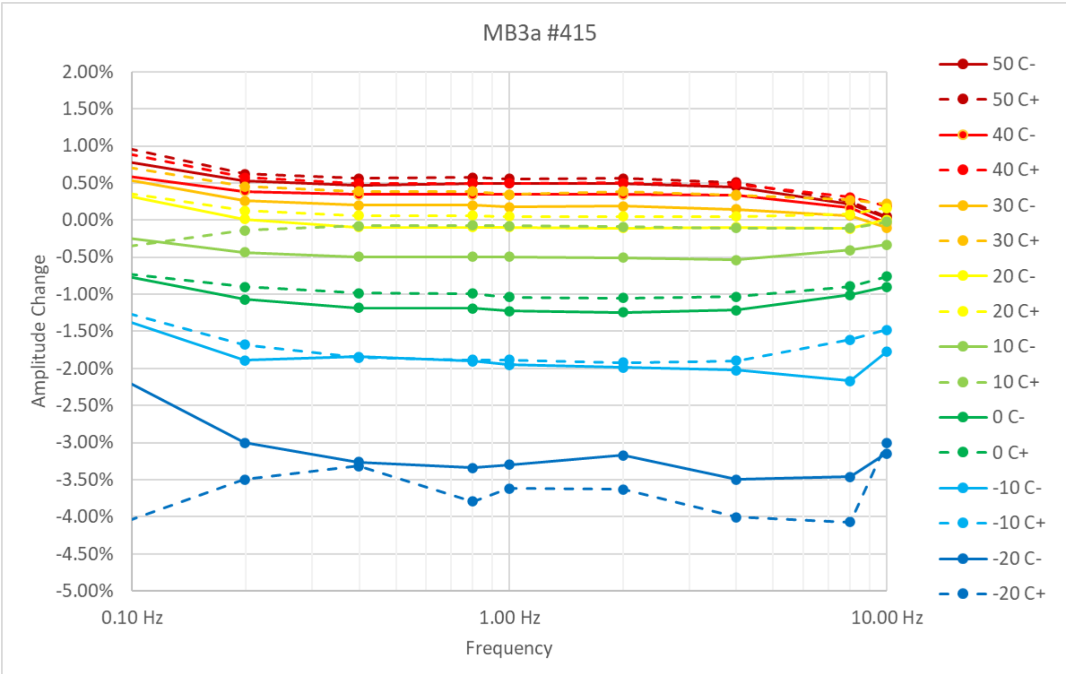

Figure 45 Amplitude Response Variation with Static Temperature, MB3a #415

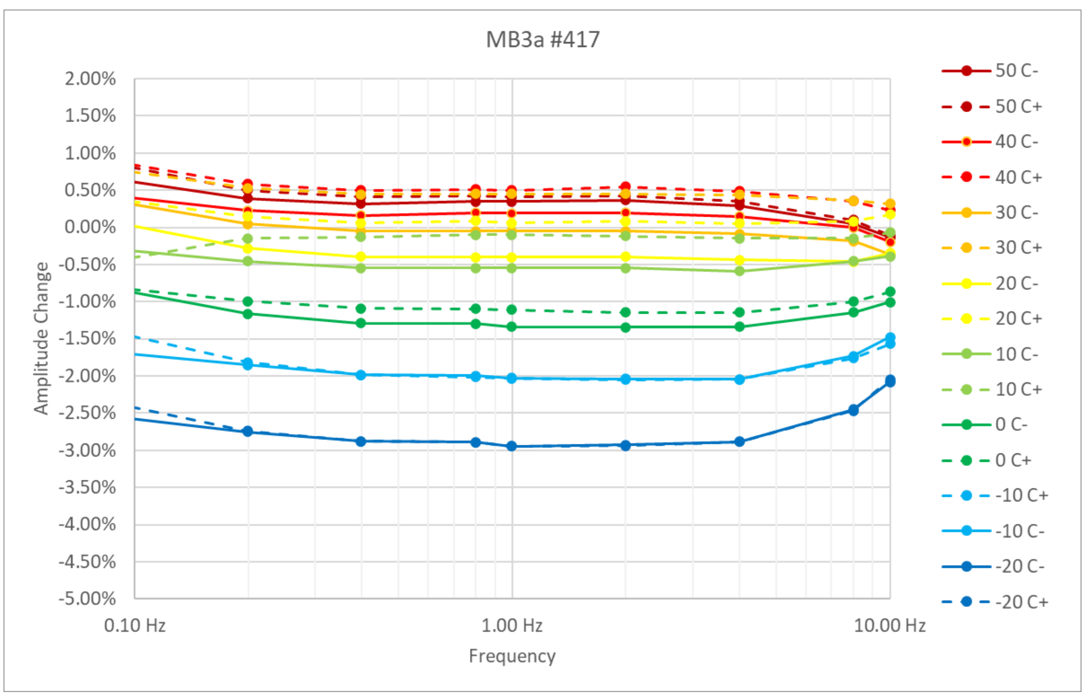

Figure 46 Amplitude Response Variation with Static Temperature, MB3a #417

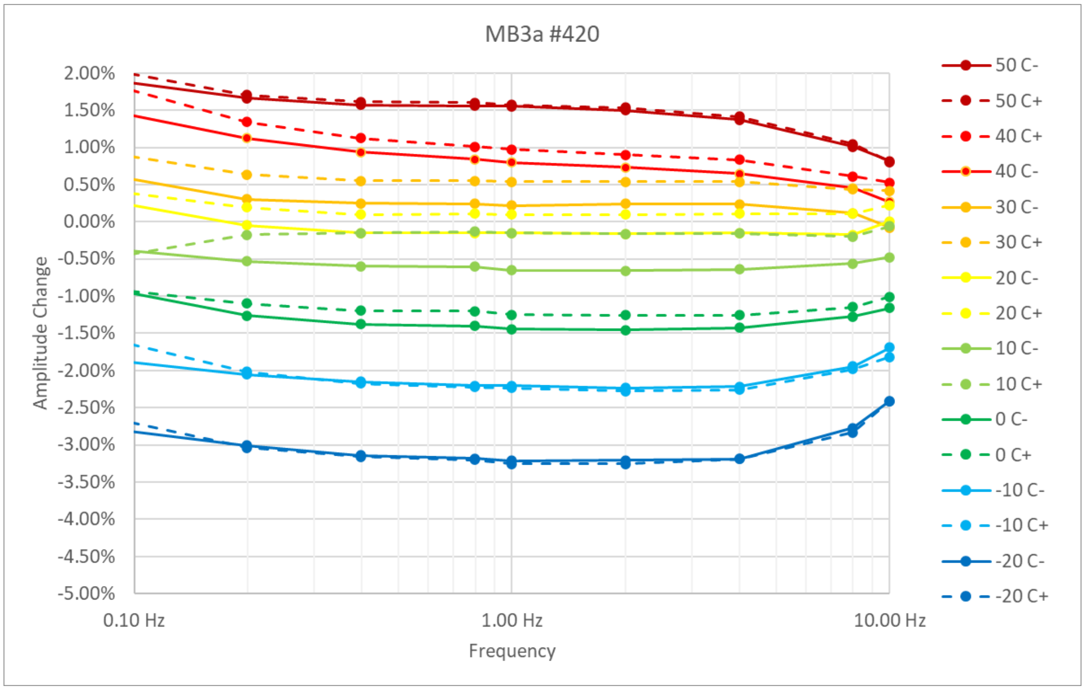

Figure 47 Amplitude Response Variation with Static Temperature, MB3a #420

There was greater variability in the results from MB3a #415 due to elevated noise present in the waveform time series that reduced the SNR. As elevated noise was not observed to be present on this sensor in other tests, this is believed to be due to the environment. MB3a #415 was placed in the back of the temperature chamber and close to the blower. It is possible that the sensor placement is the cause of the elevated noise.

The measurements at each temperature step were very consistent between the repeated measurements made in both the positive and negative directions, indicating that the results were repeatable, and the sensor had adequately equilibrated to the temperature level.

In general, all of the sensors demonstrated a reduction in sensitivity at colder temperatures, between -3% and -3.5% at -20 C, and an increase in sensitivity at hotter temperatures, between +0.5% and +1.5% at 50C.

At frequencies above 4 Hz, there appears to be less variability in amplitude sensitivity as a function of temperature. This has not been observed in earlier measurements of temperature on MB3a amplitude response (Merchant, 2019) in similar test configurations. It is unknown whether this change in performance is due to a change in the sensor design or an unaccounted-for change in the test configuration.

The plots of the change in phase sensitivity at the various steps over -20 C to +50 C, in both positive and negative directions, are shown below for each of the sensors evaluated. The change in phase at each frequency and temperature level is computed relative to a similar measurement made at that frequency just before the temperature chamber sequence was started.

