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2019 Hyperion 5313A and 5119A Infrasound Sensor Type Approval Evaluation

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ABSTRACT

Sandia National Laboratories has tested and evaluated two variations of a new model of infrasound sensor, the Hyperion 5313A and 5119A. 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 static pressure and temperature, and sensitivity to vertical acceleration. The Hyperion infrasound sensors are being evaluated for potential use in the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

ACKNOWLEDGEMENTS

The evaluation of the Hyperion 5119A sensor was sponsored under Fund-In Agreement between Sandia National Laboratories and the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

The evaluation of the Hyperion 5313A sensor was sponsored by the United States Department of Defense, Defense Threat Reduction Agency (DTRA) under the Nuclear Arms Control Technology (NACT) program.

We would like to thank Hyperion for providing the sensors to evaluate and for their presence and support in conducting the evaluation.

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ACRONYMS AND DEFINITIONS

CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
GPS	Global Position System
GNSS	Global Navigation Satellite System
HNM	High Noise Model
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories

1 INTRODUCTION

The evaluation of the 3 Hyperion 5313A infrasound sensors, serial numbers 20190219.001, 20190219.002, and 20190219.003 and the 3 Hyperion 5119A infrasound sensors, serial numbers 20190716.001, 20190716.002, and 20190716.003, was performed to determine the sensors performance characteristics relative to the manufacturer's specifications and IMS requirements.

Figure 1 Hyperion Infrasound Sensors

These two models of the Hyperion 5000 series of infrasound sensor were selected with IMS applications in mind. Both sensors include a frequency passband that extends down to 0.015 Hz and a transducer that is able to differentially cancel out the effects of vertical acceleration.

The unique features of the 5313A model include a low power consumption of approximately 33 mW with the limitation of being able to drive a few meters of analog signal cabling, 4 inlet ports with threaded garden hose connectors, a sealed electronics volume, and a manual back-volume vent screw for pressure equalization at time of installation.

The unique features of the 5119A model include a medium power consumption of approximately 250 mW with the capability to drive many tens of meters of analog signal cabling, a single inlet port intended for use with a hose-clamp, a vented electronics volume with a Gortex vent cap, and an automatic micro-vent between the sensing back-volume and electronics volume that is open when powered off and closed when powered on. The purpose of this venting scheme is to simplify transport and installation of the sensor.

The Hyperion sensor specifications and IMS application requirements are shown below.

SENSOR SPECIFICATIONS (IFS-5313A)		
General		
	Size	Diameter - 152.4 mm (6.000") Height - 117.5 mm (4.625")
	Weight	4.53 kg (10.1 lbs)
	Input Voltage	10-15 Vdc
	Power Consumption	≈ 35 mW
Analog		
	Calibrated Frequency Response	0.001 Hz to 1000 Hz
	Typical Frequency Response	0.015 Hz to 100 Hz with less than 3 dB variability
	Intrinsic Noise	≈ 200 µPa rms, 0.02 Hz to 4 Hz band
	Peak Pressure	± 100 Pa standard
	Temperature Sensitivity	< 0.03 %/°C
	Nominal Pressure Sensitivity	26.6 mV/Pa
	Seismic Sensitivity	< 5.5 mV/(m/s^2)
	Cable Drive Length	< 3 m

Figure 2 Hyperion IFS-5313A Infrasound Sensor Specifications

SENSOR SPECIFICATIONS (IFS-5119A)		
General		
	Size	Diameter - 152.4 mm (6.000") Height - 117.5 mm (4.625")
	Weight	4.53 kg (10.1 lbs)
	Input Voltage	10-15 Vdc
	Power Consumption	≈ 250 mW
Analog		
	Calibrated Frequency Response	0.001 Hz to 1000 Hz
	Typical Frequency Response	0.015 Hz to 100 Hz with less than 3 dB variability
	Intrinsic Noise	≈ 200 µPa rms, 0.02 Hz to 4 Hz band
	Peak Pressure	± 100 Pa standard
	Temperature Sensitivity	< 0.03 %/°C
	Nominal Pressure Sensitivity	70 mV/Pa
	Seismic Sensitivity	< 14 mV/(m/s^2)
	Cable Drive Length	< 75 m

Figure 3 Hyperion IFS-5119A Infrasound Sensor Specifications

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	≤100 m
Relative sensor location	≤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	≤18 dB below minimum acoustic noise[d]
Calibration	≤5% in absolute amplitude[e]
State of health	Status data transmitted to the International Data Centre
Sampling rate	≥10 samples per second
Resolution	≥1 count per 1 mPa
Dynamic range	≥108 dB
Timing accuracy	≤1 ms[f]
Standard temperature range	−10°C to +45°C[g]
Buffer at the station or National Data Centre	≥7 days
Data format	Group of Scientific Experts format
Data frame length	≤30 s
Data transmission	Continuous
Data availability	≥98%
Timely data availability	≥97%
Mission capable array	≥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 4 Minimum Requirements for Infrasound Station Specifications (from 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 National Institute for Standards Technology (NIST).

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

Figure 5 SNL 1400L Infrasound Chamber

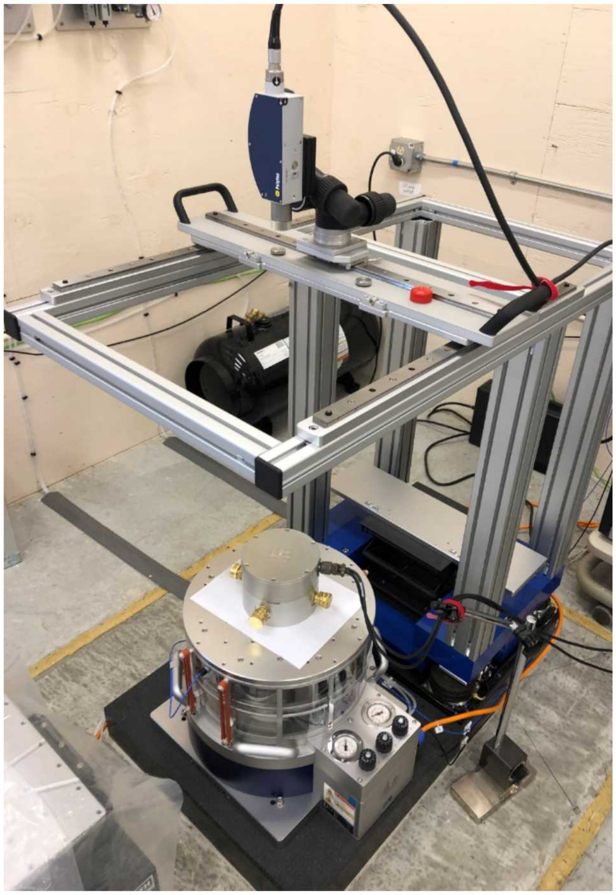


Figure 6 SNL Seismic Calibration Table

Figure 7 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 8 Vaisala PTU300 Temperature, Pressure, and RH within Infrasound Chamber

The sensors were all powered from a common laboratory power supply, configured to output 13 V.

Figure 9 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 830 hPa or 1000 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
Sensitivity vs input amplitude
Full Scale
Self-Noise
Dynamic Range
Frequency Response (Tonal, 0.01 – 10 Hz)
Passband
Static Pressure Sensitivity
Static Temperature Sensitivity
Response to Vertical Acceleration

2.3 Timeline

Testing was performed at Sandia National Laboratories in August, 2019:

Table 2 Timeline of Testing

Day	Time (UTC)	Hyperion 5313A	Hyperion 5119A
August 10 – 12, 2019		Setup sensors within 1400 L infrasound chamber with the sensor inlets capped to measure self-noise.	
August 12, 2019	Morning	Review of test plan and sensor configuration with observers. Measurement of power consumption	
	Afternoon	Measurement of sensitivity, linearity, and amplitude and phase response at 820 hPa and 23 C. Pressurized infrasound chamber to 1000 hPa and equalized the sensor sealed back-volumes	
	Overnight	Pressurized to 1000 hPa and 23 C and allowed to stabilize.	
August 13, 2018		Equalized the sensor sealed back-volumes within chamber at 1000 hPa. Pressurized infrasound chamber to 1050 hPa. Reduced pressure from 1050 hPa to 950 hPa in 5 hPa steps, measuring frequency response at each step to determine the variation in response as a function of static pressure. At the end of the day, depressurized the chamber over 1 hr to bring the static pressure back to ambient 830 hPa.	
	Overnight	Placed sensors in ambient conditions, 830 hPa and 23C.	Placed sensors in thermal chamber, programmed to operate from -20 C to 50 C and then back to 20 C in 10 C steps, measuring the frequency response at each step to determine the variation in response as a function of static temperature.
August 14, 2019		Placed sensors on seismic calibration table to measure their sensitivity to vertical acceleration.	
August 15, 2019		Placed sensors in thermal chamber, programmed to operate from -20 C to 50 C and then back to 20 C in 10 C steps, measuring the frequency response at each step to determine the variation in response as a function of static temperature.	Placed sensors on seismic calibration table to measure their sensitivity to vertical acceleration.
August 16, 2019			
	Afternoon	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 consumption 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.

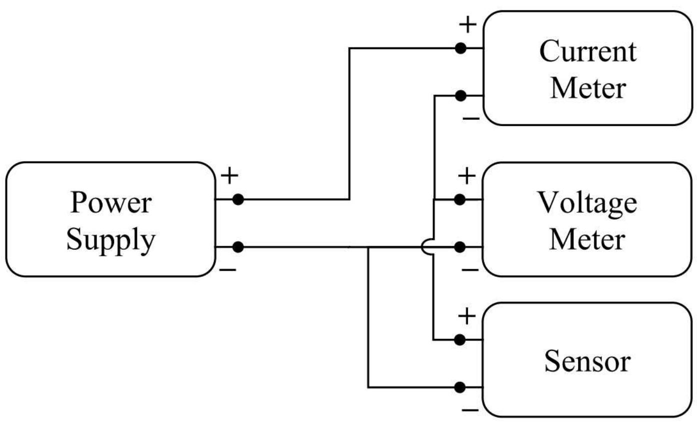


Figure 10 Power Consumption Configuration Diagram

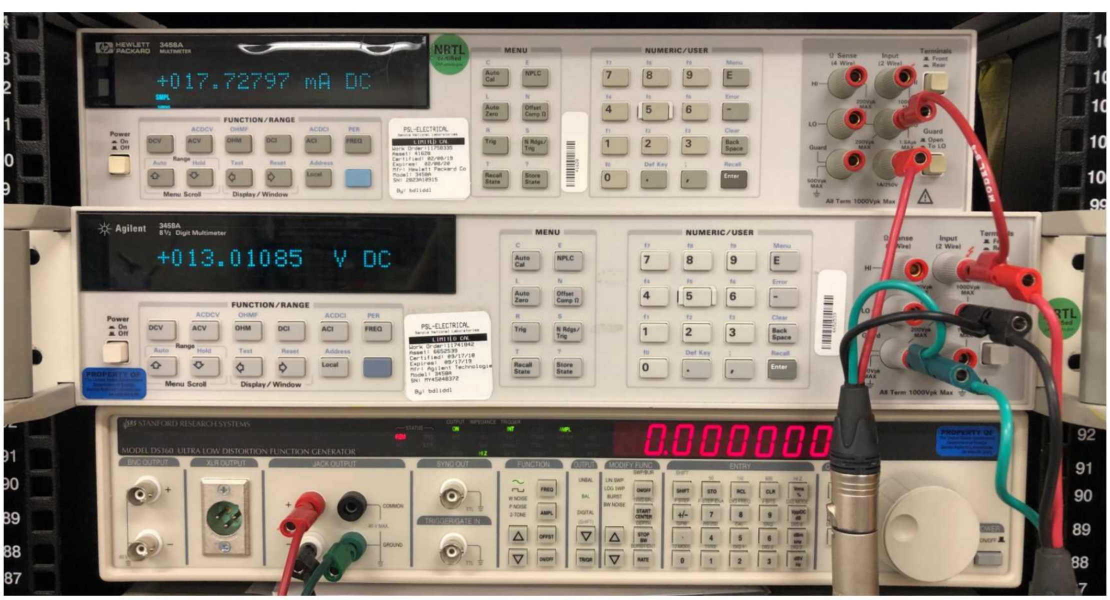


Figure 11 Power Consumption Configuration Picture

Table 3 Power Consumption Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Power Supply	Protek DC Power Supply 3003B	N/A	12 V
Voltage Meter	Agilent 3458A	MY45048372	DC Voltage Mode
Current Meter	HP 3458A	2823A10915	DC Current Mode

The meters used to measure current and voltage have active calibrations from the Primary Standard Laboratory at Sandia.

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.

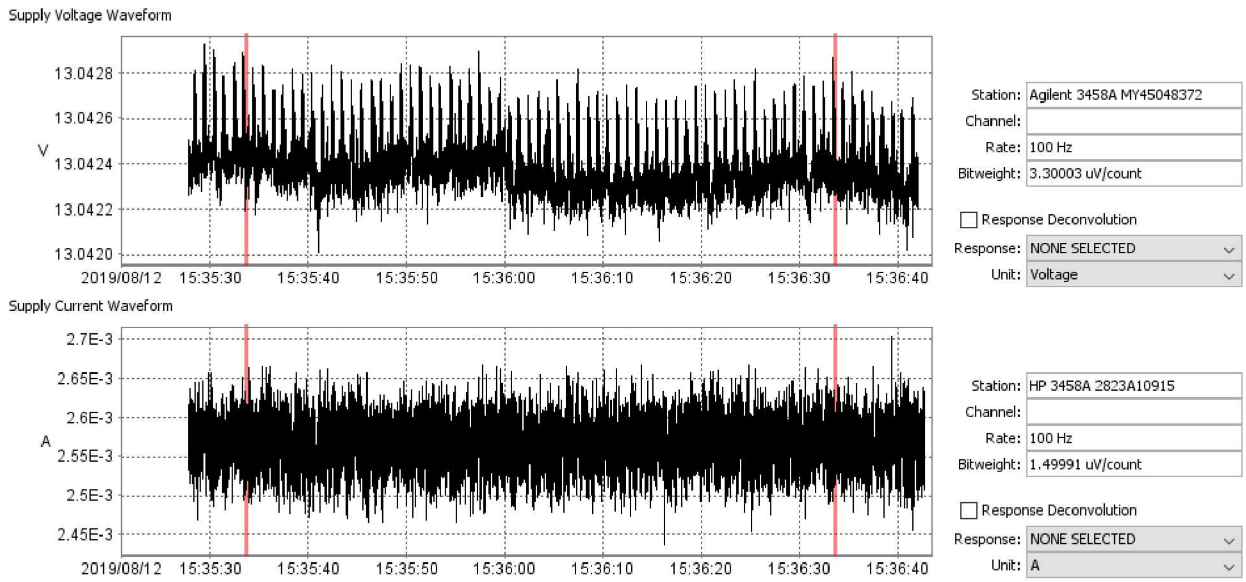


Figure 12 Power Consumption Voltage and Current Time Series, Hyperion 5313A

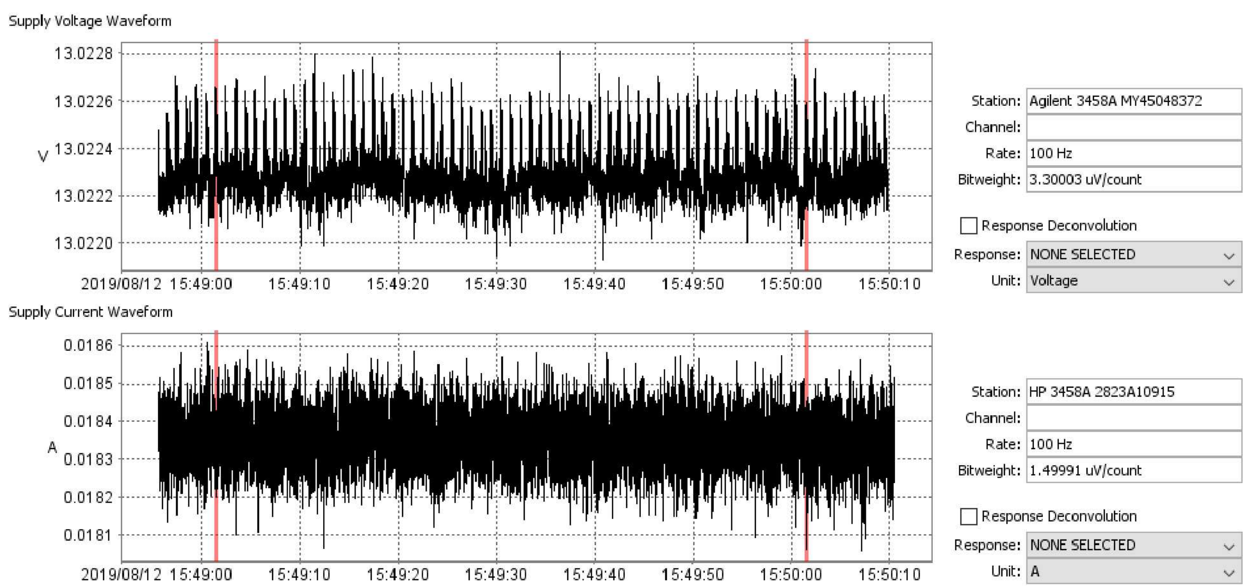


Figure 13 Power Consumption Voltage and Current Time Series, Hyperion 5119A

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
Hyperion 5313A 20190219.001	13.04 V	0.1328 mV	2.568 mA	32.67 uA	33.50 mW	0.4265 mW
Hyperion 5313A 20190219.002	13.04 V	0.1399 mV	2.426 mA	25.69 uA	31.64 mW	0.3354 mW
Hyperion 5313A 20190219.003	13.04 V	0.1208 mV	2.491 mA	33.91 uA	32.48 mW	0.4426 mW
Hyperion 5119A 20190716.001	13.02 V	0.1198 mV	18.35 mA	75.55 uA	239.0 mW	0.9861 mW
Hyperion 5119A 20190716.002	13.02 V	0.1249 mV	17.82 mA	78.67 uA	232.0 mW	1.027 mW
Hyperion 5119A 20190716.003	13.02 V	0.3589 mV	19.69 mA	316.0 uA	256.4 mW	4.123 mW

The Hyperion infrasound sensors were observed to consume between 31.6 and 33.5 mW for the 5313A version and between 232 and 256 mW for the 5119A versions. These results are consistent with the information provided by the manufacturer regarding these two models.

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. For an infrasound sensor, the sensitivity value is expressed at a given frequency in units of V/Pa or V/(Pa/s), depending upon whether the sensor is measuring pressure or pressure rate.

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.

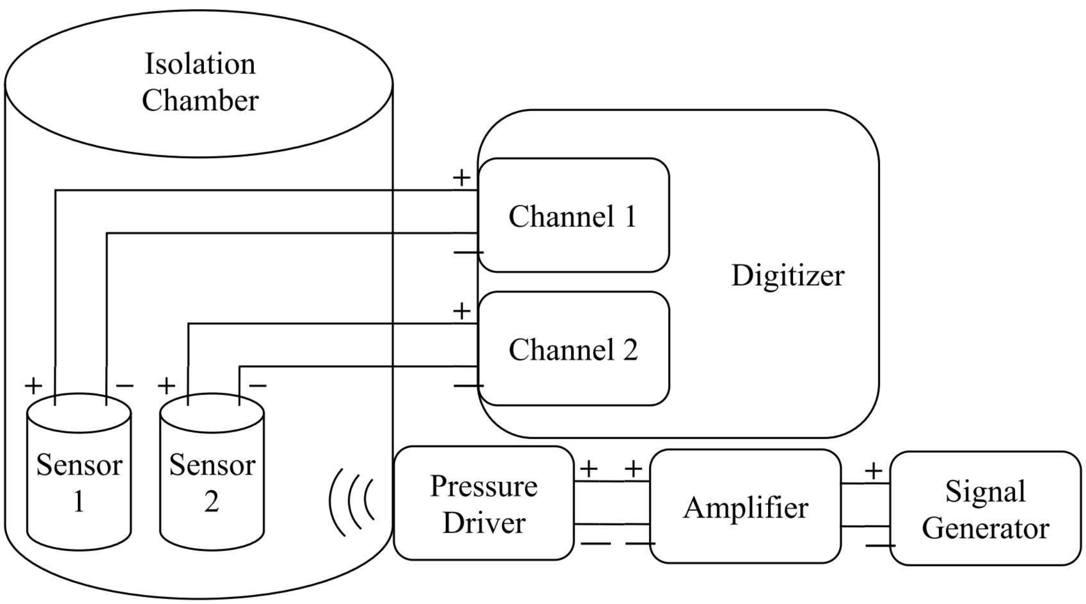


Figure 14 Sensitivity Configuration Diagram

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	2812287	2.117 mV/Pa at 10 Hz, 830 hPa, 23 C
Infrasound Chamber	SNL	1400 L Chamber	830 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, 0.5 V sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A

The 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.

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:

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

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

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 are repeated 10 times and the resulting averages are reported.

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.

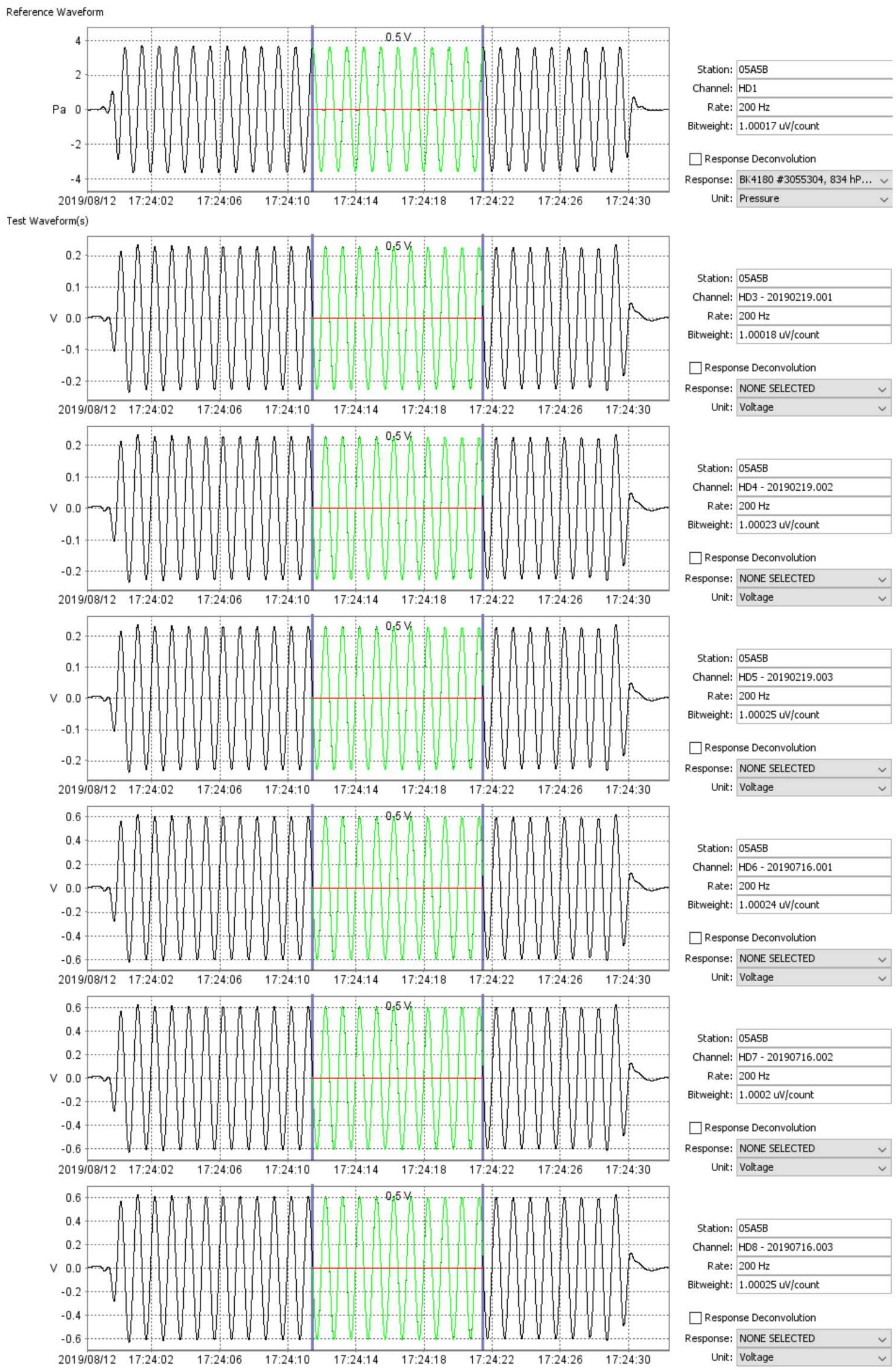


Figure 15 Sensitivity Time Series

The following table contains the computed mean and sample standard deviation of 10 iterations of sensitivities measurements for each of the sensors under test. The sensitivities were tested at a dynamic pressure amplitude of 8.6 Pa, ambient static pressure of 834 hPa, temperature of 23.6 C, and humidity of 55%.