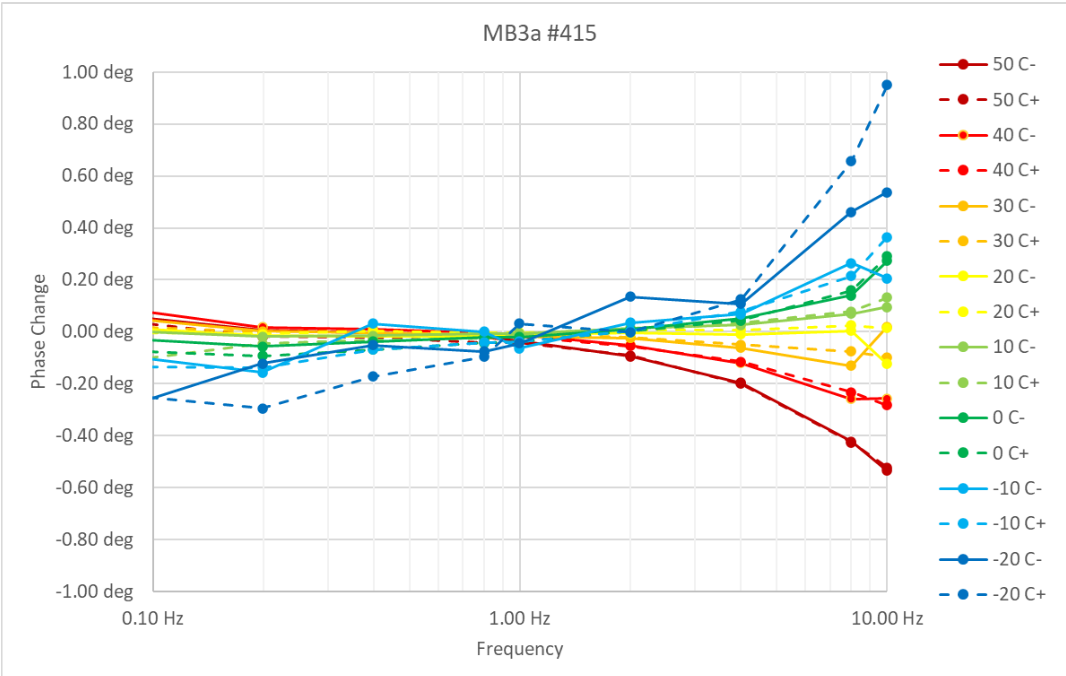

Figure 48 Phase Response Variation with Static Temperature, MB3a #415

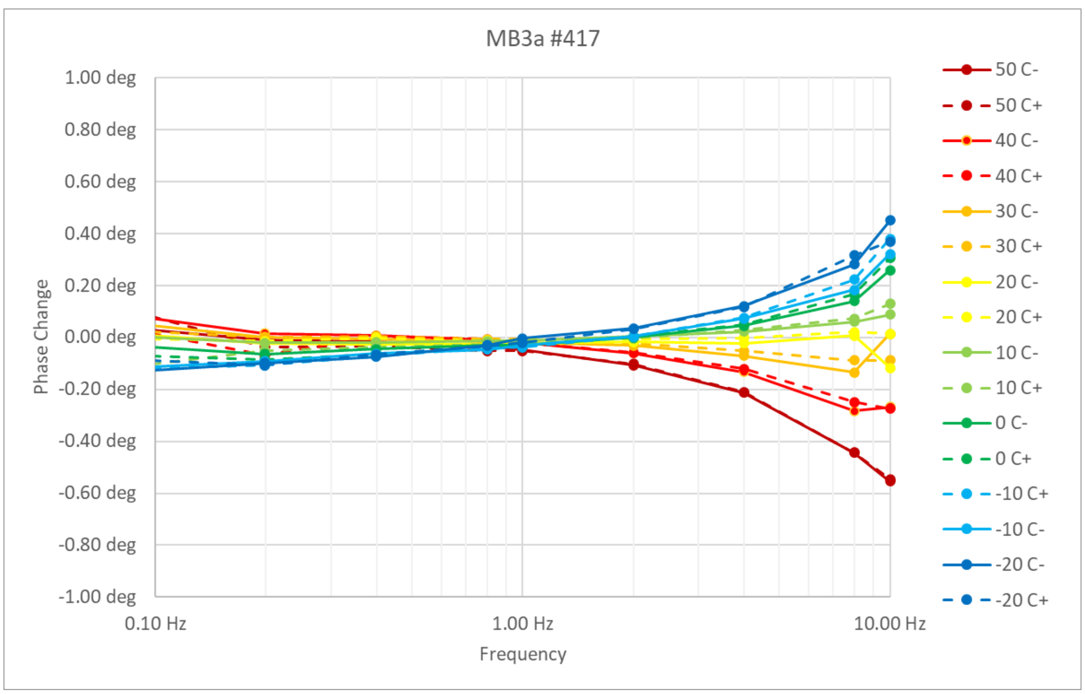

Figure 49 Phase Response Variation with Static Temperature, MB3a #417

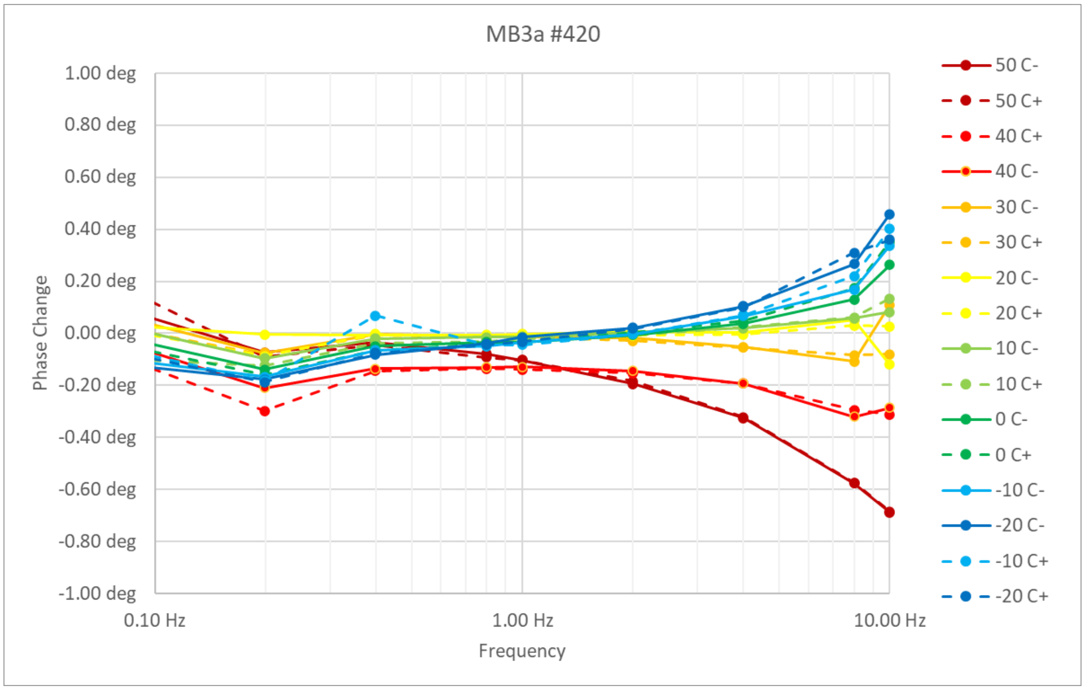

Figure 50 Phase Response Variation with Static Temperature, MB3a #420

Similar to the amplitude measurements, there was greater variability in the results from MB3a #415 due to reduced SNR.

The measurements at each temperature step were very consistent between the repeated measurements made in both the positive and negative directions, indicating that the results were repeatable, and the sensor had adequately equilibrated to the temperature level.

Although there was some change in phase response that appears to be due to temperature, the change in phase is very small at less than +/- 0.2 degrees at frequencies at and below 2 Hz. At frequencies above 2 Hz, there were small variations in phase response as a function of temperature, reaching changes as much as +/- 0.8 degrees at 10 Hz.

Table 28 Static Temperature Relative Amplitude and Phase Uncertainty

Uncertainty (k=2)	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
Amplitude	0.47%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Phase	0.28 deg	0.24 deg	0.20 deg	0.09 deg	0.09 deg	0.09 deg	0.09 deg	0.09 deg	0.09 deg

Below are the tables of values measured for each of the sensors under test.

Table 29 Static Temperature Amplitude Response Variation: MB3a #415

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
10 C-	-0.25%	-0.44%	-0.49%	-0.50%	-0.50%	-0.50%	-0.53%	-0.41%	-0.33%
0 C-	-0.76%	-1.07%	-1.18%	-1.19%	-1.23%	-1.25%	-1.21%	-1.01%	-0.90%
-10 C-	-1.37%	-1.89%	-1.84%	-1.90%	-1.95%	-1.99%	-2.02%	-2.17%	-1.78%
-20 C-	-2.19%	-3.00%	-3.26%	-3.34%	-3.30%	-3.17%	-3.50%	-3.46%	-3.15%
-20 C+	-4.05%	-3.50%	-3.31%	-3.80%	-3.62%	-3.63%	-4.00%	-4.07%	-3.01%
-10 C+	-1.26%	-1.68%	-1.85%	-1.88%	-1.88%	-1.92%	-1.90%	-1.61%	-1.48%
0 C+	-0.73%	-0.90%	-0.99%	-0.99%	-1.04%	-1.05%	-1.03%	-0.89%	-0.76%
10 C+	-0.36%	-0.14%	-0.08%	-0.07%	-0.08%	-0.09%	-0.11%	-0.11%	-0.03%
20 C+	0.36%	0.13%	0.06%	0.06%	0.05%	0.05%	0.05%	0.08%	0.16%
30 C+	0.71%	0.46%	0.38%	0.39%	0.35%	0.39%	0.34%	0.27%	0.22%
40 C+	0.89%	0.57%	0.49%	0.50%	0.50%	0.50%	0.49%	0.31%	0.19%
50 C+	0.96%	0.62%	0.56%	0.57%	0.56%	0.56%	0.51%	0.25%	0.05%
50 C-	0.78%	0.52%	0.47%	0.50%	0.50%	0.49%	0.45%	0.22%	0.03%
40 C-	0.60%	0.39%	0.35%	0.35%	0.35%	0.35%	0.33%	0.16%	-0.04%
30 C-	0.54%	0.26%	0.20%	0.20%	0.18%	0.19%	0.15%	0.06%	-0.10%
20 C-	0.32%	0.01%	-0.10%	-0.10%	-0.10%	-0.11%	-0.10%	-0.12%	0.01%

Table 30 Static Temperature Amplitude Response Variation: MB3a #417

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
10 C-	-0.31%	-0.46%	-0.55%	-0.55%	-0.55%	-0.55%	-0.59%	-0.45%	-0.39%
0 C-	-0.87%	-1.16%	-1.29%	-1.30%	-1.34%	-1.34%	-1.34%	-1.14%	-1.01%
-10 C-	-1.70%	-1.85%	-1.99%	-2.00%	-2.03%	-2.04%	-2.04%	-1.73%	-1.47%
-20 C-	-2.57%	-2.75%	-2.88%	-2.89%	-2.94%	-2.93%	-2.89%	-2.45%	-2.08%
-20 C+	-2.41%	-2.74%	-2.88%	-2.89%	-2.94%	-2.94%	-2.89%	-2.47%	-2.05%
-10 C+	-1.46%	-1.81%	-1.99%	-2.01%	-2.02%	-2.05%	-2.04%	-1.76%	-1.57%
0 C+	-0.83%	-1.00%	-1.09%	-1.10%	-1.11%	-1.14%	-1.14%	-1.00%	-0.87%
10 C+	-0.41%	-0.15%	-0.13%	-0.10%	-0.10%	-0.12%	-0.15%	-0.15%	-0.07%
20 C+	0.35%	0.15%	0.06%	0.09%	0.06%	0.08%	0.05%	0.08%	0.17%
30 C+	0.76%	0.53%	0.45%	0.45%	0.45%	0.45%	0.44%	0.36%	0.32%
40 C+	0.85%	0.59%	0.50%	0.51%	0.50%	0.55%	0.49%	0.35%	0.23%
50 C+	0.81%	0.50%	0.41%	0.43%	0.41%	0.43%	0.35%	0.10%	-0.11%
50 C-	0.62%	0.39%	0.32%	0.35%	0.35%	0.37%	0.29%	0.05%	-0.14%
40 C-	0.40%	0.22%	0.16%	0.20%	0.19%	0.20%	0.15%	0.00%	-0.20%
30 C-	0.31%	0.05%	-0.05%	-0.05%	-0.05%	-0.05%	-0.09%	-0.18%	-0.37%
20 C-	0.03%	-0.28%	-0.40%	-0.40%	-0.40%	-0.40%	-0.44%	-0.46%	-0.35%

Table 31 Static Temperature Amplitude Response Variation: MB3a #420

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
10 C-	-0.39%	-0.53%	-0.60%	-0.60%	-0.65%	-0.66%	-0.64%	-0.56%	-0.48%
0 C-	-0.96%	-1.26%	-1.37%	-1.40%	-1.44%	-1.46%	-1.42%	-1.27%	-1.16%
-10 C-	-1.89%	-2.06%	-2.15%	-2.20%	-2.20%	-2.24%	-2.22%	-1.94%	-1.69%
-20 C-	-2.82%	-3.01%	-3.14%	-3.18%	-3.21%	-3.20%	-3.19%	-2.77%	-2.41%
-20 C+	-2.70%	-3.03%	-3.16%	-3.20%	-3.25%	-3.25%	-3.19%	-2.83%	-2.41%
-10 C+	-1.65%	-2.02%	-2.17%	-2.22%	-2.23%	-2.28%	-2.26%	-1.98%	-1.82%
0 C+	-0.93%	-1.10%	-1.20%	-1.20%	-1.25%	-1.26%	-1.26%	-1.14%	-1.01%
10 C+	-0.43%	-0.18%	-0.15%	-0.13%	-0.15%	-0.16%	-0.16%	-0.20%	-0.06%
20 C+	0.39%	0.20%	0.10%	0.11%	0.10%	0.10%	0.11%	0.11%	0.22%
30 C+	0.88%	0.64%	0.55%	0.55%	0.54%	0.54%	0.54%	0.44%	0.42%
40 C+	1.77%	1.34%	1.13%	1.01%	0.97%	0.90%	0.83%	0.61%	0.53%
50 C+	2.00%	1.70%	1.61%	1.60%	1.57%	1.54%	1.41%	1.04%	0.80%
50 C-	1.87%	1.66%	1.57%	1.56%	1.55%	1.50%	1.37%	1.01%	0.82%
40 C-	1.43%	1.13%	0.94%	0.84%	0.80%	0.73%	0.65%	0.45%	0.26%
30 C-	0.58%	0.30%	0.25%	0.24%	0.22%	0.24%	0.24%	0.12%	-0.08%
20 C-	0.23%	-0.05%	-0.15%	-0.15%	-0.15%	-0.16%	-0.15%	-0.17%	0.01%