Table 6 Sensitivity at 0.25 Hz

	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
Datasheet Amplitude	26.61 mV/Pa	26.56 mV/Pa	26.78 mV/Pa	69.26 mV/Pa	69.97 mV/Pa	69.71 mV/Pa
Measured Amplitude	26.17 mV/Pa	26.07 mV/Pa	26.27 mV/Pa	69.01 mV/Pa	69.74 mV/Pa	69.76 mV/Pa
Measured Amplitude Std Dev	0.02 mV/Pa	0.02 mV/Pa	0.02 mV/Pa	0.06 mV/Pa	0.06 mV/Pa	0.06 mV/Pa
Datasheet Phase	3.934 deg	3.934 deg	3.934 deg	3.934 deg	3.934 deg	3.934 deg
Measured Phase	4.32 deg	4.30 deg	4.39 deg	4.31 deg	4.30 deg	4.37 deg
Measured Phase Std Dev	0.05 deg	0.05 deg	0.05 deg	0.06 deg	0.05 deg	0.05 deg

Table 7 Sensitivity at 1 Hz

	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
Datasheet Amplitude	26.658 mV/Pa	26.604 mV/Pa	26.822 mV/Pa	69.373 mV/Pa	70.087 mV/Pa	69.821 mV/Pa
Measured Amplitude	26.19 mV/Pa	26.09 mV/Pa	26.31 mV/Pa	68.99 mV/Pa	69.82 mV/Pa	69.86 mV/Pa
Measured Amplitude Std Dev	0.02 mV/Pa	0.02 mV/Pa	0.02 mV/Pa	0.05 mV/Pa	0.05 mV/Pa	0.05 mV/Pa
Datasheet Phase	0.9843 deg	0.9843 deg	0.9843 deg	0.9843 deg	0.9843 deg	0.9843 deg
Measured Phase	1.20 deg	1.22 deg	1.21 deg	1.10 deg	1.16 deg	1.23 deg
Measured Phase Std Dev	0.03 deg	0.03 deg	0.03 deg	0.03 deg	0.03 deg	0.03 deg

The measured sensitivities were all consistent within 2% of the provided manufacturer's sensitivities for the 5313A sensors and within 0.5% for the 5119A sensors for both 0.25 and 1 Hz. The measured phases were all consistent within 0.5 degrees at 0.25 Hz and within 0.25 degrees at 1 Hz, based upon the nominal response model provided with the sensors.

3.3 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.

3.3.1 Measurand

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

3.3.2 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.

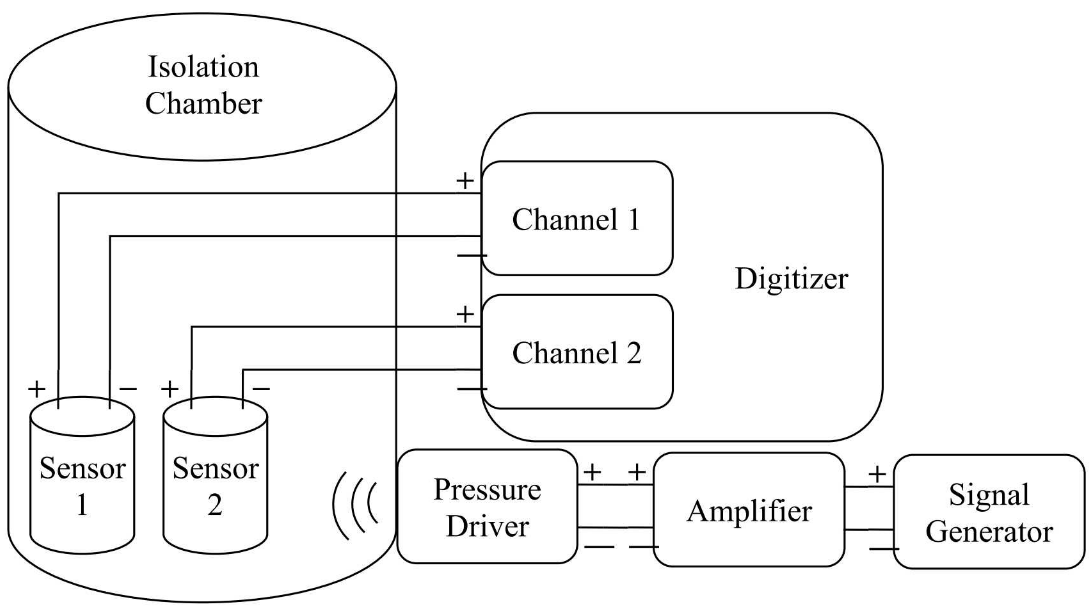


Figure 16 Sensitivity vs Input Amplitude Configuration Diagram

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.

Table 8 Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	2812287	2.117 mV/Pa at 10 Hz, 830 hPa, 23 C
Infrasound Chamber	SNL	1400 L Chamber	830 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, 60 mV – 1 V 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.

3.3.3 Analysis

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

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

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

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

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 amplitude level:

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

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

3.3.4 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.

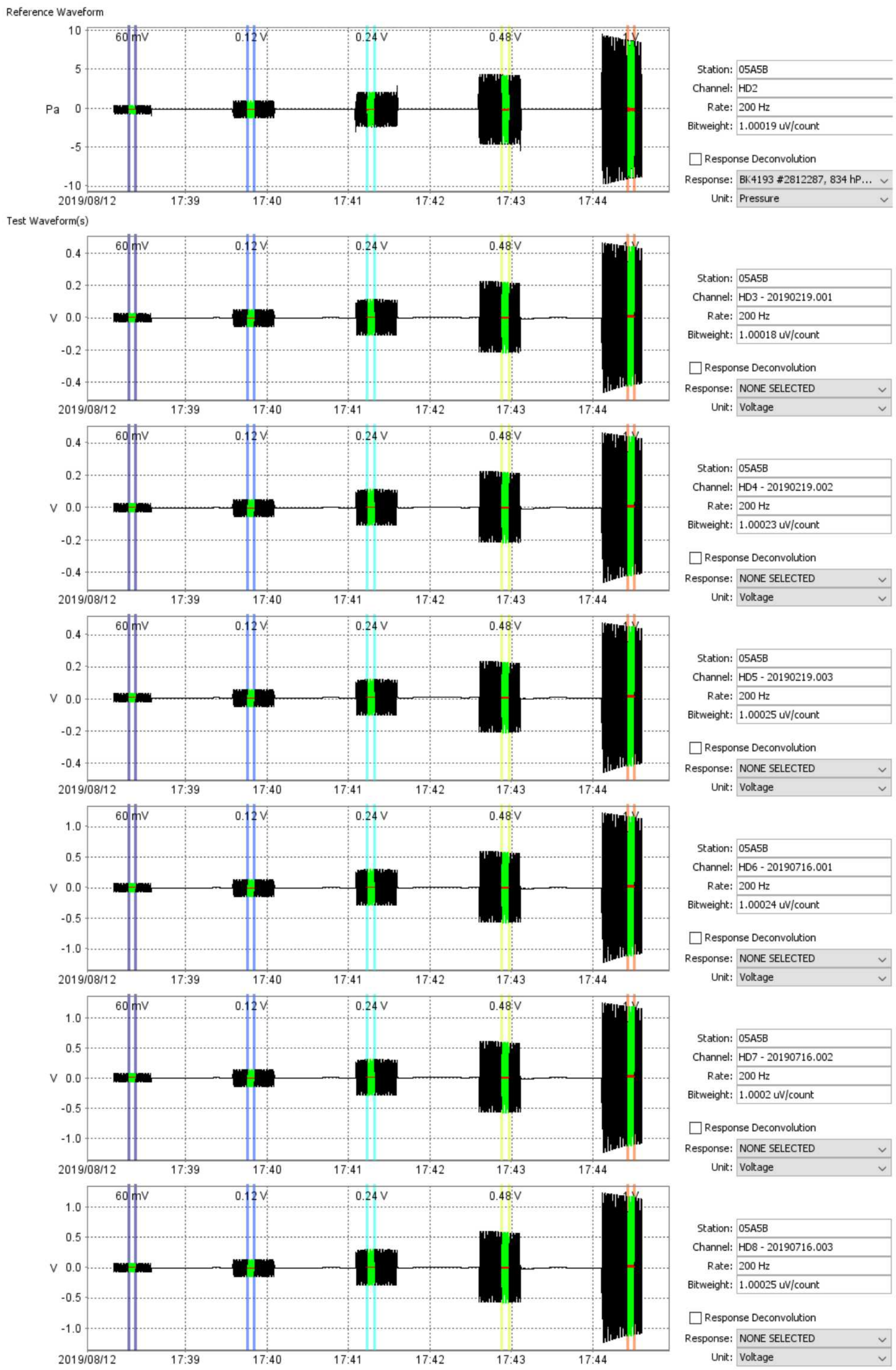


Figure 17 Sensitivity vs Input Amplitude Time Series

The following chart represents the changes in amplitude and phase sensitivity, relative to the measurement at 8 Pa, that were observed across the input amplitude range for the Hyperion infrasound sensors.

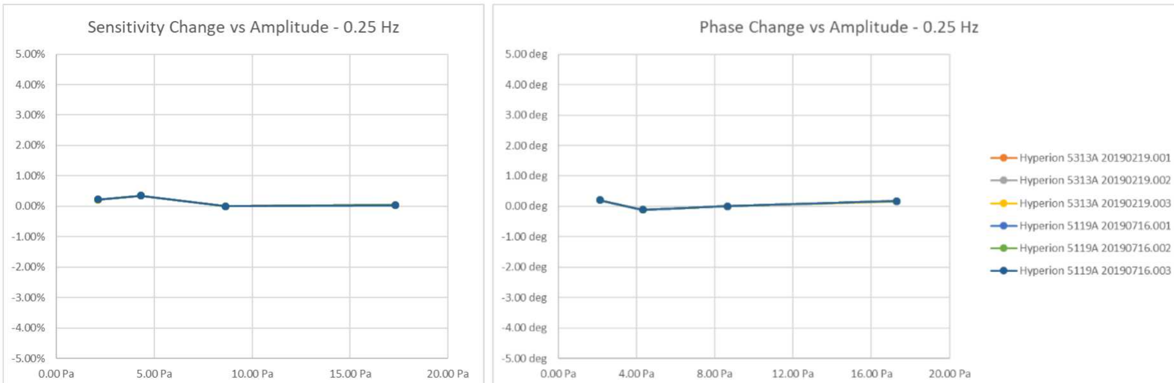


Figure 18 Sensitivity and Phase vs Input Amplitude at 0.25 Hz

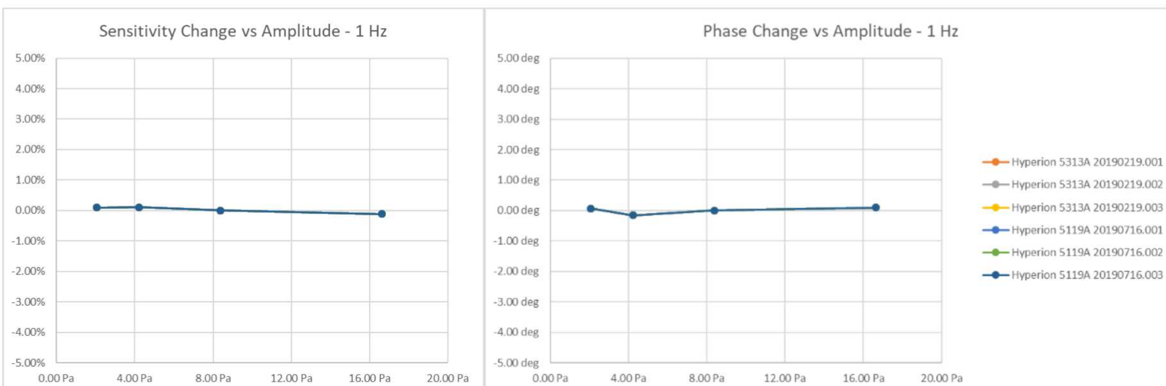


Figure 19 Sensitivity and Phase vs Input Amplitude at 1 Hz

We observe that there is no consistent trend in the amplitude or phase sensitivity with respect to dynamic input pressure. The sensors under test all demonstrated the same sensitivity across 2 Pa to 17 Pa to within +/- 0.35 % in amplitude and +/- 0.15 degrees in phase.

All of the sensors had nearly identical variations versus input pressure amplitude, therefore it is believed that these variations are due to the reference sensor. The larger changes at lower pressure levels are consistent with the reduced signal to noise ratio on the reference sensor, which increases the uncertainty in the measurement.

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

Table 9 Change in Amplitude vs Input Amplitude Results at 0.25 Hz

Amplitude	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
2.12 Pa	0.21%	0.22%	0.21%	0.22%	0.22%	0.22%
4.31 Pa	0.35%	0.35%	0.35%	0.35%	0.35%	0.35%
8.64 Pa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
17.30 Pa	0.04%	0.04%	0.04%	0.04%	0.04%	0.04%

Table 10 Change in Phase vs Input Amplitude Results at 0.25 Hz

Amplitude	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
2.12 Pa	0.21 deg	0.20 deg	0.20 deg	0.20 deg	0.21 deg	0.21 deg
4.31 Pa	-0.11 deg	-0.11 deg	-0.11 deg	-0.11 deg	-0.11 deg	-0.11 deg
8.64 Pa	0.00 deg	0.00 deg	0.00 deg	0.00 deg	0.00 deg	0.00 deg
17.30 Pa	0.17 deg	0.17 deg	0.17 deg	0.17 deg	0.17 deg	0.17 deg

Table 11 Change in Amplitude vs Input Amplitude Results at 1 Hz

Amplitude	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
2.07 Pa	0.09%	0.09%	0.09%	0.09%	0.10%	0.10%
4.22 Pa	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%
8.38 Pa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
16.64 Pa	-0.12%	-0.12%	-0.12%	-0.12%	-0.12%	-0.12%

Table 12 Change in Phase vs Input Amplitude Results at 1 Hz

Amplitude	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
2.07 Pa	0.06 deg	0.06 deg	0.06 deg	0.07 deg	0.06 deg	0.06 deg
4.22 Pa	-0.15 deg	-0.15 deg	-0.15 deg	-0.15 deg	-0.16 deg	-0.15 deg
8.38 Pa	0.00 deg	0.00 deg	0.00 deg	0.00 deg	0.00 deg	0.00 deg
16.64 Pa	0.10 deg	0.10 deg	0.10 deg	0.10 deg	0.10 deg	0.10 deg

3.4 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.

3.4.1 Measurand

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

3.4.2 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.

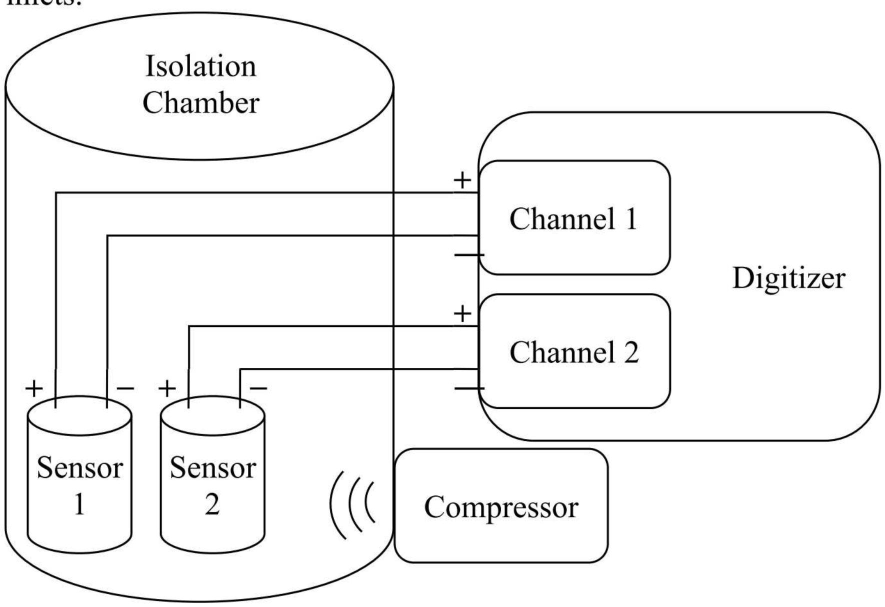


Figure 20 Full Scale Configuration Diagram

Table 13 Full Scale Sensitivity vs Input Amplitude Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Digitizer	Guralp Affinity	405A5B	200 Hz, 1x gain, 40 Vpp
Infrasound Chamber	SNL	1400 L Chamber	830 hPa, 23 C
Compressor	N/A	N/A	N/A

The pressure driver 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, a compressor was used to generate the necessary amplitude to clip the sensors.

The static pressure in the infrasound chamber was increased rapidly using a compressor in order to demonstrate the positive clip level on the sensors. The static pressure in the infrasound chamber was then rapidly reduced in order to demonstrate a negative clip level on the sensors.

3.4.3 Analysis

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

3.4.4 Result

The figure below shows a representative waveform time series for each model of the sensors under test. The time series for the other serial numbers not shown were otherwise identical in appearance.

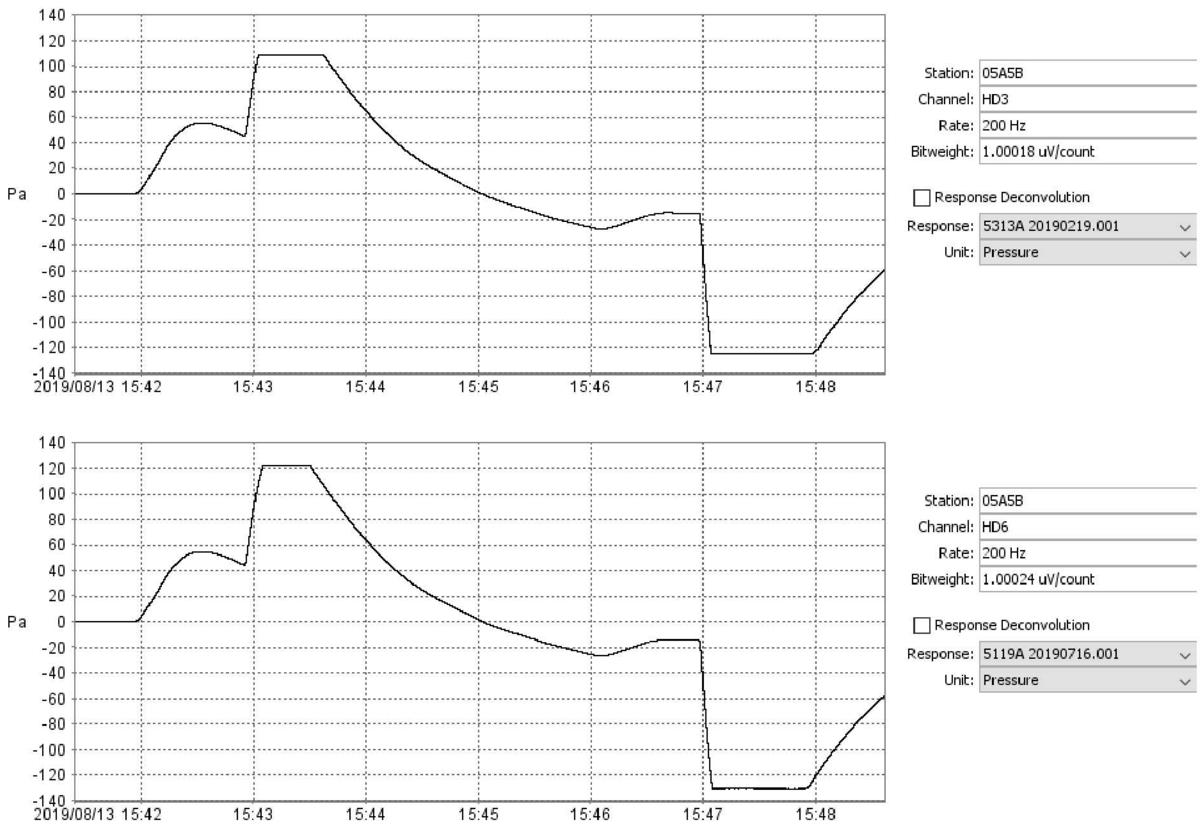


Figure 21 Full Scale Time Series

The positive and negative clip levels are clearly visible where the sensor output does not increase any further, starting just after 15:43 for the positive clip and just after 15:47 for the negative clip.

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 infrasound chamber was being pressurized.

Table 14 Full Scale Observed Pressure

	Minimum	Maximum
Hyperion 5313A 20190219.001	-124.72 Pa	108.40 Pa
Hyperion 5313A 20190219.002	-125.15 Pa	109.26 Pa
Hyperion 5313A 20190219.003	-123.15 Pa	107.18 Pa
Hyperion 5119A 20190716.001	-130.75 Pa	122.11 Pa
Hyperion 5119A 20190716.002	-129.46 Pa	120.11 Pa
Hyperion 5119A 20190716.003	-129.60 Pa	121.67 Pa

The Hyperion 5313A sensors all demonstrated a full-scale range exceeding -123 Pa and 107 Pa. The Hyperion 5119A sensors all demonstrated a full-scale range exceeding -129 Pa and 120 Pa.

The specification from the manufacturer is that the full-scale range of the sensors is between +/- 100 Pa. The measured results all exceed this specification.

3.5 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.

3.5.1 Measurand

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

3.5.2 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.

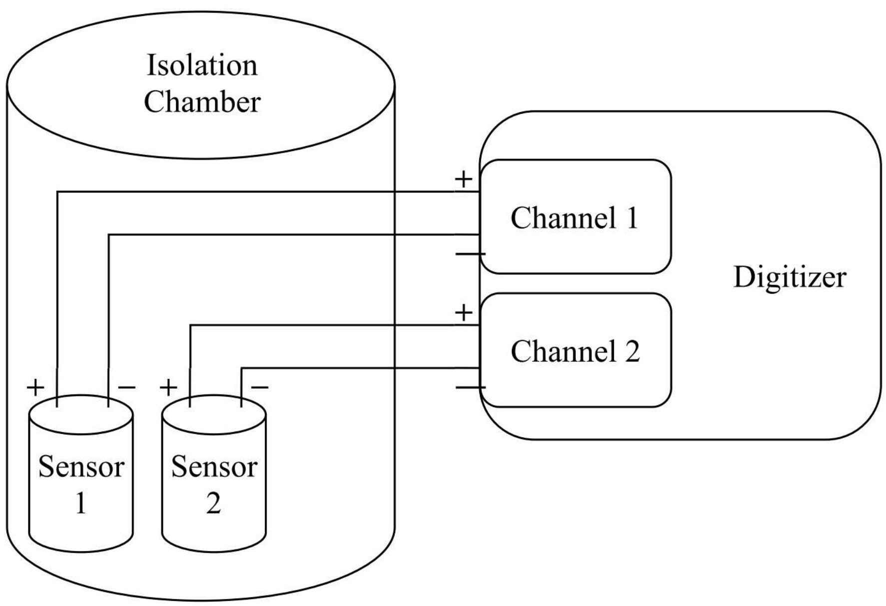


Figure 22 Self-Noise Configuration Diagram

Figure 23 Self-Noise Configuration Picture

Table 15 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	830 hPa, 23 C

The digitizer records the output of the reference sensors. A minimum of 24 hours of data is recorded once the temperature and pressure conditions within the isolation chamber have stabilized.

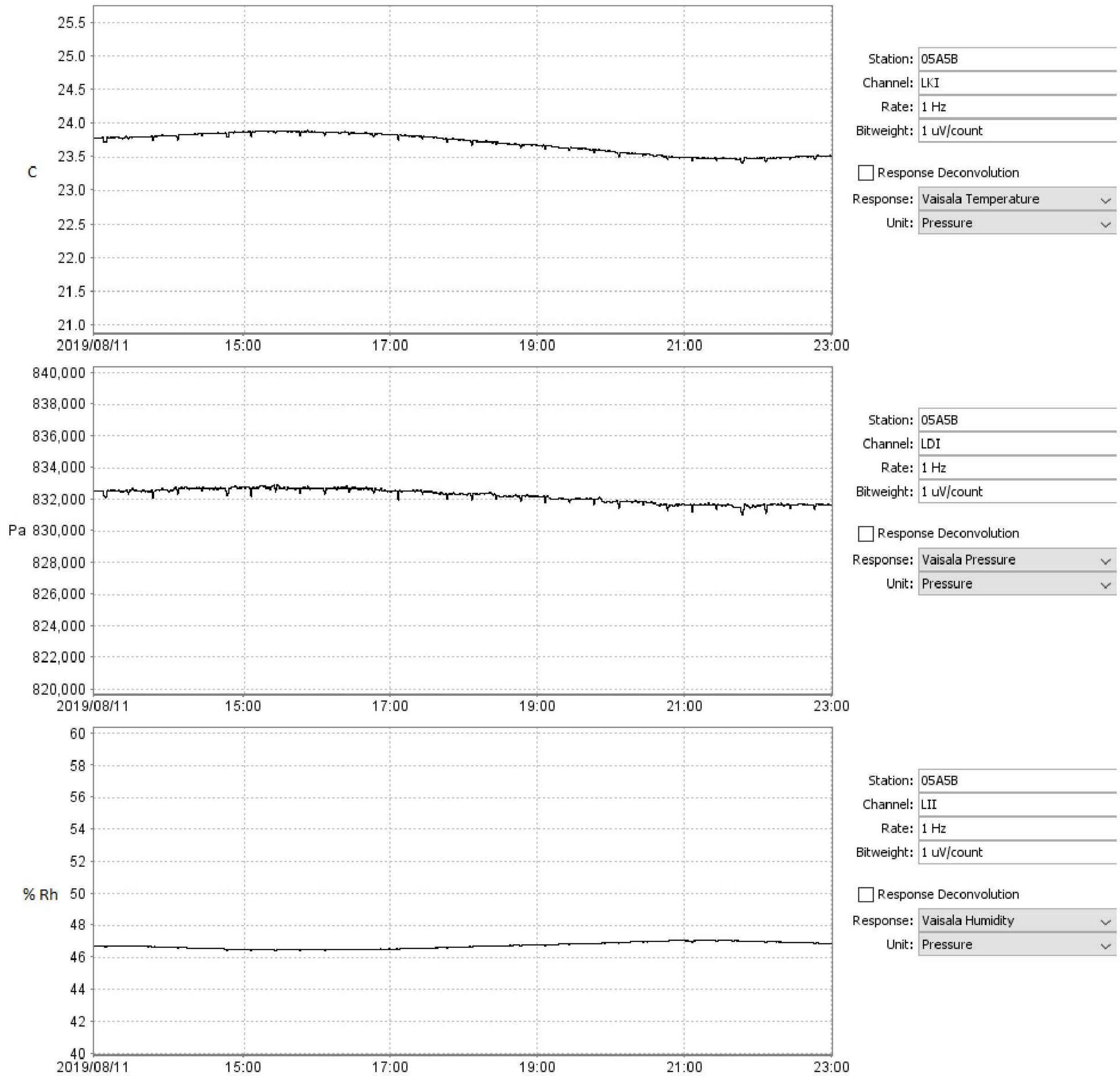


Figure 24 Self-Noise Environmental Conditions

Environmental conditions over the period of self-noise, as shown in the plot of the recorded temperature, pressure, and relative humidity were 23.7 C, 832 hPa, and 47 % RH.