Table 32 Static Temperature Phase Response Variation: MB3a #415

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
10 C-	0.00 deg	-0.02 deg	-0.01 deg	-0.01 deg	-0.01 deg	0.01 deg	0.03 deg	0.07 deg	0.10 deg
0 C-	-0.03 deg	-0.06 deg	-0.04 deg	-0.02 deg	-0.02 deg	0.01 deg	0.05 deg	0.14 deg	0.27 deg
-10 C-	-0.11 deg	-0.16 deg	0.03 deg	0.00 deg	-0.06 deg	0.04 deg	0.07 deg	0.26 deg	0.21 deg
-20 C-	-0.26 deg	-0.12 deg	-0.05 deg	-0.07 deg	-0.04 deg	0.14 deg	0.11 deg	0.46 deg	0.54 deg
-20 C+	-0.25 deg	-0.29 deg	-0.17 deg	-0.10 deg	0.03 deg	0.00 deg	0.12 deg	0.66 deg	0.95 deg
-10 C+	-0.14 deg	-0.14 deg	-0.07 deg	-0.04 deg	-0.04 deg	0.00 deg	0.08 deg	0.21 deg	0.36 deg
0 C+	-0.08 deg	-0.09 deg	-0.07 deg	-0.04 deg	-0.04 deg	0.00 deg	0.04 deg	0.16 deg	0.29 deg
10 C+	-0.10 deg	-0.05 deg	-0.03 deg	-0.02 deg	-0.01 deg	0.00 deg	0.03 deg	0.08 deg	0.13 deg
20 C+	0.00 deg	-0.01 deg	0.00 deg	0.00 deg	0.00 deg	0.00 deg	0.01 deg	0.02 deg	0.01 deg
30 C+	0.02 deg	0.00 deg	0.00 deg	-0.01 deg	-0.01 deg	-0.02 deg	-0.05 deg	-0.08 deg	-0.10 deg
40 C+	0.05 deg	0.00 deg	0.00 deg	-0.01 deg	-0.02 deg	-0.05 deg	-0.11 deg	-0.23 deg	-0.28 deg
50 C+	0.03 deg	-0.02 deg	-0.02 deg	-0.04 deg	-0.04 deg	-0.09 deg	-0.20 deg	-0.43 deg	-0.52 deg
50 C-	0.05 deg	0.01 deg	0.00 deg	-0.02 deg	-0.03 deg	-0.09 deg	-0.20 deg	-0.42 deg	-0.53 deg
40 C-	0.08 deg	0.02 deg	0.01 deg	0.00 deg	-0.01 deg	-0.05 deg	-0.12 deg	-0.26 deg	-0.26 deg
30 C-	0.04 deg	0.00 deg	0.00 deg	-0.01 deg	-0.02 deg	-0.02 deg	-0.06 deg	-0.13 deg	0.02 deg
20 C-	0.01 deg	-0.01 deg	-0.02 deg	-0.02 deg	-0.01 deg	0.00 deg	-0.01 deg	0.00 deg	-0.12 deg

Table 33 Static Temperature Phase Response Variation: MB3a #417

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
10 C-	0.00 deg	-0.02 deg	-0.02 deg	-0.01 deg	-0.01 deg	0.01 deg	0.02 deg	0.06 deg	0.09 deg
0 C-	-0.04 deg	-0.06 deg	-0.05 deg	-0.03 deg	-0.03 deg	0.00 deg	0.04 deg	0.14 deg	0.26 deg
-10 C-	-0.11 deg	-0.09 deg	-0.06 deg	-0.05 deg	-0.03 deg	0.00 deg	0.07 deg	0.18 deg	0.32 deg
-20 C-	-0.13 deg	-0.10 deg	-0.07 deg	-0.03 deg	0.00 deg	0.03 deg	0.12 deg	0.28 deg	0.45 deg
-20 C+	-0.09 deg	-0.11 deg	-0.07 deg	-0.03 deg	-0.02 deg	0.03 deg	0.12 deg	0.32 deg	0.37 deg
-10 C+	-0.12 deg	-0.11 deg	-0.07 deg	-0.04 deg	-0.04 deg	0.00 deg	0.08 deg	0.22 deg	0.38 deg
0 C+	-0.07 deg	-0.09 deg	-0.06 deg	-0.04 deg	-0.04 deg	0.00 deg	0.05 deg	0.17 deg	0.31 deg
10 C+	-0.10 deg	-0.05 deg	-0.04 deg	-0.03 deg	-0.02 deg	0.00 deg	0.03 deg	0.07 deg	0.13 deg
20 C+	-0.01 deg	-0.01 deg	0.00 deg	-0.01 deg	-0.01 deg	-0.01 deg	0.00 deg	0.02 deg	0.01 deg
30 C+	0.02 deg	0.00 deg	0.00 deg	-0.01 deg	-0.01 deg	-0.02 deg	-0.05 deg	-0.09 deg	-0.09 deg
40 C+	0.01 deg	-0.07 deg	0.00 deg	-0.01 deg	-0.02 deg	-0.06 deg	-0.12 deg	-0.25 deg	-0.27 deg
50 C+	0.08 deg	-0.04 deg	-0.03 deg	-0.05 deg	-0.05 deg	-0.10 deg	-0.21 deg	-0.44 deg	-0.55 deg
50 C-	0.03 deg	-0.01 deg	-0.02 deg	-0.03 deg	-0.05 deg	-0.11 deg	-0.21 deg	-0.44 deg	-0.55 deg
40 C-	0.07 deg	0.02 deg	0.01 deg	-0.01 deg	-0.02 deg	-0.06 deg	-0.13 deg	-0.28 deg	-0.27 deg
30 C-	0.04 deg	0.00 deg	-0.01 deg	-0.02 deg	-0.02 deg	-0.03 deg	-0.07 deg	-0.13 deg	0.01 deg
20 C-	0.01 deg	-0.02 deg	-0.03 deg	-0.03 deg	-0.02 deg	-0.02 deg	-0.02 deg	0.01 deg	-0.12 deg

Table 34 Static Temperature Phase Response Variation: MB3a #420

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
10 C-	0.00 deg	-0.10 deg	-0.02 deg	-0.01 deg	-0.01 deg	0.00 deg	0.02 deg	0.06 deg	0.08 deg
0 C-	-0.04 deg	-0.14 deg	-0.05 deg	-0.03 deg	-0.03 deg	-0.01 deg	0.04 deg	0.13 deg	0.26 deg
-10 C-	-0.11 deg	-0.17 deg	-0.07 deg	-0.05 deg	-0.03 deg	0.00 deg	0.07 deg	0.17 deg	0.34 deg
-20 C-	-0.13 deg	-0.18 deg	-0.08 deg	-0.04 deg	-0.01 deg	0.02 deg	0.10 deg	0.27 deg	0.46 deg
-20 C+	-0.10 deg	-0.19 deg	-0.07 deg	-0.04 deg	-0.03 deg	0.02 deg	0.10 deg	0.31 deg	0.36 deg
-10 C+	-0.09 deg	-0.18 deg	0.07 deg	-0.05 deg	-0.04 deg	0.00 deg	0.07 deg	0.22 deg	0.40 deg
0 C+	-0.07 deg	-0.16 deg	-0.06 deg	-0.04 deg	-0.04 deg	0.00 deg	0.05 deg	0.17 deg	0.35 deg
10 C+	-0.10 deg	-0.12 deg	-0.04 deg	-0.03 deg	-0.02 deg	-0.01 deg	0.02 deg	0.06 deg	0.13 deg
20 C+	-0.01 deg	-0.09 deg	0.00 deg	-0.01 deg	-0.01 deg	-0.01 deg	0.00 deg	0.03 deg	0.03 deg
30 C+	0.00 deg	-0.08 deg	-0.01 deg	-0.01 deg	-0.01 deg	-0.03 deg	-0.05 deg	-0.08 deg	-0.08 deg
40 C+	-0.14 deg	-0.30 deg	-0.14 deg	-0.14 deg	-0.14 deg	-0.15 deg	-0.19 deg	-0.29 deg	-0.31 deg
50 C+	0.12 deg	-0.09 deg	-0.04 deg	-0.09 deg	-0.10 deg	-0.18 deg	-0.32 deg	-0.57 deg	-0.68 deg
50 C-	0.06 deg	-0.07 deg	-0.04 deg	-0.08 deg	-0.10 deg	-0.19 deg	-0.32 deg	-0.58 deg	-0.69 deg
40 C-	-0.07 deg	-0.21 deg	-0.14 deg	-0.13 deg	-0.13 deg	-0.14 deg	-0.19 deg	-0.32 deg	-0.29 deg
30 C-	0.04 deg	-0.07 deg	0.00 deg	-0.01 deg	-0.01 deg	-0.02 deg	-0.05 deg	-0.11 deg	0.11 deg
20 C-	0.02 deg	0.00 deg	-0.01 deg	-0.01 deg	0.00 deg	0.01 deg	0.00 deg	0.05 deg	-0.12 deg

3.12 Static Pressure Response Variation

The sensitivity variation with static pressure is defined as being the observable change in sensor sensitivity as the ambient static pressure is varied. The purpose of this test is to confirm that the sensor's sensitivity will be sufficiently stable when they are deployed in an environment where the barometric pressure will vary over time from when the sensor was first installed.

3.12.1 Measurand

The measured quantity is the percent change in sensitivity as a function of barometric pressure.

3.12.2 Configuration

The infrasound sensor under test and a reference sensor with known response characteristics are placed inside of a pressure isolation chamber. The isolation chamber serves to attenuate any external ambient variations in pressure.

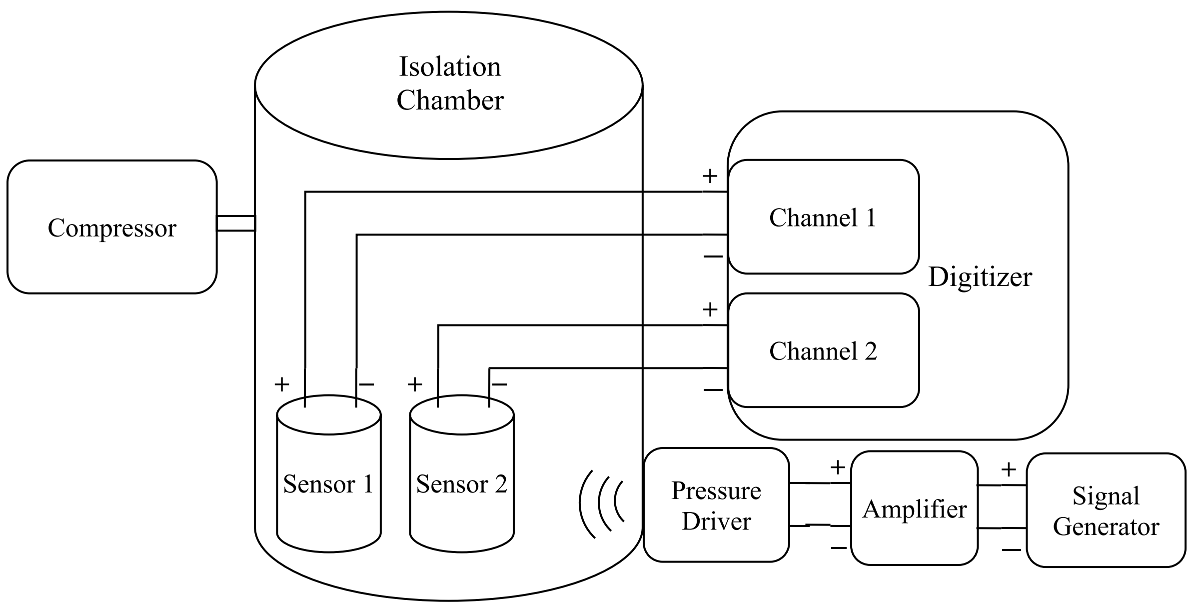

Figure 51 Static Pressure Response Configuration Diagram

A pressure driver is attached to an inlet port on the isolation chamber. The pressure driver is driven with a sinusoid from a signal generator. The pressure driver serves to generate a pressure wave with characteristics defined by the signal generator. This pressure wave is recorded by both the reference sensor and the sensor under test.

In addition, a compressor is attached to the isolation chamber and used to change the static pressure within the isolation chamber during the evaluation.

Table 35 Static Pressure Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	3085404	2.115 mV/Pa at 1 Hz, 1013 hPa, 23 C, 0.005 dB/kPa correction
Infrasound Chamber	SNL	1400 L Chamber	1000 hPa, 23 C
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain 40 Vpp
Voltage Signal Source	Stanford Research Systems DS360	N/A	0.1 Hz – 10 Hz, 0.5 V sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A

The isolation chamber is pressurized to a known static pressure at which the sensors are equalized according to the manufacturer's direction, in this case 1013 hPa.

The static pressure was increased in 25 hPa steps to 1063 hPa and then decreased in 25 hPa steps to 983 hPa. The temperature within the chamber is maintained at 23.8 C, +/- 0.2 C, during this test. At each pressurization step, the sensors were allowed to re-equilibrate for a minimum of 5 minutes before the sensitivity of each sensor under test was evaluated against the reference sensor at selected frequencies between 0.1 and 10 Hz.