3.5.3 Analysis

The measured sensitivities are applied to the collected data:

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

The PSD is computed from the time series (Merchant, 2011) from the time series using a 32k-sample Hann window. The window length and data duration were chosen such that there were several points below the lower limit of the evaluation pass-band of 0.01 Hz and the 95% confidence interval is less than 0.5 dB. The resulting 95% confidence interval was determined to be 0.658 dB.

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

Over frequencies (in Hertz):

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

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:

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

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

3.5.4 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.

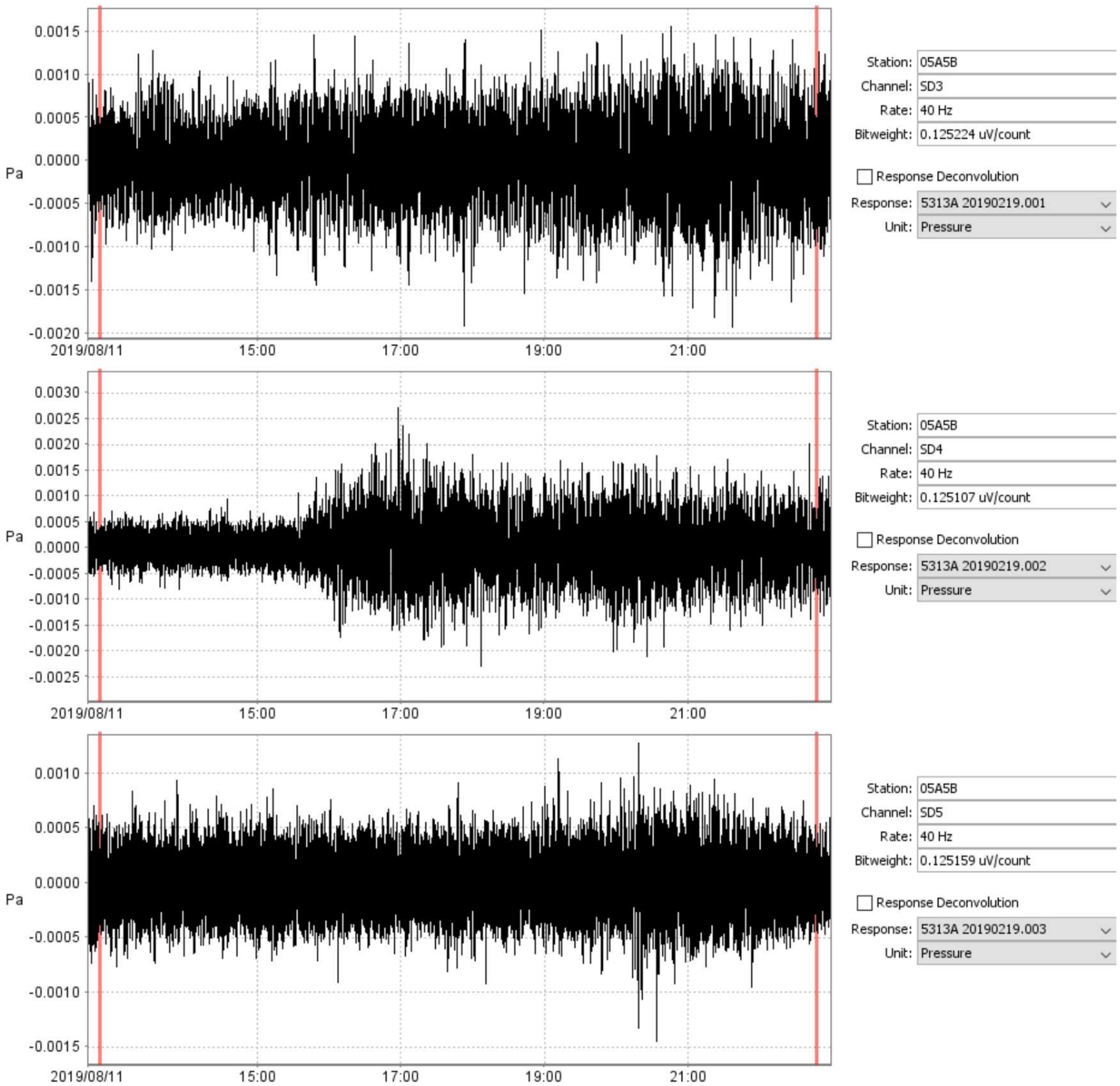


Figure 25 Self-Noise Time Series, Hyperion 5313A

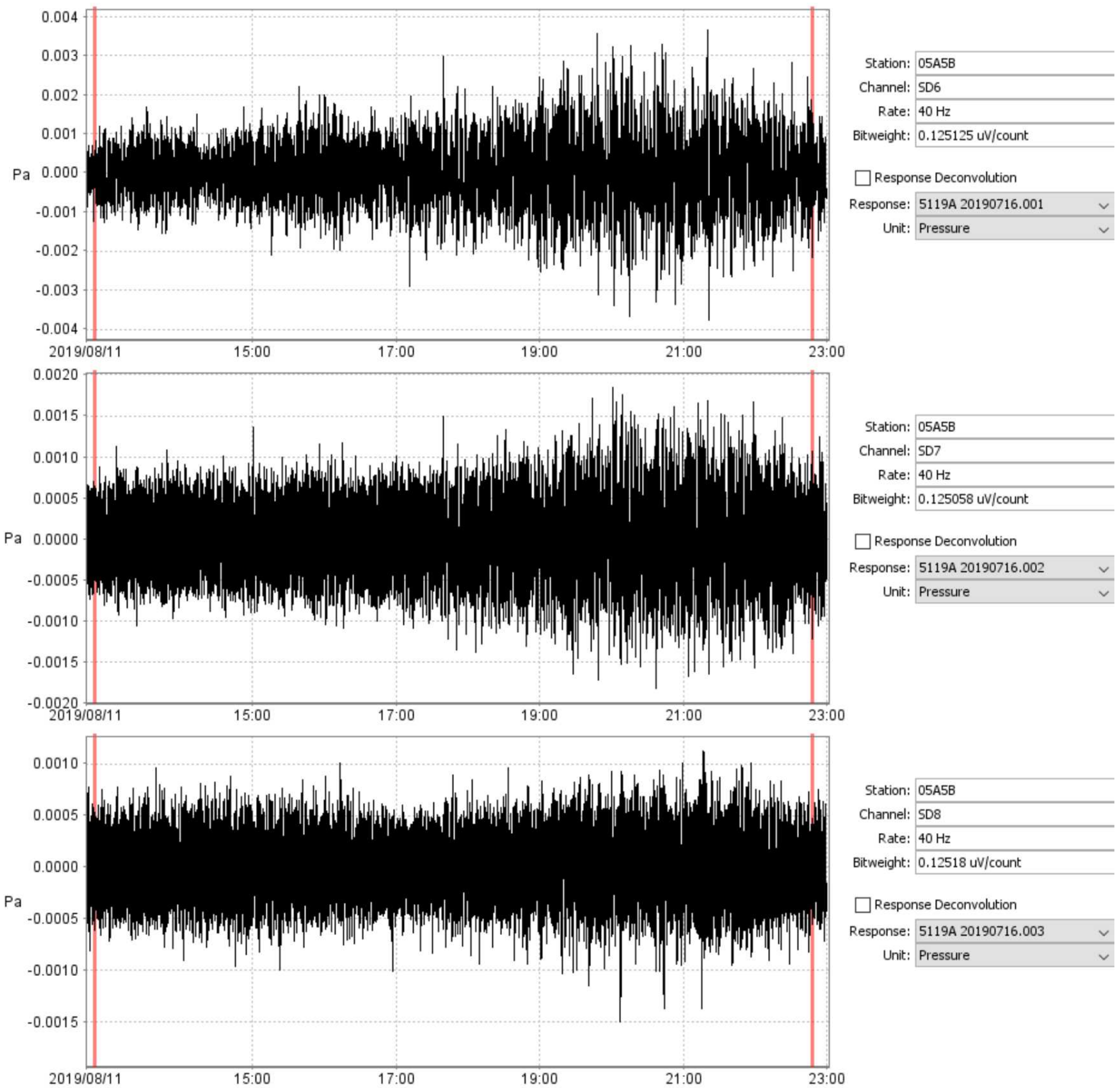


Figure 26 Self-Noise Time Series, Hyperion 5119A

The self-noise data was collected over the weekend while conditions were stable and quiet. The sensor inputs were capped and the sensors placed within the 1400L Infrasound Chamber. A 10 hour window of time was selected when environmental conditions were most stable in order to obtain the best measurement of the sensor self-noise.

The sensor sensitivities measured at these conditions were applied to the time series to obtain the sensor output in Pascals.

The power spectra plots below show the self-noise spectra corresponding to the time series shown earlier. The respective self-noise spectra are plotted alongside the Bowman Low Noise Model in green, the expected Hyperion 5000 noise model provided by the manufacturer in red, and the IMS requirement for the maximum noise level shown in blue. The noise floor of the digitizer used in the testbed, converted to Pascal using the nominal sensor sensitivity, is plotted in purple to confirm that the digitizer is not impacting the estimate of sensor self-noise.

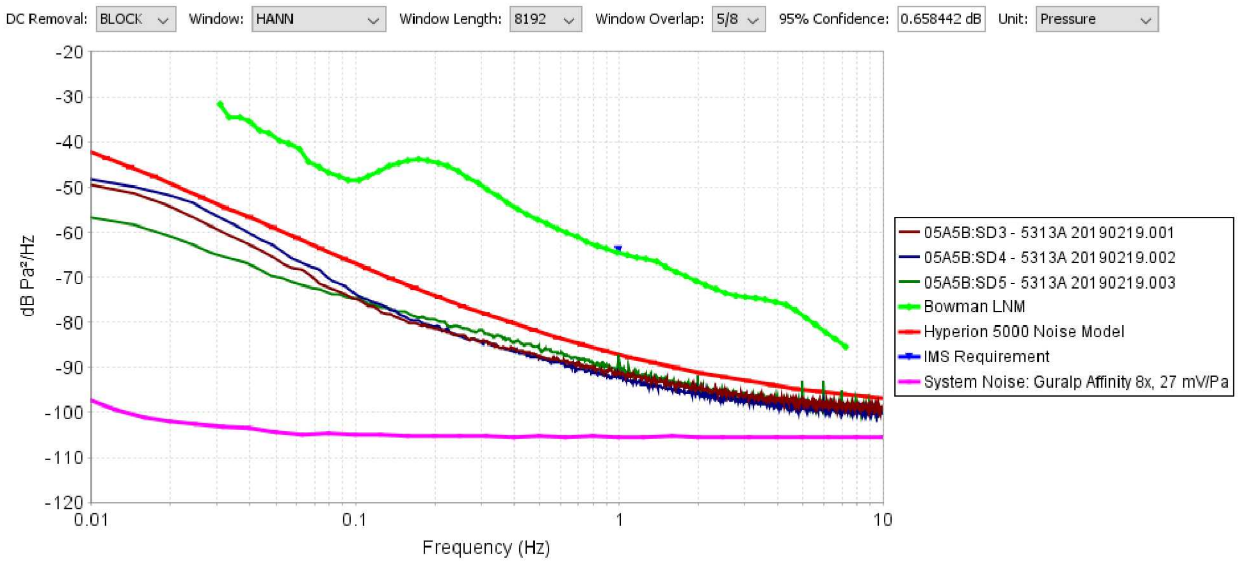


Figure 27 Self-Noise Power Spectra, Hyperion 5313A

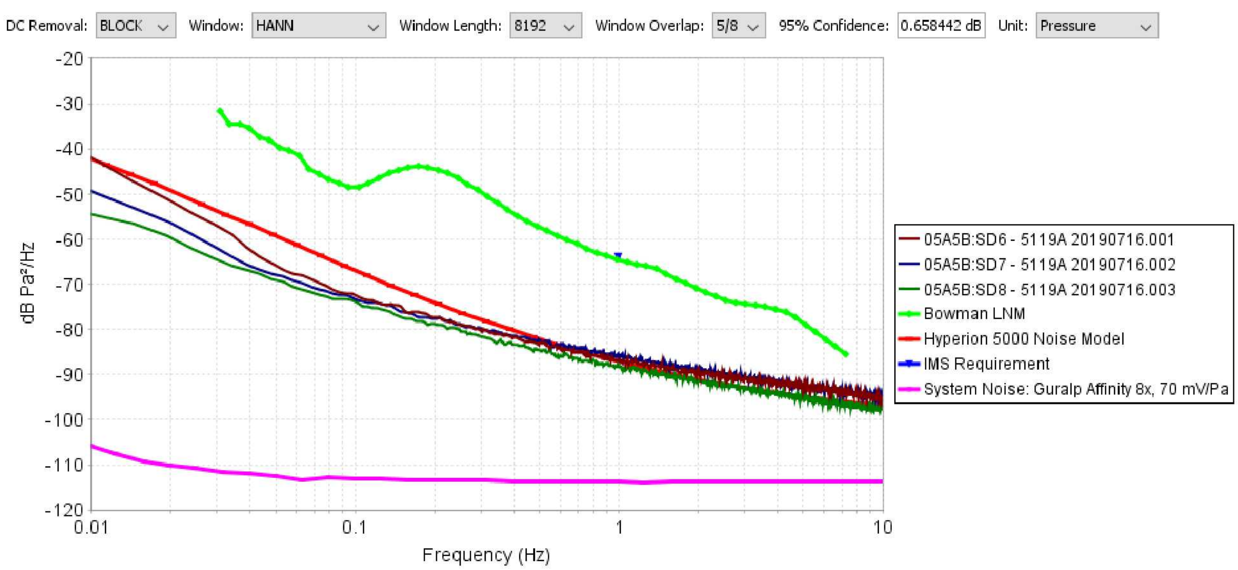


Figure 28 Self-Noise Power Spectra, Hyperion 5119A

There are some slight variations in self-noise between the individual sensors, most noticeably at lower frequencies below 0.1 Hz. However, they are all consistent with the nominal 5000 series noise model provided by Hyperion.

In general, the 5313A sensors were slightly quieter than the 5119A sensors at frequencies above 0.1 Hz, likely due to the difference in their sensitivity and the relative contribution of electronic versus transducer noise. However, this difference in noise level is unlikely to be noticeable in field conditions since the self-noise is so much lower than the expected site noise.

The following table contains self-noise levels in dB relative to 1 Pa^2/Hz. The 95% PSD confidence interval is +/- 0.658 dB.

Table 16 Self-Noise Power Spectra

Frequency	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
0.0100 Hz	-50.23 dB	-48.41 dB	-57.08 dB	-43.17 dB	-50.18 dB	-54.78 dB
0.0125 Hz	-50.48 dB	-49.08 dB	-57.66 dB	-45.88 dB	-51.97 dB	-55.75 dB
0.0160 Hz	-53.03 dB	-51.39 dB	-59.64 dB	-50.18 dB	-55.03 dB	-58.11 dB
0.0200 Hz	-54.45 dB	-51.75 dB	-61.08 dB	-50.92 dB	-56.31 dB	-59.74 dB
0.0250 Hz	-57.10 dB	-53.72 dB	-62.92 dB	-55.12 dB	-59.33 dB	-62.56 dB
0.0315 Hz	-60.36 dB	-57.24 dB	-65.47 dB	-58.06 dB	-63.36 dB	-65.57 dB
0.0400 Hz	-62.57 dB	-60.24 dB	-66.87 dB	-62.45 dB	-65.92 dB	-66.84 dB
0.0500 Hz	-65.66 dB	-62.56 dB	-69.94 dB	-65.48 dB	-67.77 dB	-69.09 dB
0.0630 Hz	-68.43 dB	-66.91 dB	-71.85 dB	-68.17 dB	-70.08 dB	-71.48 dB
0.0800 Hz	-72.22 dB	-70.03 dB	-73.48 dB	-71.27 dB	-71.92 dB	-73.13 dB
0.100 Hz	-75.11 dB	-73.96 dB	-74.85 dB	-72.47 dB	-73.48 dB	-73.84 dB
0.125 Hz	-77.79 dB	-76.31 dB	-76.75 dB	-74.32 dB	-74.38 dB	-75.55 dB
0.160 Hz	-80.13 dB	-79.38 dB	-78.36 dB	-76.09 dB	-76.53 dB	-77.83 dB
0.200 Hz	-81.42 dB	-81.00 dB	-79.63 dB	-77.35 dB	-77.55 dB	-79.05 dB
0.250 Hz	-82.98 dB	-83.15 dB	-81.22 dB	-79.12 dB	-79.14 dB	-80.25 dB
0.315 Hz	-84.57 dB	-84.70 dB	-82.72 dB	-80.54 dB	-80.26 dB	-81.96 dB
0.40 Hz	-86.13 dB	-86.57 dB	-84.35 dB	-81.88 dB	-81.54 dB	-83.59 dB
0.50 Hz	-87.54 dB	-87.94 dB	-85.84 dB	-83.07 dB	-82.44 dB	-84.67 dB
0.63 Hz	-88.83 dB	-89.50 dB	-87.40 dB	-84.64 dB	-83.89 dB	-86.00 dB
0.80 Hz	-90.26 dB	-91.14 dB	-89.11 dB	-85.87 dB	-85.00 dB	-87.26 dB
1.00 Hz	-91.41 dB	-92.43 dB	-90.39 dB	-86.88 dB	-85.89 dB	-88.38 dB
1.25 Hz	-92.52 dB	-93.77 dB	-91.96 dB	-87.85 dB	-87.04 dB	-89.33 dB
1.60 Hz	-93.77 dB	-94.96 dB	-93.40 dB	-88.89 dB	-88.13 dB	-90.45 dB
2.00 Hz	-94.76 dB	-95.98 dB	-94.63 dB	-89.75 dB	-89.02 dB	-91.45 dB
2.50 Hz	-95.71 dB	-96.91 dB	-95.73 dB	-90.41 dB	-89.97 dB	-92.38 dB
3.15 Hz	-96.59 dB	-97.71 dB	-96.71 dB	-91.19 dB	-90.88 dB	-93.31 dB
4.00 Hz	-97.28 dB	-98.36 dB	-97.59 dB	-91.95 dB	-91.76 dB	-94.29 dB
5.00 Hz	-97.94 dB	-98.99 dB	-98.35 dB	-92.68 dB	-92.63 dB	-95.22 dB
6.30 Hz	-98.44 dB	-99.45 dB	-98.86 dB	-93.52 dB	-93.50 dB	-96.20 dB
8.00 Hz	-98.90 dB	-99.84 dB	-99.43 dB	-94.46 dB	-94.30 dB	-97.06 dB
10.00 Hz	-99.27 dB	-100.17 dB	-99.86 dB	-95.39 dB	-95.05 dB	-97.89 dB

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

Table 17 Self Noise RMS

Sensor	20 mHz - 4 Hz
Hyperion 5313A 20190219.001	0.000184875 Pa rms
Hyperion 5313A 20190219.002	0.000251556 Pa rms
Hyperion 5313A 20190219.003	0.000123156 Pa rms
Hyperion 5119A 20190716.001	0.000246827 Pa rms
Hyperion 5119A 20190716.002	0.000175905 Pa rms
Hyperion 5119A 20190716.003	0.000138198 Pa rms

3.6 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.

3.6.1 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).

3.6.2 Configuration

There is no test configuration for the dynamic range test.

The full-scale value used for the largest signal comes from the manufacturer's nominal specifications of a maximum of 2.7 V output for the 5313A sensors and a 7 V output for the 5119A sensors, scaled by each sensor's sensitivity determine in section 3.2 Sensitivity. The value for the smallest signal comes from the evaluated sensor self-noise determined in section 3.5 Self-Noise.

3.6.3 Analysis

The dynamic range over a given pass-band is:

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

Where

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

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

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

3.6.4 Result

The following table contains the dynamic range levels over the 0.02 – 4 Hz application passband.

Table 18 Dynamic Range

	20 mHz - 4 Hz
Hyperion 5313A 20190219.001	111.93 dB
Hyperion 5313A 20190219.002	109.29 dB
Hyperion 5313A 20190219.003	115.42 dB
Hyperion 5119A 20190716.001	109.28 dB
Hyperion 5119A 20190716.002	112.12 dB
Hyperion 5119A 20190716.003	114.21 dB

The Hyperion 5313A sensors had dynamic range levels across the 0.02 – 4 Hz passband of between 109.29 dB and 115.42 dB. The Hyperion 5119A sensors had dynamic range levels across the 0.02 – 4 Hz passband of between 109.28 and 114.21 dB.

All of the sensors dynamic range levels exceeded the minimum 108 dB requirement for use within the IMS.

3.7 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.

3.7.1 Measurand

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

3.7.2 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.

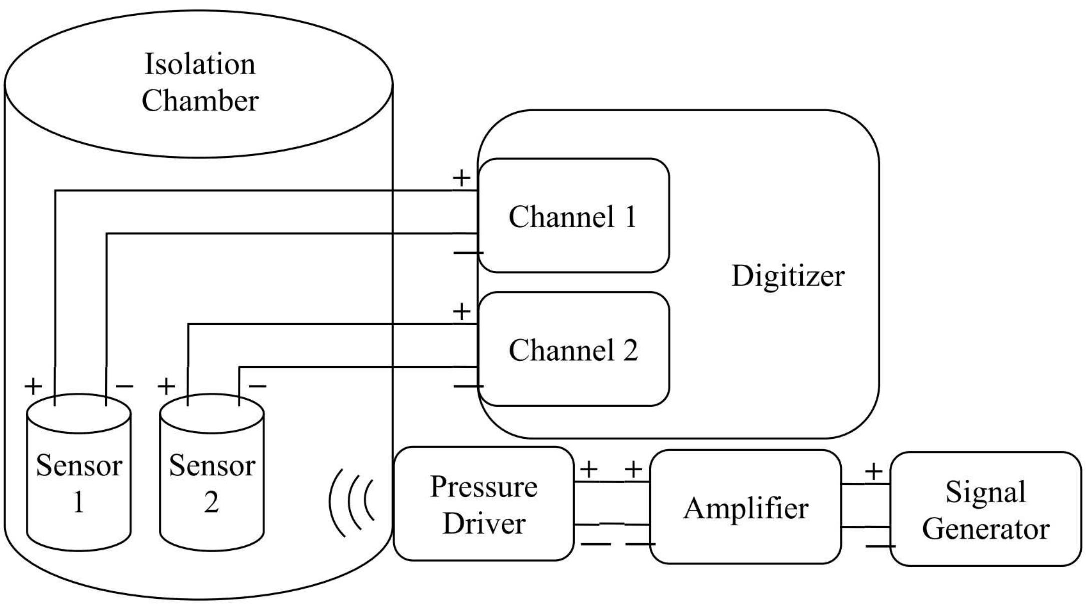


Figure 29 Frequency Response Configuration Diagram

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 19 Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	SNL	Laser speaker #1	1.107 mV/Pa at 1 Hz, 830 hPa, 23 C
Reference Sensor	B&K 4193	2812287	2.117 mV/Pa at 10 Hz, 830 hPa, 23 C
Infrasound Chamber	SNL	1400 L Chamber	830 hPa and 1000 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, 0.5 V sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A

The 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 laser measurement of speaker displacement was used as the reference for frequencies at 0.2 Hz and below and the B&K 4193 microphone was used as the reference for frequencies above 0.2 Hz. 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.

3.7.3 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.

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:

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

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

The sensor amplitude sensitivity in Volts / Pascal is computed:

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

The sensor phase sensitivity in degrees is computed:

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

3.7.4 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.