In this test, the B&K 4193 microphone was used as the reference to measure the dynamic pressure inside of the chamber. Corrections to the sensitivity of the microphone were performed to account for the different static pressure level at each step, according to the microphone datasheet of 0.005 dB/kPa of barometric pressure.

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

3.12.3 Analysis

For the tonal analysis, a minimum of 10 cycles, or 10 seconds at 1 Hz, of data is defined on the data for the recorded signal segment. The time series data for the reference sensor is corrected using the calibrated reference response to convert from voltage to pressure. Both the time series for the reference sensor and the sensors under test are filtered with a 2-octave band-pass filter from f / 2 to f * 2 for a nominal frequency of f.

A four-parameter sine fit (Merchant, 2011; IEEE-STD1281) is applied to the time segment from the reference sensor in Pascals and the sensor under test in volts in order to determine the sinusoid's amplitude, frequency, phase, and DC offset:

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

$$V_{test} \sin(2\, pi\, f_{test}\, t + \theta_{test}) + V_{dc\, test}$$

The sensor amplitude sensitivity in Volts / Pascal is computed:

$$S_{amp} = \frac{V_{test}}{P_{ref}}$$

The sensor phase sensitivity in degrees is computed:

$$S_{phase} = \theta_{test} - \theta_{ref}$$

The change in response, expressed as a percentage in amplitude and degrees in phase, at each barometric pressure are computed relative to a reference barometric pressure:

$$Change\ S_{amp}(Barometric) = 100 * \frac{(S_{amp}(Barometric) - S_{amp}(Ref\ Barometric))}{S_{amp}(Ref\ Barometric)}$$

$$Change\ S_{phase}(Barometric) = S_{phase}(Barometric) - S_{phase}(Ref\ Barometric)$$

3.12.4 Result

The figure below shows a representative waveform time series for the tonal recording made on the reference sensor and sensors under test. The window regions bounded by the colored lines indicate the segment of data used for analysis.

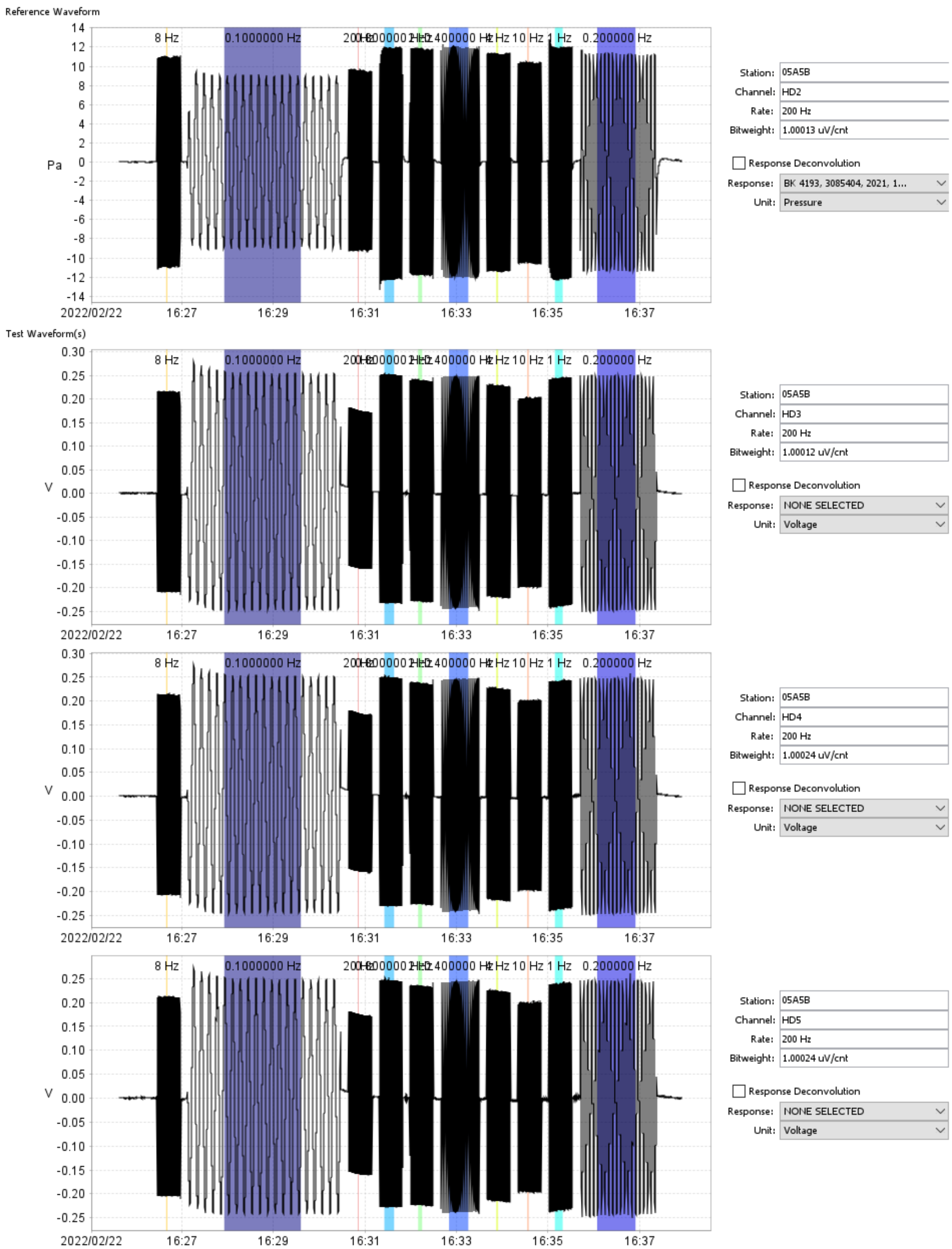

Figure 52 Static Pressure Response Waveforms

The top waveform is the reference, with the unit of Pascals of pressure, and the remaining waveforms are from the sensors under test, with units in Volts.

The plots of the change in amplitude response at the steps over +/- 50 hPa, in both positive and negative directions, are shown below for each of the sensors evaluated. The amplitude change at each frequency and barometric pressure level is computed relative to a similar measurement made at that frequency just before the pressurization changes were started.

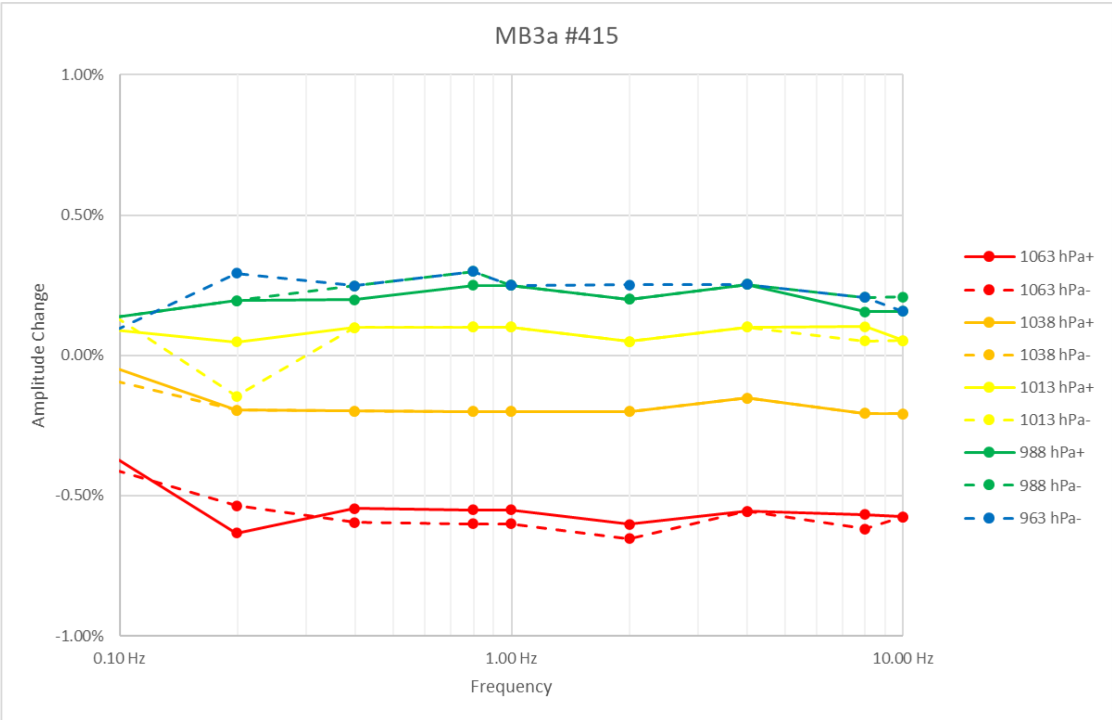

Figure 53 Amplitude Response Variation with Static Pressure, MB3a #415

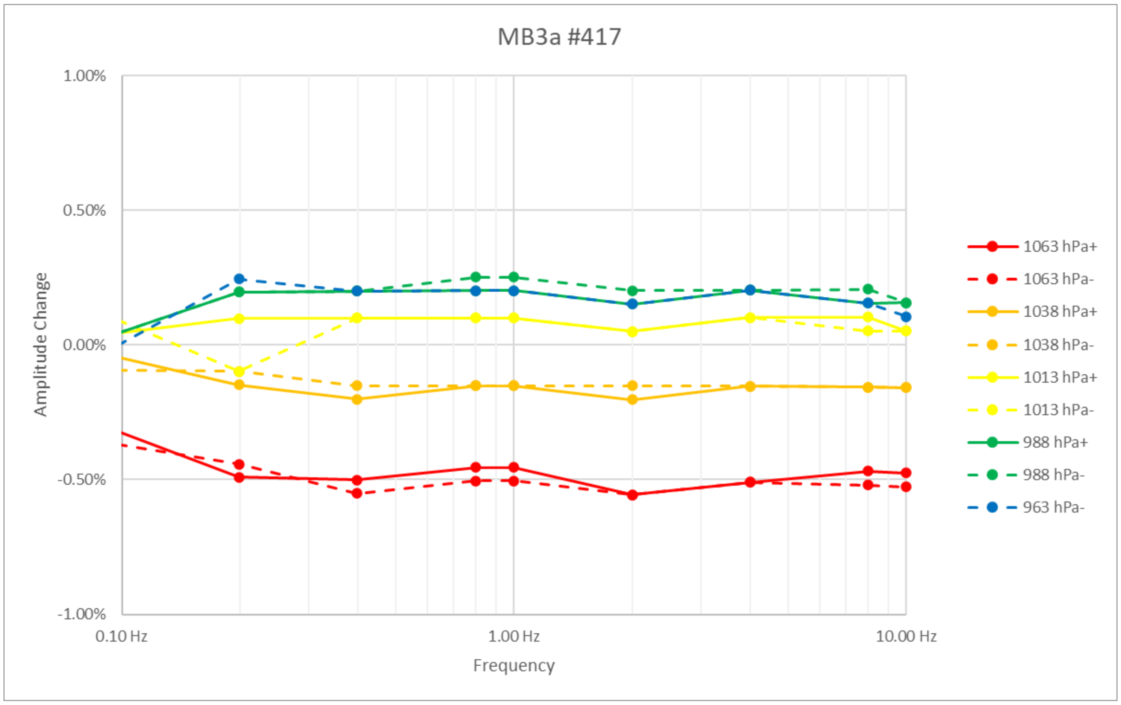

Figure 54 Amplitude Response Variation with Static Pressure, MB3a #417

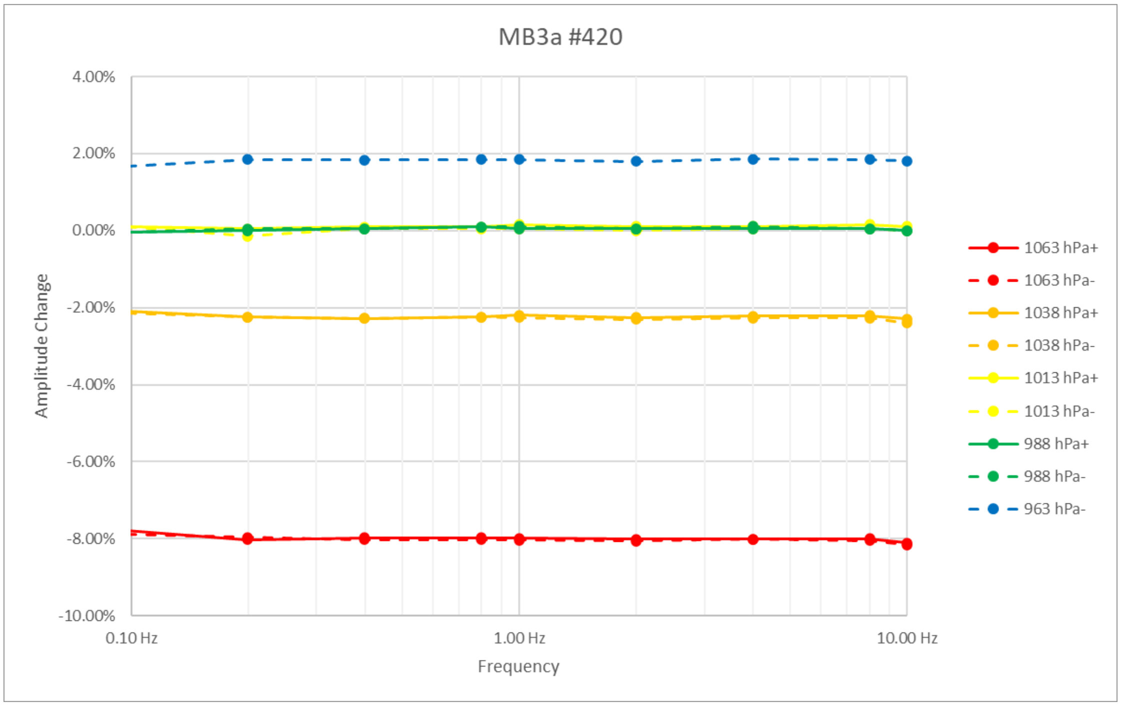

Figure 55 Amplitude Response Variation with Static Pressure, MB3a #420

Two of the MB3a, #415 and #417, exhibited small changes in amplitude response of less than +/- 0.2% for changes in barometric pressure of +/- 25 hPa. At changes of +/- 50 hPa of barometric pressure, which is far larger than would be expected to be seen in the environment variation of an operational station, changes in amplitude response were less than 0.5 %. These changes are small relative to the estimate of total combined uncertainty for relative measurement of amplitude that are as much as 0.5 % at 0.1 Hz and 0.3% for 0.2 Hz and above.

The third MB3a, #420, had larger variations in amplitude response with barometric pressure. The response changed by -2% at +25 hPa and -8% at +50 hPa. There was no observable change at -25 hPa and a +2% change at -50 hPa.

The plots of the change in phase response at the various steps over +/- 50 hPa, in both positive and negative directions, are shown below for each of the sensors evaluated. The phase change at each frequency and barometric pressure level is computed relative to a similar measurement made at that frequency just before the pressurization changes were started.

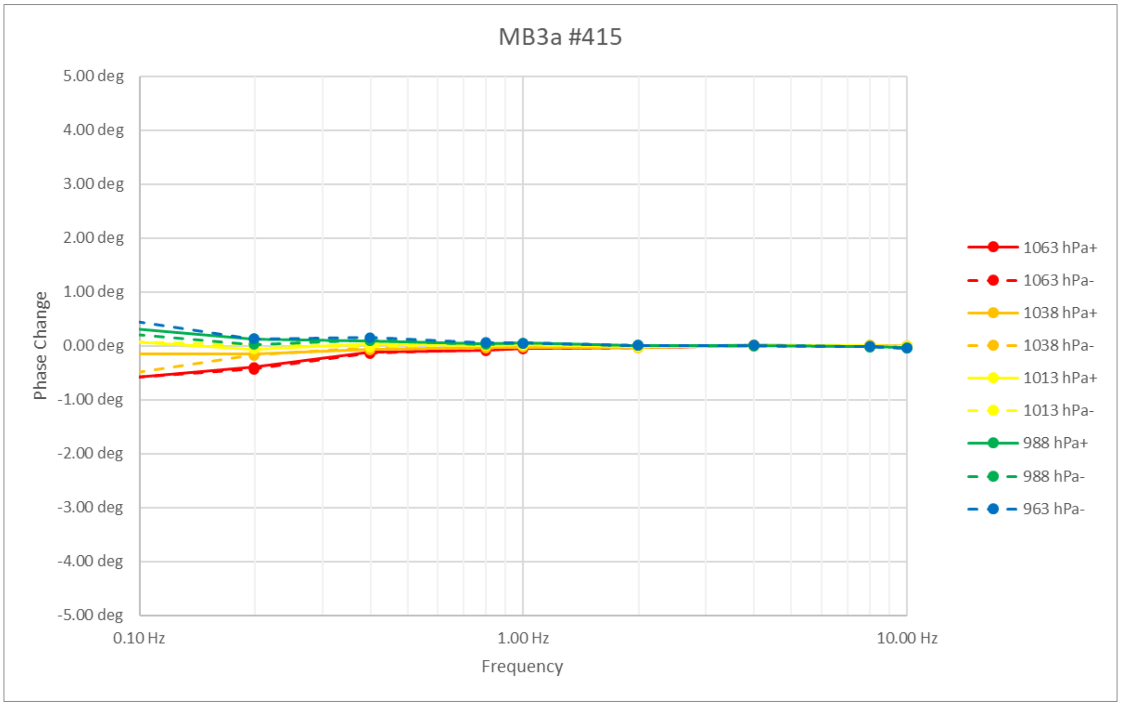

Figure 56 Phase Response Variation with Static Pressure, MB3a #415

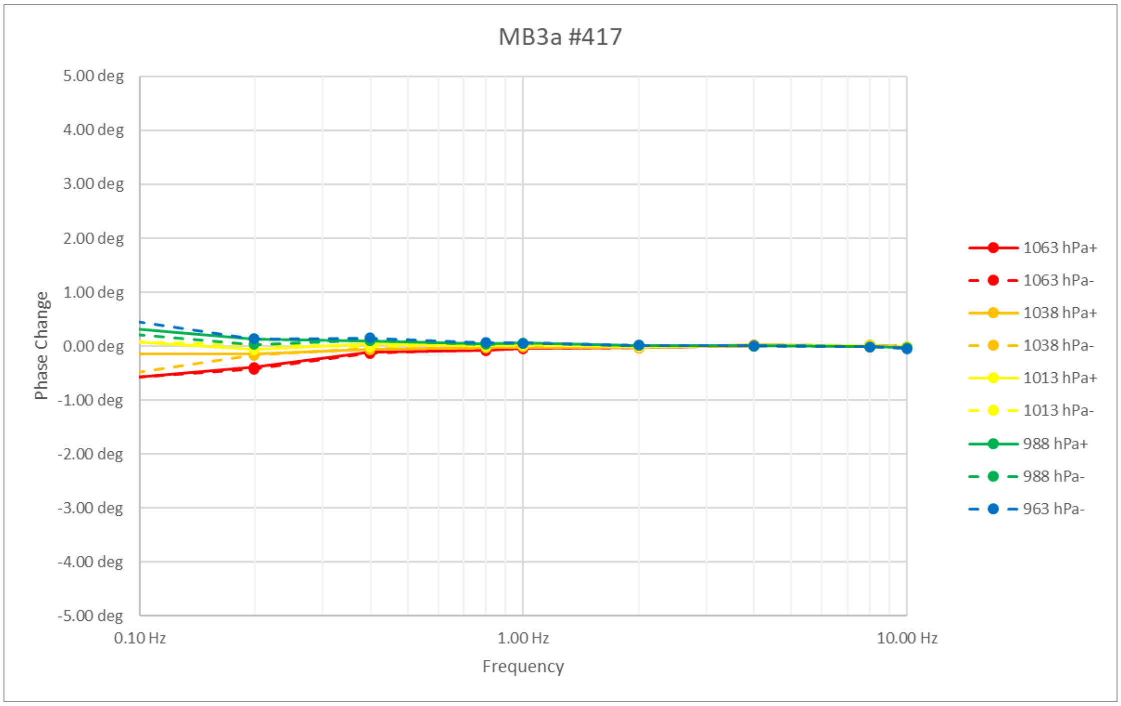

Figure 57 Phase Response Variation with Static Pressure, MB3a #417

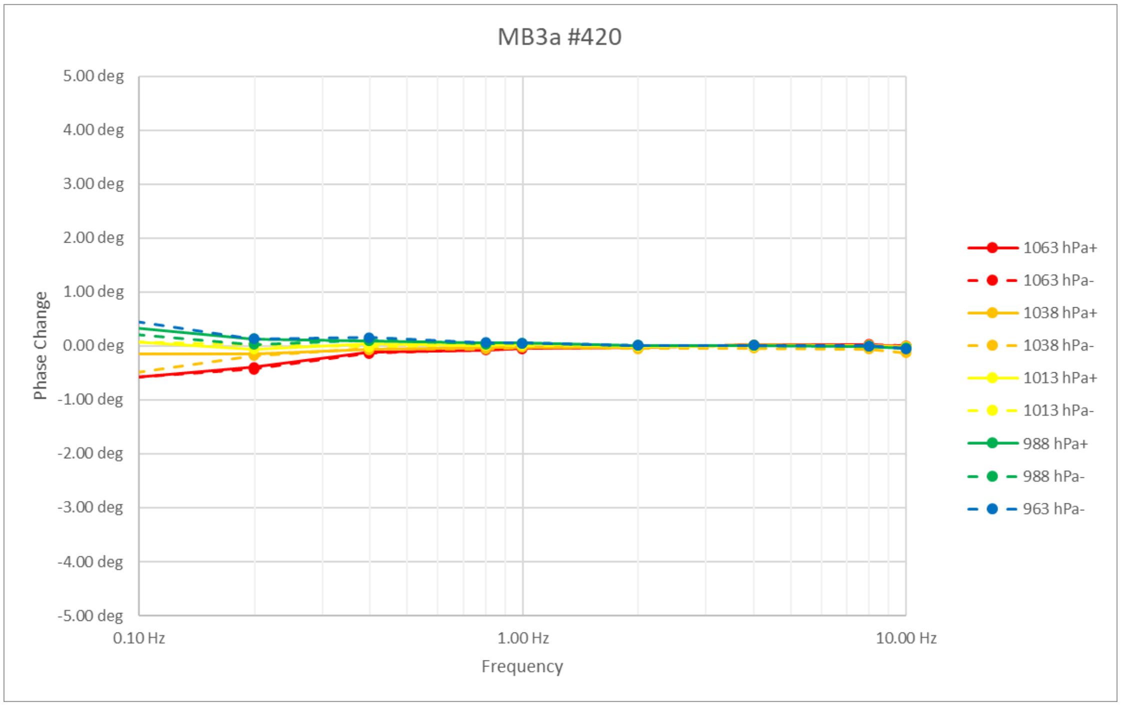

Figure 58 Phase Response Variation with Static Pressure, MB3a #420

The measurements at each barometric pressure step were very consistent between the repeated measurements made in both the positive and negative directions, indicating that the results were repeatable. The observed change in phase at low frequencies, as much as +/- 0.6 degree at 0.1 Hz, was consistent between all of the MB3a sensors as well as other models of infrasound sensors that were being tested simultaneously.

Given that the estimated total combined measurement uncertainty for relative phase at 0.1 Hz is 0.3 degrees and a different model of sensor that was being tested at the same time had near identical results, this result appears to be due to the contribution of the reference sensor. Therefore, there does not appear to be any significant variation in phase response for the MB3a due to variations in barometric pressure.

Table 36 Static Pressure Relative Amplitude and Phase Uncertainty

Uncertainty (k=2)	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz	10 Hz
Amplitude	0.47%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Phase	0.28 deg	0.24 deg	0.20 deg	0.09 deg	0.09 deg	0.09 deg	0.09 deg	0.09 deg	0.09 deg

Below are the tables of values measured for each of the sensors under test.