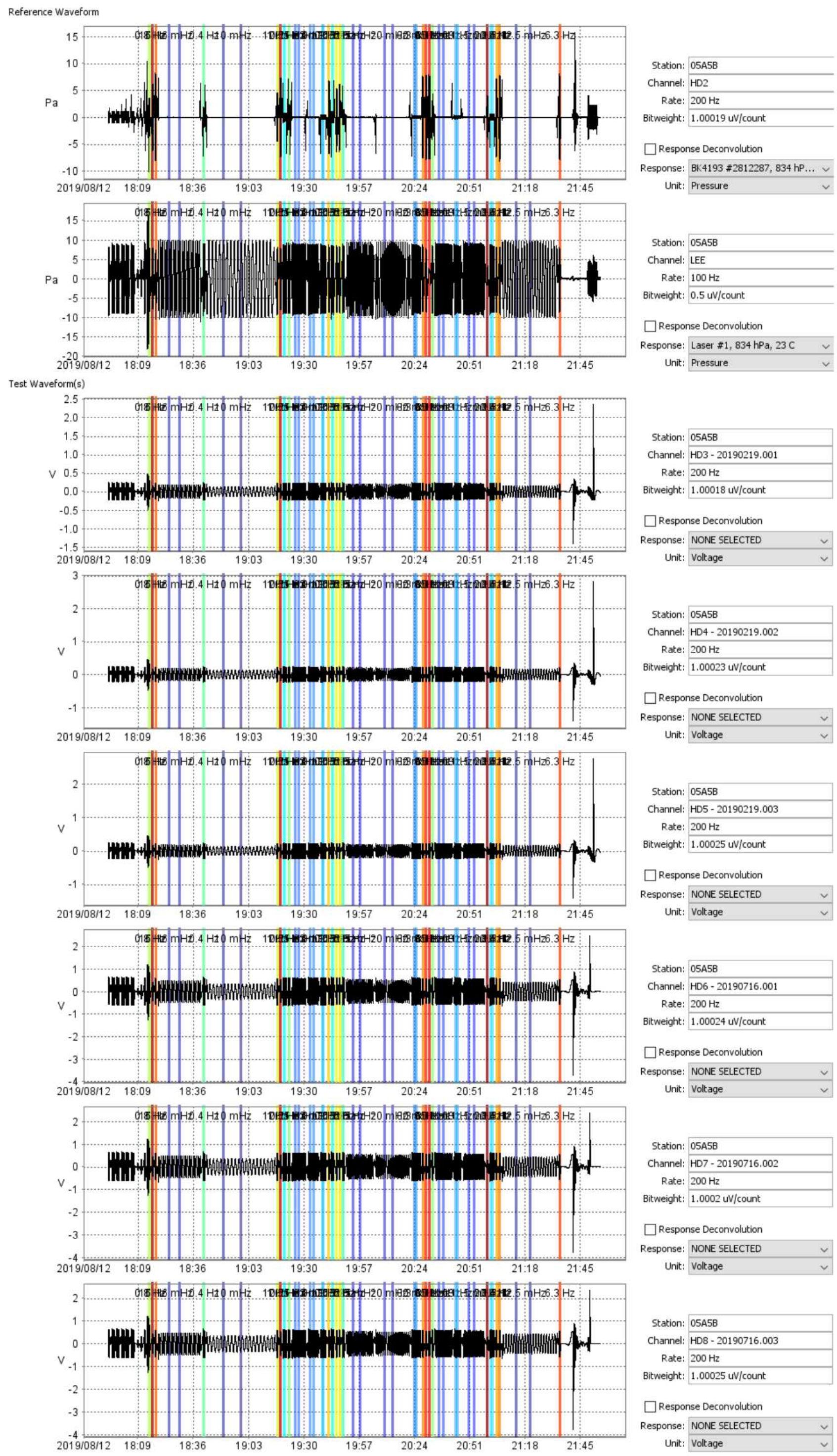


Figure 30 Frequency Response Time Series

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

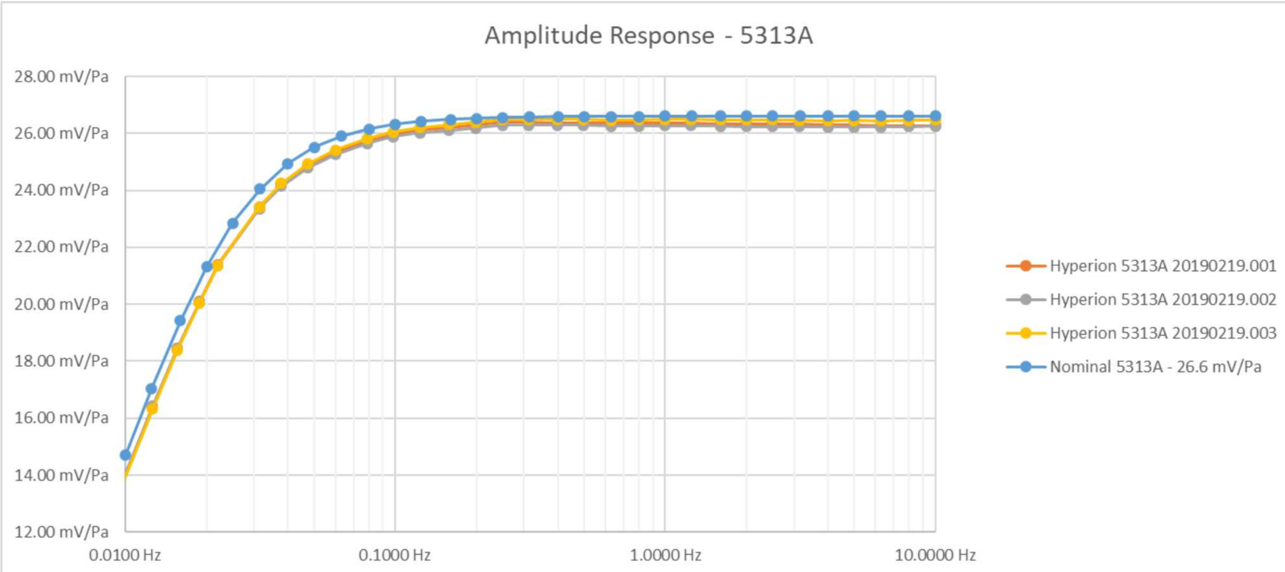


Figure 31 Amplitude Response, Hyperion 5313A

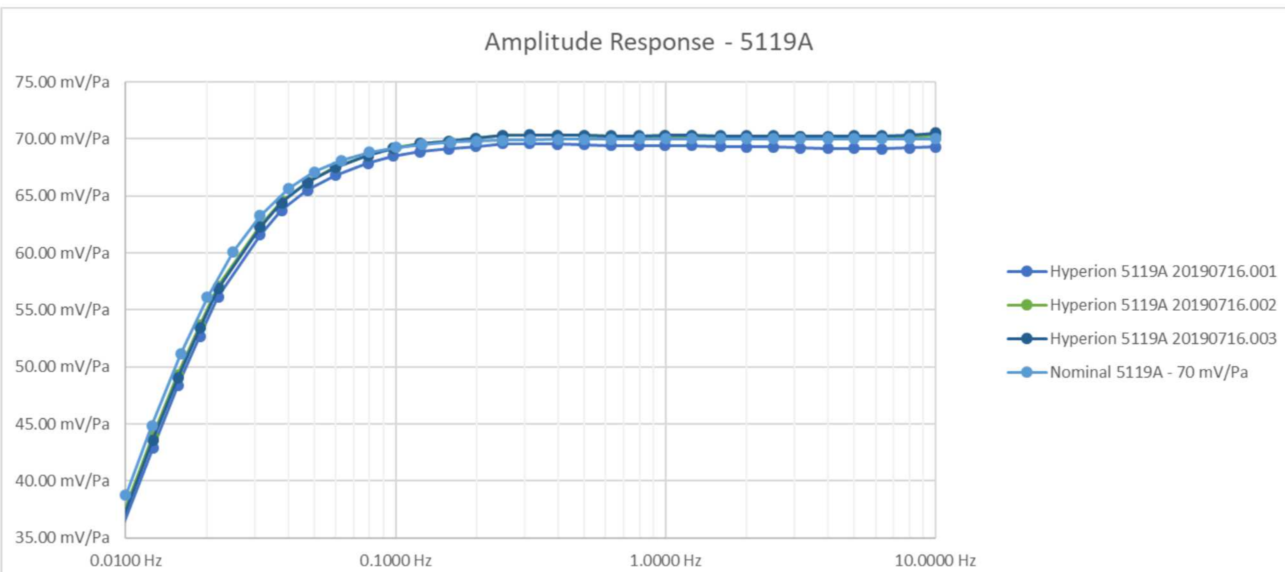


Figure 32 Amplitude Response, Hyperion 5119A

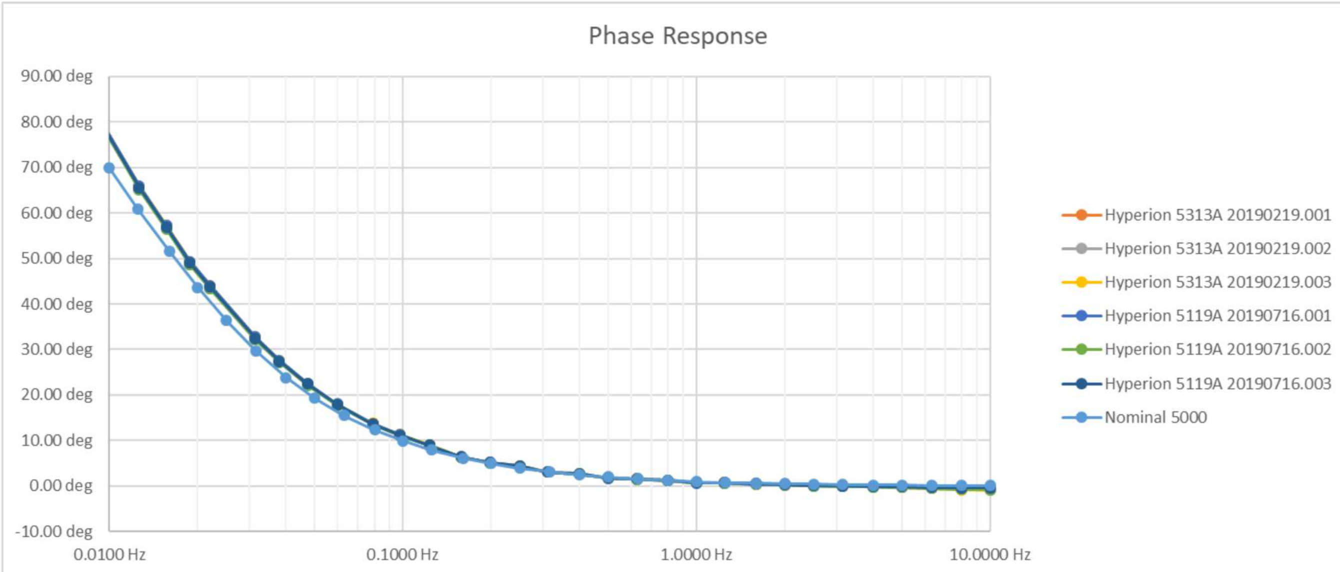


Figure 33 Phase Response

The amplitude and phase responses correspond well to the nominal models provided by Hyperion. Some variation in the amplitude response curves are visible, consistent with the unique sensitivity in each sensor. All of the phase responses measured on the sensors were very similar, within 0.5 degrees of one another.