Table 37 Static Pressure Amplitude Response Variation: MB3a #415

	1038 hPa+	1063 hPa+	1063 hPa-	1038 hPa-	1013 hPa-	988 hPa-	963 hPa-	988 hPa+	1013 hPa+
0.10 Hz	-0.05%	-0.36%	-0.41%	-0.09%	0.14%	0.14%	0.09%	0.14%	0.09%
0.20 Hz	-0.19%	-0.63%	-0.54%	-0.19%	-0.15%	0.19%	0.29%	0.19%	0.05%
0.40 Hz	-0.20%	-0.55%	-0.60%	-0.20%	0.10%	0.25%	0.25%	0.20%	0.10%
0.80 Hz	-0.20%	-0.55%	-0.60%	-0.20%	0.10%	0.30%	0.30%	0.25%	0.10%
1.00 Hz	-0.20%	-0.55%	-0.60%	-0.20%	0.10%	0.25%	0.25%	0.25%	0.10%
2.00 Hz	-0.20%	-0.60%	-0.65%	-0.20%	0.05%	0.20%	0.25%	0.20%	0.05%
4.00 Hz	-0.15%	-0.56%	-0.56%	-0.15%	0.10%	0.25%	0.25%	0.25%	0.10%
8.00 Hz	-0.21%	-0.57%	-0.62%	-0.21%	0.05%	0.21%	0.21%	0.15%	0.10%
10.00 Hz	-0.21%	-0.58%	-0.58%	-0.21%	0.05%	0.21%	0.16%	0.16%	0.05%

Table 38 Static Pressure Amplitude Response Variation: MB3a #417

	1038 hPa+	1063 hPa+	1063 hPa-	1038 hPa-	1013 hPa-	988 hPa-	963 hPa-	988 hPa+	1013 hPa+
0.10 Hz	-0.05%	-0.32%	-0.37%	-0.09%	0.09%	0.05%	0.00%	0.05%	0.05%
0.20 Hz	-0.15%	-0.49%	-0.44%	-0.10%	-0.10%	0.20%	0.25%	0.20%	0.10%
0.40 Hz	-0.20%	-0.50%	-0.55%	-0.15%	0.10%	0.20%	0.20%	0.20%	0.10%
0.80 Hz	-0.15%	-0.45%	-0.50%	-0.15%	0.10%	0.25%	0.20%	0.20%	0.10%
1.00 Hz	-0.15%	-0.45%	-0.50%	-0.15%	0.10%	0.25%	0.20%	0.20%	0.10%
2.00 Hz	-0.20%	-0.56%	-0.56%	-0.15%	0.05%	0.20%	0.15%	0.15%	0.05%
4.00 Hz	-0.15%	-0.51%	-0.51%	-0.15%	0.10%	0.20%	0.20%	0.20%	0.10%
8.00 Hz	-0.16%	-0.47%	-0.52%	-0.16%	0.05%	0.21%	0.16%	0.16%	0.10%
10.00 Hz	-0.16%	-0.47%	-0.53%	-0.16%	0.05%	0.16%	0.11%	0.16%	0.05%

Table 39 Static Pressure Amplitude Response Variation: MB3a #420

	1038 hPa+	1063 hPa+	1063 hPa-	1038 hPa-	1013 hPa-	988 hPa-	963 hPa-	988 hPa+	1013 hPa+
0.10 Hz	-2.10%	-7.79%	-7.88%	-2.14%	0.09%	-0.05%	1.68%	-0.05%	0.09%
0.20 Hz	-2.24%	-8.02%	-7.97%	-2.24%	-0.15%	0.05%	1.84%	0.00%	0.05%
0.40 Hz	-2.29%	-7.97%	-8.02%	-2.29%	0.05%	0.05%	1.83%	0.05%	0.10%
0.80 Hz	-2.25%	-7.98%	-8.03%	-2.25%	0.05%	0.10%	1.84%	0.10%	0.10%
1.00 Hz	-2.20%	-7.98%	-8.03%	-2.25%	0.05%	0.10%	1.84%	0.05%	0.15%
2.00 Hz	-2.26%	-8.01%	-8.06%	-2.31%	0.00%	0.05%	1.80%	0.05%	0.10%
4.00 Hz	-2.22%	-8.01%	-8.01%	-2.27%	0.05%	0.10%	1.86%	0.05%	0.10%
8.00 Hz	-2.21%	-8.00%	-8.05%	-2.26%	0.05%	0.05%	1.84%	0.05%	0.16%
10.00 Hz	-2.29%	-8.11%	-8.16%	-2.40%	0.00%	0.00%	1.81%	0.00%	0.11%

Table 40 Static Pressure Phase Response Variation: MB3a #415

	1038 hPa+	1063 hPa+	1063 hPa-	1038 hPa-	1013 hPa-	988 hPa-	963 hPa-	988 hPa+	1013 hPa+
0.10 Hz	-0.15 deg	-0.59 deg	-0.59 deg	-0.49 deg	0.07 deg	0.21 deg	0.45 deg	0.32 deg	0.07 deg
0.20 Hz	-0.15 deg	-0.39 deg	-0.43 deg	-0.17 deg	0.03 deg	0.03 deg	0.13 deg	0.13 deg	-0.06 deg
0.40 Hz	-0.07 deg	-0.12 deg	-0.13 deg	-0.04 deg	-0.02 deg	0.10 deg	0.15 deg	0.09 deg	0.04 deg
0.80 Hz	-0.03 deg	-0.08 deg	-0.06 deg	-0.04 deg	0.02 deg	0.03 deg	0.06 deg	0.05 deg	0.01 deg
1.00 Hz	-0.02 deg	-0.04 deg	-0.05 deg	0.00 deg	0.01 deg	0.05 deg	0.05 deg	0.05 deg	0.03 deg
2.00 Hz	-0.03 deg	-0.03 deg	-0.03 deg	-0.02 deg	0.00 deg	0.01 deg	0.01 deg	0.01 deg	-0.01 deg
4.00 Hz	0.02 deg	0.01 deg	0.01 deg	0.01 deg	0.00 deg	0.01 deg	0.01 deg	0.00 deg	0.00 deg
8.00 Hz	-0.01 deg	0.01 deg	0.00 deg	0.01 deg	0.01 deg	-0.02 deg	-0.01 deg	-0.02 deg	0.00 deg
10.00 Hz	0.00 deg	-0.01 deg	-0.01 deg	-0.01 deg	-0.01 deg	-0.03 deg	-0.04 deg	-0.03 deg	-0.01 deg

Table 41 Static Pressure Phase Response Variation: MB3a #417

	1038 hPa+	1063 hPa+	1063 hPa-	1038 hPa-	1013 hPa-	988 hPa-	963 hPa-	988 hPa+	1013 hPa+
0.10 Hz	-0.15 deg	-0.59 deg	-0.59 deg	-0.49 deg	0.07 deg	0.21 deg	0.45 deg	0.32 deg	0.07 deg
0.20 Hz	-0.15 deg	-0.39 deg	-0.43 deg	-0.17 deg	0.03 deg	0.03 deg	0.13 deg	0.13 deg	-0.06 deg
0.40 Hz	-0.07 deg	-0.12 deg	-0.13 deg	-0.04 deg	-0.01 deg	0.10 deg	0.15 deg	0.09 deg	0.04 deg
0.80 Hz	-0.03 deg	-0.08 deg	-0.06 deg	-0.04 deg	0.02 deg	0.03 deg	0.06 deg	0.05 deg	0.01 deg
1.00 Hz	-0.02 deg	-0.04 deg	-0.05 deg	0.00 deg	0.01 deg	0.06 deg	0.06 deg	0.05 deg	0.03 deg
2.00 Hz	-0.03 deg	-0.03 deg	-0.03 deg	-0.02 deg	0.00 deg	0.01 deg	0.01 deg	0.01 deg	-0.01 deg
4.00 Hz	0.02 deg	0.01 deg	0.01 deg	0.01 deg	0.01 deg	0.01 deg	0.01 deg	0.01 deg	0.00 deg
8.00 Hz	0.00 deg	0.01 deg	0.01 deg	0.01 deg	0.01 deg	-0.01 deg	-0.01 deg	-0.01 deg	0.00 deg
10.00 Hz	-0.01 deg	-0.01 deg	-0.01 deg	-0.02 deg	-0.02 deg	-0.03 deg	-0.05 deg	-0.03 deg	-0.02 deg

Table 42 Static Pressure Phase Response Variation: MB3a #420

	1038 hPa+	1063 hPa+	1063 hPa-	1038 hPa-	1013 hPa-	988 hPa-	963 hPa-	988 hPa+	1013 hPa+
0.10 Hz	-0.15 deg	-0.59 deg	-0.59 deg	-0.50 deg	0.07 deg	0.21 deg	0.45 deg	0.33 deg	0.08 deg
0.20 Hz	-0.15 deg	-0.40 deg	-0.43 deg	-0.18 deg	0.03 deg	0.03 deg	0.14 deg	0.13 deg	-0.06 deg
0.40 Hz	-0.07 deg	-0.12 deg	-0.13 deg	-0.05 deg	-0.02 deg	0.10 deg	0.15 deg	0.10 deg	0.04 deg
0.80 Hz	-0.03 deg	-0.08 deg	-0.06 deg	-0.06 deg	0.02 deg	0.03 deg	0.07 deg	0.05 deg	0.01 deg
1.00 Hz	-0.02 deg	-0.04 deg	-0.05 deg	-0.02 deg	0.01 deg	0.06 deg	0.06 deg	0.05 deg	0.03 deg
2.00 Hz	-0.03 deg	-0.02 deg	-0.02 deg	-0.05 deg	0.00 deg	0.01 deg	0.01 deg	0.01 deg	-0.01 deg
4.00 Hz	0.02 deg	0.02 deg	0.02 deg	-0.04 deg	0.00 deg	0.01 deg	0.01 deg	0.01 deg	0.00 deg
8.00 Hz	0.00 deg	0.03 deg	0.02 deg	-0.06 deg	0.00 deg	-0.01 deg	0.00 deg	-0.01 deg	0.01 deg
10.00 Hz	-0.01 deg	-0.01 deg	0.00 deg	-0.13 deg	-0.03 deg	-0.04 deg	-0.05 deg	-0.04 deg	-0.02 deg

3.13 Response to Acceleration

The response to acceleration is defined as being the linear time-invariant (LTI) change in the sensor output signal amplitude and phase relative to an input acceleration.

3.13.1 Measurand

The quantity being measured is the sensor's response to acceleration in V/(m/s^2) as a function of frequency.

3.13.2 Configuration

The sensor is placed on a seismic calibration table to measure its sensitivity to vertical acceleration.

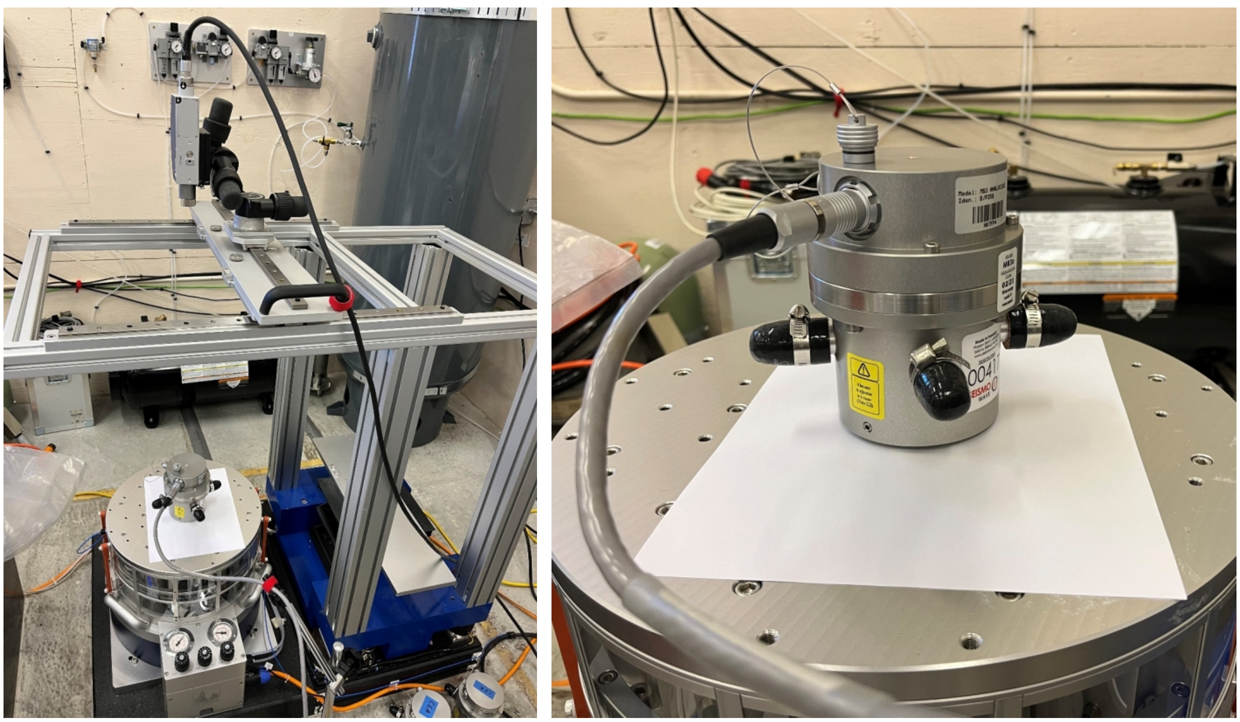

Figure 59 Response to Acceleration Testbed Equipment

Table 43 Response to Acceleration Testbed Equipment

	Manufacturer / Model	Serial #	Configuration
Calibration System	Spektra CS-18P	#6	1 m/s^2 amplitude, 2 Hz – 100 Hz

The Spektra CS-18P Seismic Calibration system provides integrated control, data acquisition, and analysis systems to provide a primary calibration of a sensor's amplitude and phase sensitivity utilizing sinusoidal driving signals of varying amplitude and frequency.

The sensor's pressure inlets are capped during this test to reduce the measurement of ambient noise and improve the signal to noise ratio.

3.13.3 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 acceleration. Measurements are made using sinusoidal tones at each of the specified frequencies, averaged over multiple readings.

The sensor amplitude sensitivity in Volts / (m/s^2) is computed:

$$Sensitivity = \frac{V_{SUT}}{Acceleration}$$

The sensor phase sensitivity in degrees is computed:

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

3.13.4 Result

The following table contains the measured amplitude and phase response of the sensors to vertical acceleration:

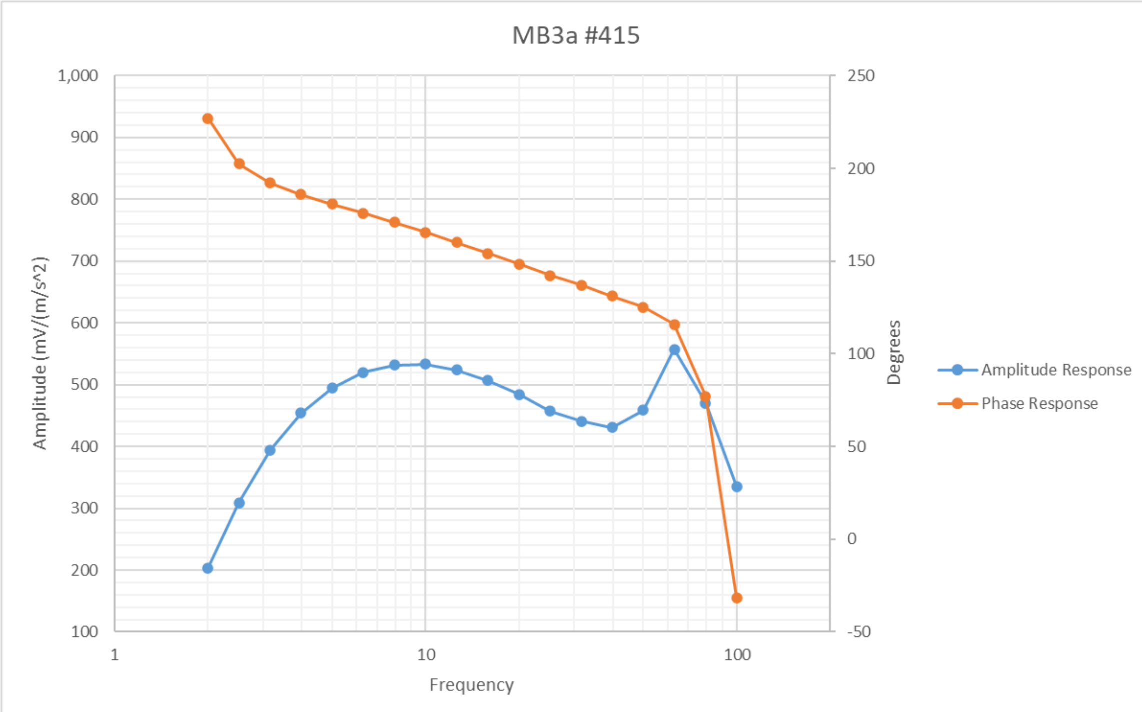

Figure 60 Response to Vertical Acceleration, MB3a #415

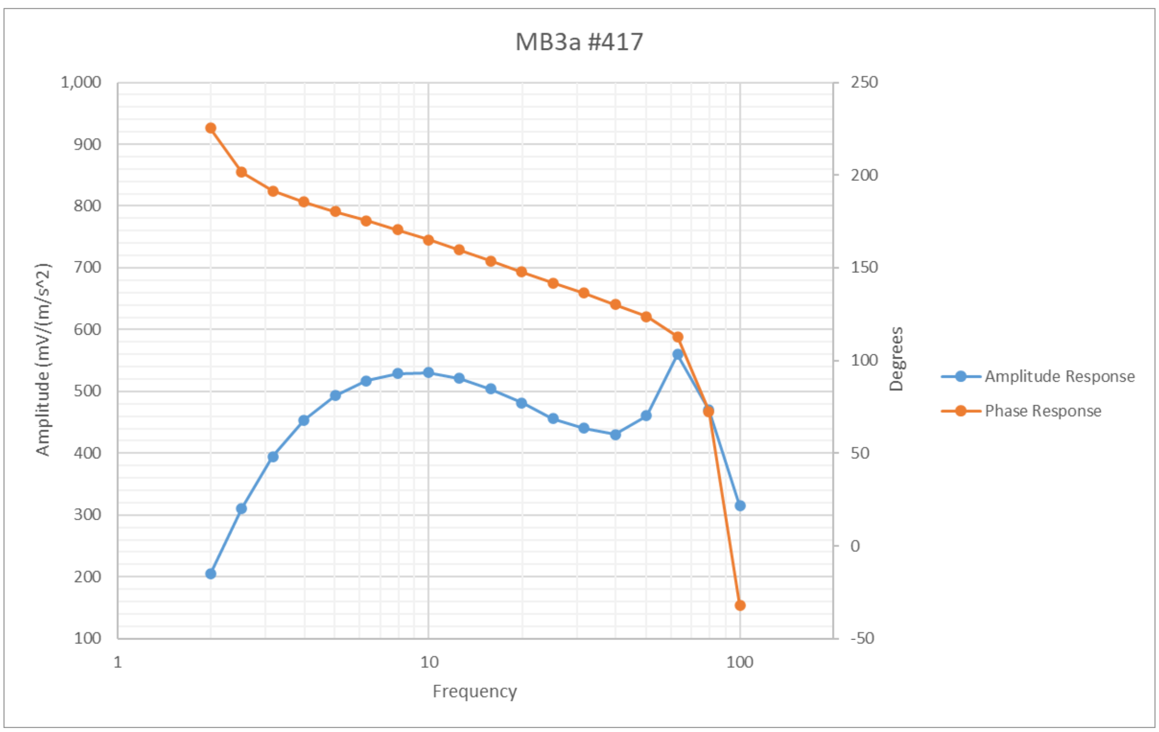

Figure 61 Response to Vertical Acceleration, MB3a #417

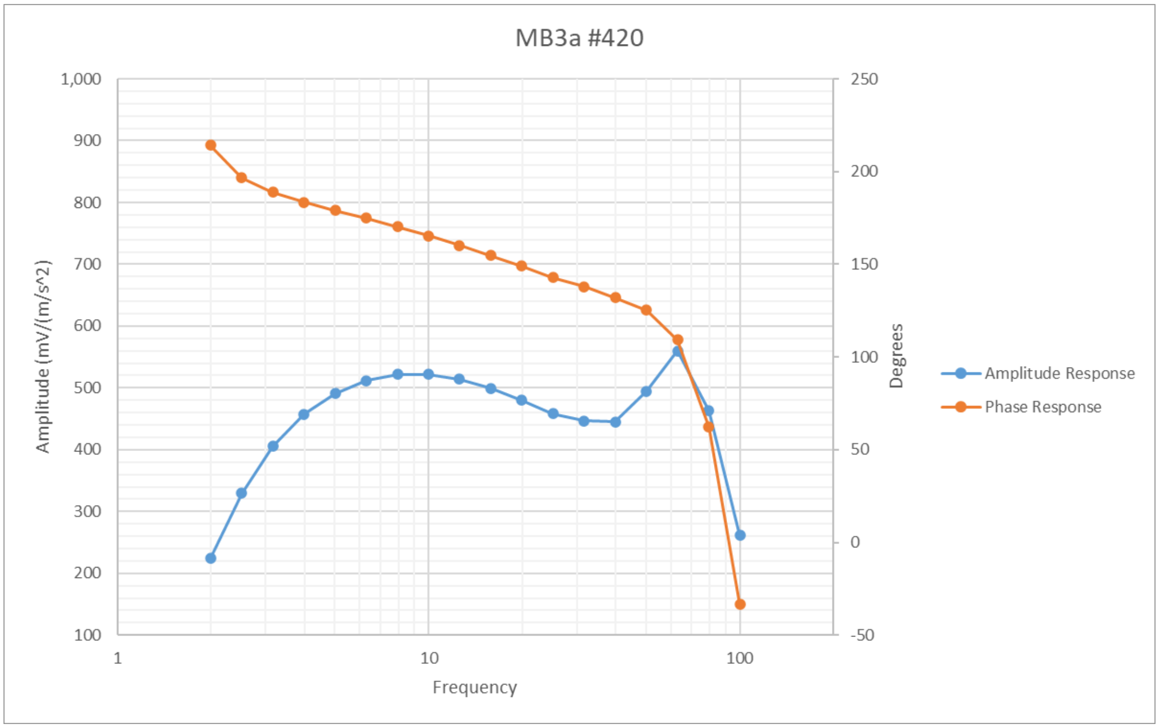

Figure 62 Response to Vertical Acceleration, MB3a #420

Table 44 Response to Vertical Acceleration

Frequency	MB3a #415		MB3a #417		MB3a #420		Uncertainty (k=2)	
	Amplitude (mV/(m/s^2))	Phase (degrees)	Amplitude (mV/(m/s^2))	Phase (degrees)	Amplitude (mV/(m/s^2))	Phase (degrees)	Amplitude	Phase
2.00 Hz	203.6	225.37	204.9	225.37	224.4	214.15	0.7%	1 deg
2.51 Hz	308.8	201.44	310.7	201.44	329.5	196.69	0.7%	1 deg
3.16 Hz	393.9	191.57	394.6	191.57	405.8	188.77	0.7%	1 deg
3.98 Hz	454.1	185.41	453.3	185.41	457.3	183.51	0.7%	1 deg
5.01 Hz	494.7	180.33	492.9	180.33	491.0	179.09	0.7%	1 deg
6.31 Hz	519.7	175.49	517.2	175.49	511.6	174.79	0.7%	1 deg
7.94 Hz	531.8	170.50	529.1	170.50	521.5	170.27	0.7%	1 deg
10.00 Hz	532.9	165.21	530.1	165.21	522.2	165.40	0.7%	1 deg
12.59 Hz	523.8	159.62	521.1	159.62	514.4	160.17	1.5%	1.5 deg
15.85 Hz	506.7	153.80	504.3	153.80	499.4	154.65	1.5%	1.5 deg
19.95 Hz	484.2	147.83	481.9	147.83	480.0	148.95	1.5%	1.5 deg
25.12 Hz	457.5	141.70	455.9	141.70	458.3	142.93	1.5%	1.5 deg
31.62 Hz	440.8	136.49	440.8	136.49	446.5	137.86	1.5%	1.5 deg
39.81 Hz	430.5	130.21	430.4	130.21	445.3	131.89	1.5%	1.5 deg
50.12 Hz	458.8	123.67	461.0	123.67	494.8	125.25	1.5%	1.5 deg
63.10 Hz	557.5	112.97	559.6	112.97	560.0	109.19	1.5%	1.5 deg
79.43 Hz	470.5	72.57	470.1	72.57	462.6	62.22	1.5%	1.5 deg
100.00 Hz	335.7	-32.24	314.8	-32.24	261.2	-33.42	1.5%	1.5 deg

The MB3a manual specifies that the sensors have a sensitivity to vertical acceleration less than 30 Pa/(m/s^2). Accounting for the MB3a nominal pressure sensitivity of 20 mV/Pa, this specification is equivalent to less than 600 mV/(m/s^2). The measured response to vertical acceleration was confirmed to be less than the value specified in the manual.

4 SUMMARY

Power Consumption
The MB3a sensors consumed 0.29 W, consistent with the manufacturer specification of 0.3 W.

Sensitivity
The MB3a sensors were found to have sensitivity values that were consistent with the manufacturer's datasheets at 0.25 Hz and 1 Hz.

Frequency Response
The MB3a sensors all demonstrated a frequency response that matched the nominal model over 0.02 Hz to 4 Hz in both amplitude and phase to +/- 0.04 dB (0.5 %) and +/- 0.5 degrees.

Passband
The MB3a sensors all had a measured passband from between 0.0101 Hz and exceeding the upper evaluation range of 10 Hz, covering the IMS passband of 0.02 Hz to 4 Hz.

Sensitivity vs Power Supply Voltage
The sensitivity at 1 Hz, in both amplitude and phase, of the MB3a sensors did not change as the power supply voltage was incremented from 9 V to 20 V.

Sensitivity vs Input Amplitude
The sensitivity at 1 Hz, in both amplitude and phase, of the MB3a sensors did not change with respect to an increased dynamic input pressure level ranging from 1 Pa to 28 Pa.

Full Scale
All the MB3a sensors had a full-scale at 1 Hz of better than +/- 1000 Pa, exceeding the manufacturer's specification of +/- 955 Pa at 1 Hz.

Self-Noise
The measured self-noise levels of the MB3a sensors were below the sensor noise model over 0.01 Hz to 10 Hz. Their self-noise was entirely below the Low-Noise-Model across 0.02 Hz to 4 Hz and more than 20 dB below the IMS minimum requirement at 1 Hz. The noise power over 0.02 Hz to 4 Hz was less than 0.64 mPa rms on all sensors, lower than the datasheet value of 1.75 mPa rms.

Dynamic Range
The measured MB3a dynamic ranges were greater than 121 dB over the 0.02 to 4 Hz IMS passband, exceeding the manufacturer specification of 117 dB and the IMS minimum requirement of 108 dB.

Calibrator Frequency Response
The MB3a calibrator frequency response was demonstrated to be within 2% and 0.5 degrees of the nominal response of 6 Pa/V and 0 degrees.

Static Temperature Response Variation
The MB3a sensor amplitude response was measured to vary by between 0.5 % and 1.5 % at elevated temperature of 50 C and by -3% to -3.5% at colder temperatures of -20 C. Over the 0.02 Hz to 4 Hz passband, the phase response varied by less than +/- 0.4 degrees over -20 C to 50 C temperature ranges.

Static Pressure Response Variation
The MB3a sensor response was measured across +/- 50 hPa of variation in barometric pressure. Two of the MB3a sensors, #415 and #417, had only small changes in amplitude response of less than +/- 0.5 %, at levels consistent with the combined uncertainty estimate for relative measures. The third MB3a, #420, had changes in amplitude response as much at +2% at -50 hPa of barometric pressure and -8% at +50 hPa of barometric pressure. All three sensors had only very small changes in phase response of less than +/- 0.6 degrees, at levels consistent with the combined uncertainty estimate for relative measures.

Response to Acceleration
The measured response to vertical acceleration over 2 Hz to 100 Hz on the MB3a sensors was less than the datasheet value of 30 Pa/(m/s^2) or 600 mV/(m/s^2).

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APPENDEX A: TEST REFERENCES

Guralp Affinity #405A5B Bit weights

The Guralp Affinity #405A5B used for data collected was calibrated against a reference meter HP 3458A #2823A10915 just prior to use in the data collection for this test. The digitizer bit weights were calculated using a 1 Hz sinusoid, simultaneously recorded on both the digitizer and Agilent meter. The bit weights used in this test were determined to be:

Table 45 Guralp Affinity #405A5B Channel bit weights

Digitizer Channel	Bit-weight	Sensor
Channel 1	1.00015 uV/cnt	Setra 278 Reference
Channel 2	1.00013 uV/cnt	B&K 4193 Reference
Channel 3	1.00012 uV/cnt	MB3a #415
Channel 4	1.00024 uV/cnt	MB3a #417
Channel 5	1.00024 uV/cnt	MB3a #420
Channel 6	1.00023 uV/cnt	
Channel 7	1.00013 uV/cnt	
Channel 8	1.00023 uV/cnt	

In addition, the input terminated noise of the digitizer channels was measured to confirm that the digitizer channels contained the expected levels of self-noise that was below the sensor self-noise.

B&K 4193 #3085404 Response

The response model for the reference B&K 4193, #3085404 was determined from a calibration performed by LNE, traceable to the SI over 0.01 to 20 Hz.

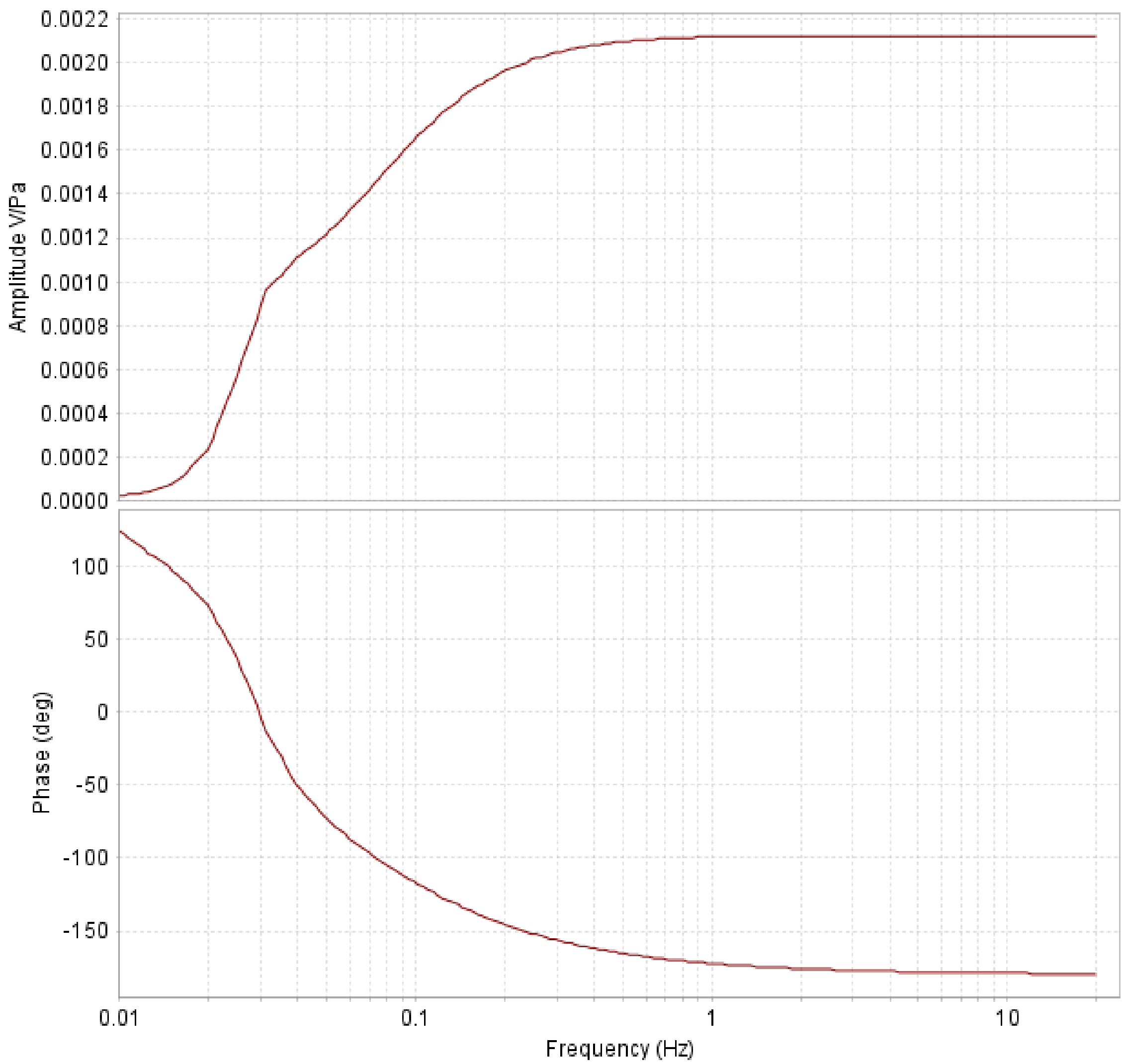

Figure 63 B&K 4193 #3085404 Response

The sensitivity of the B&K 4193 was determined to be 2.115 mV/Pa at conditions of 23 C and 1013 hPa. To correct the amplitude response at barometric pressures other than 1013 hPa, the B&K 4193 datasheet correction factor of 0.005 dB/kPa is applied.

Setra 278 #6937528 Calibration

The Setra 278 #7632595 micro barometer was calibrated by Sandia's Primary Standards Laboratory using pressure levels from 500 hPa to 1100 hPa. The calibrated transfer function related pressure in millibar to volts is:

$$\text{Pressure (millibar)} = 499.87698 + 120.05874 * V$$

MB3a Response

The nominal response model for the MB3a sensors was provided by the manufacturer at the time of evaluation.

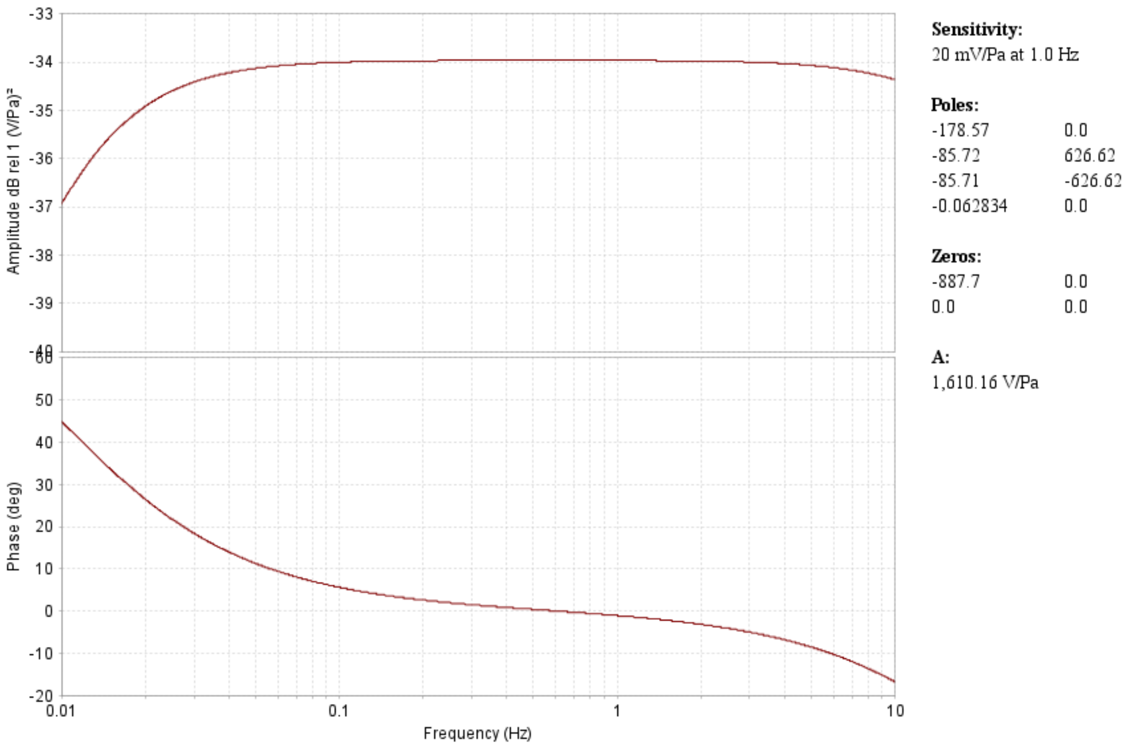

Figure 64 MB3a Nominal Response

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