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

Table 20 Amplitude Response

Frequency	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
0.0094 Hz	13.40 mV/Pa	13.42 mV/Pa	13.31 mV/Pa	34.98 mV/Pa	35.90 mV/Pa	35.57 mV/Pa
0.0126 Hz	16.40 mV/Pa	16.42 mV/Pa	16.32 mV/Pa	42.89 mV/Pa	43.90 mV/Pa	43.57 mV/Pa
0.0156 Hz	18.46 mV/Pa	18.45 mV/Pa	18.40 mV/Pa	48.35 mV/Pa	49.33 mV/Pa	49.04 mV/Pa
0.0188 Hz	20.10 mV/Pa	20.08 mV/Pa	20.06 mV/Pa	52.70 mV/Pa	53.67 mV/Pa	53.42 mV/Pa
0.0220 Hz	21.39 mV/Pa	21.36 mV/Pa	21.37 mV/Pa	56.16 mV/Pa	57.09 mV/Pa	56.88 mV/Pa
0.0314 Hz	23.41 mV/Pa	23.36 mV/Pa	23.43 mV/Pa	61.58 mV/Pa	62.41 mV/Pa	62.28 mV/Pa
0.0378 Hz	24.20 mV/Pa	24.14 mV/Pa	24.24 mV/Pa	63.73 mV/Pa	64.52 mV/Pa	64.42 mV/Pa
0.0472 Hz	24.86 mV/Pa	24.78 mV/Pa	24.91 mV/Pa	65.50 mV/Pa	66.24 mV/Pa	66.18 mV/Pa
0.0598 Hz	25.35 mV/Pa	25.26 mV/Pa	25.42 mV/Pa	66.83 mV/Pa	67.53 mV/Pa	67.49 mV/Pa
0.0789 Hz	25.73 mV/Pa	25.64 mV/Pa	25.81 mV/Pa	67.87 mV/Pa	68.56 mV/Pa	68.54 mV/Pa
0.0978 Hz	25.97 mV/Pa	25.88 mV/Pa	26.06 mV/Pa	68.51 mV/Pa	69.20 mV/Pa	69.18 mV/Pa
0.1231 Hz	26.12 mV/Pa	26.02 mV/Pa	26.21 mV/Pa	68.89 mV/Pa	69.58 mV/Pa	69.58 mV/Pa
0.1577 Hz	26.20 mV/Pa	26.11 mV/Pa	26.30 mV/Pa	69.12 mV/Pa	69.82 mV/Pa	69.82 mV/Pa
0.199 Hz	26.29 mV/Pa	26.19 mV/Pa	26.39 mV/Pa	69.34 mV/Pa	70.05 mV/Pa	70.06 mV/Pa
0.249 Hz	26.38 mV/Pa	26.28 mV/Pa	26.48 mV/Pa	69.58 mV/Pa	70.30 mV/Pa	70.32 mV/Pa
0.312 Hz	26.39 mV/Pa	26.29 mV/Pa	26.50 mV/Pa	69.59 mV/Pa	70.33 mV/Pa	70.35 mV/Pa
0.40 Hz	26.38 mV/Pa	26.28 mV/Pa	26.49 mV/Pa	69.54 mV/Pa	70.30 mV/Pa	70.32 mV/Pa
0.50 Hz	26.38 mV/Pa	26.28 mV/Pa	26.49 mV/Pa	69.52 mV/Pa	70.30 mV/Pa	70.33 mV/Pa
0.63 Hz	26.35 mV/Pa	26.25 mV/Pa	26.46 mV/Pa	69.43 mV/Pa	70.23 mV/Pa	70.25 mV/Pa
0.80 Hz	26.35 mV/Pa	26.25 mV/Pa	26.47 mV/Pa	69.43 mV/Pa	70.25 mV/Pa	70.28 mV/Pa
1.00 Hz	26.36 mV/Pa	26.27 mV/Pa	26.48 mV/Pa	69.44 mV/Pa	70.27 mV/Pa	70.31 mV/Pa
1.25 Hz	26.36 mV/Pa	26.27 mV/Pa	26.49 mV/Pa	69.42 mV/Pa	70.27 mV/Pa	70.31 mV/Pa
1.60 Hz	26.34 mV/Pa	26.25 mV/Pa	26.47 mV/Pa	69.35 mV/Pa	70.23 mV/Pa	70.27 mV/Pa
2.00 Hz	26.33 mV/Pa	26.24 mV/Pa	26.46 mV/Pa	69.31 mV/Pa	70.20 mV/Pa	70.25 mV/Pa
2.50 Hz	26.33 mV/Pa	26.24 mV/Pa	26.47 mV/Pa	69.29 mV/Pa	70.20 mV/Pa	70.26 mV/Pa
3.15 Hz	26.31 mV/Pa	26.23 mV/Pa	26.46 mV/Pa	69.23 mV/Pa	70.17 mV/Pa	70.24 mV/Pa
4.00 Hz	26.29 mV/Pa	26.22 mV/Pa	26.44 mV/Pa	69.18 mV/Pa	70.13 mV/Pa	70.21 mV/Pa
5.00 Hz	26.29 mV/Pa	26.22 mV/Pa	26.45 mV/Pa	69.18 mV/Pa	70.16 mV/Pa	70.26 mV/Pa
6.30 Hz	26.27 mV/Pa	26.21 mV/Pa	26.44 mV/Pa	69.15 mV/Pa	70.13 mV/Pa	70.26 mV/Pa
8.00 Hz	26.26 mV/Pa	26.23 mV/Pa	26.46 mV/Pa	69.21 mV/Pa	70.20 mV/Pa	70.36 mV/Pa
10.00 Hz	26.26 mV/Pa	26.26 mV/Pa	26.48 mV/Pa	69.31 mV/Pa	70.31 mV/Pa	70.51 mV/Pa

Table 21 Phase Response

Frequency	Hyperion 5313A 20190219.001	Hyperion 5313A 20190219.002	Hyperion 5313A 20190219.003	Hyperion 5119A 20190716.001	Hyperion 5119A 20190716.002	Hyperion 5119A 20190716.003
0.0094 Hz	79.63 deg	79.33 deg	80.01 deg	79.99 deg	79.14 deg	79.55 deg
0.0126 Hz	65.60 deg	65.28 deg	66.00 deg	66.00 deg	65.10 deg	65.55 deg
0.0156 Hz	56.87 deg	56.62 deg	57.30 deg	57.29 deg	56.50 deg	56.91 deg
0.0188 Hz	48.96 deg	48.69 deg	49.36 deg	49.37 deg	48.58 deg	48.99 deg
0.0220 Hz	43.67 deg	43.42 deg	44.05 deg	44.06 deg	43.34 deg	43.72 deg
0.0314 Hz	32.42 deg	32.20 deg	32.74 deg	32.75 deg	32.15 deg	32.47 deg
0.0378 Hz	27.38 deg	27.19 deg	27.66 deg	27.67 deg	27.16 deg	27.43 deg
0.0472 Hz	22.35 deg	22.20 deg	22.59 deg	22.59 deg	22.19 deg	22.41 deg
0.0598 Hz	17.85 deg	17.73 deg	18.06 deg	18.04 deg	17.73 deg	17.91 deg
0.0789 Hz	13.60 deg	13.51 deg	13.77 deg	13.74 deg	13.51 deg	13.66 deg
0.0978 Hz	11.15 deg	11.07 deg	11.28 deg	11.24 deg	11.07 deg	11.20 deg
0.1231 Hz	8.95 deg	8.89 deg	9.07 deg	9.02 deg	8.90 deg	9.01 deg
0.1577 Hz	6.35 deg	6.30 deg	6.45 deg	6.38 deg	6.31 deg	6.40 deg
0.199 Hz	5.01 deg	4.98 deg	5.09 deg	5.02 deg	4.98 deg	5.06 deg
0.249 Hz	4.30 deg	4.27 deg	4.37 deg	4.28 deg	4.27 deg	4.34 deg
0.312 Hz	3.00 deg	2.98 deg	3.06 deg	2.97 deg	2.98 deg	3.04 deg
0.40 Hz	2.76 deg	2.76 deg	2.81 deg	2.72 deg	2.75 deg	2.81 deg
0.50 Hz	1.78 deg	1.78 deg	1.82 deg	1.72 deg	1.76 deg	1.82 deg
0.63 Hz	1.56 deg	1.57 deg	1.59 deg	1.49 deg	1.54 deg	1.60 deg
0.80 Hz	1.23 deg	1.24 deg	1.25 deg	1.14 deg	1.20 deg	1.26 deg
1.00 Hz	0.75 deg	0.77 deg	0.75 deg	0.65 deg	0.71 deg	0.77 deg
1.25 Hz	0.72 deg	0.74 deg	0.70 deg	0.61 deg	0.66 deg	0.74 deg
1.60 Hz	0.50 deg	0.53 deg	0.47 deg	0.38 deg	0.43 deg	0.51 deg
2.00 Hz	0.34 deg	0.38 deg	0.29 deg	0.21 deg	0.26 deg	0.36 deg
2.50 Hz	0.15 deg	0.19 deg	0.07 deg	0.01 deg	0.04 deg	0.16 deg
3.15 Hz	0.04 deg	0.10 deg	-0.06 deg	-0.10 deg	-0.09 deg	0.05 deg
4.00 Hz	-0.05 deg	0.01 deg	-0.21 deg	-0.21 deg	-0.22 deg	-0.05 deg
5.00 Hz	-0.12 deg	-0.04 deg	-0.33 deg	-0.28 deg	-0.32 deg	-0.12 deg
6.30 Hz	-0.26 deg	-0.16 deg	-0.55 deg	-0.44 deg	-0.52 deg	-0.28 deg
8.00 Hz	-0.39 deg	-0.28 deg	-0.80 deg	-0.60 deg	-0.72 deg	-0.44 deg
10.00 Hz	-0.37 deg	-0.24 deg	-0.94 deg	-0.60 deg	-0.79 deg	-0.45 deg

3.8 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).

3.8.1 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.

Lower frequency (in Hz)

Upper frequency (in Hz)

3.8.2 Configuration

There is no test configuration for the passband test. The amplitude response used in computing the passband is determined in section 3.7 Frequency Response.

3.8.3 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.

3.8.4 Result

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

Table 22 Passband

	Lower Limit	Upper Limit
Hyperion 5313A 20190219.001	0.0160 Hz	> 10 Hz
Hyperion 5313A 20190219.002	0.0159 Hz	> 10 Hz
Hyperion 5313A 20190219.003	0.0163 Hz	> 10 Hz
Hyperion 5119A 20190716.001	0.0162 Hz	> 10 Hz
Hyperion 5119A 20190716.002	0.0159 Hz	> 10 Hz
Hyperion 5119A 20190716.003	0.0161 Hz	> 10 Hz

All the Hyperion 5313A and 5119A sensors had a lower limit on the passband that was between 0.0159 and 0.0163 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.

3.9 Static Temperature Sensitivity Variation

The sensitivity variation with static temperature is defined as being the observable change in sensor sensitivity as the ambient static temperature is varied. The purpose of this test is to confirm that the sensor sensitivity 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.

3.9.1 Measurand

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

3.9.2 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 sensor under test via a manifold. The diagram below represents this configuration:

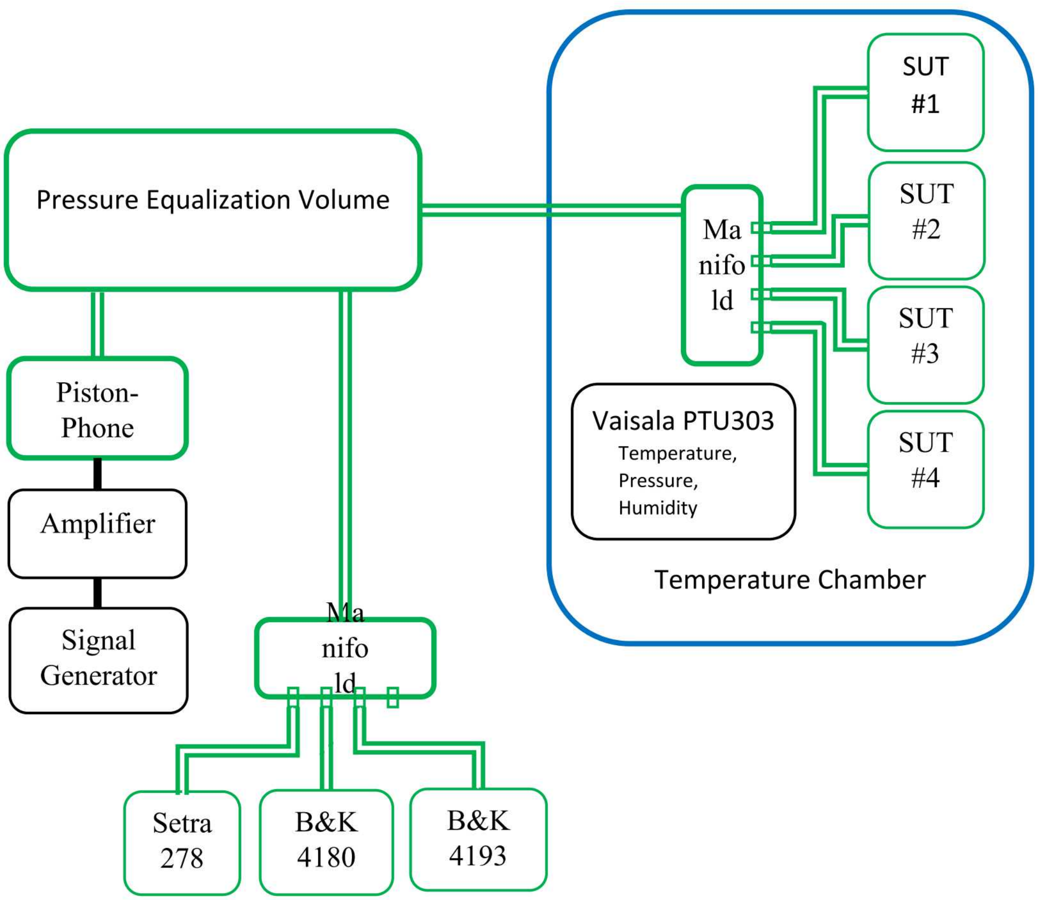


Figure 34 Sensitivity Variation with Static Temperature Configuration Diagram

In the configuration diagram above, 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.

Note that 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 amplitude. 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.

Figure 35 Sensitivity Variation with Static Temperature Configuration Picture

Table 23 Frequency Response Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	B&K 4193	2812287	2.117 mV/Pa at 10 Hz, 830 hPa, 23 C
Reference Sensor	Setra 278	6837528	83.3903 uV/Pa
Thermal Chamber	ESPEC		-20 C to 50 C in 10 C steps.
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, 0.5 V sinusoid
Voltage Amplifier	AE Techron 7224p	N/A	20x gain DC Coupled Amplifier
Pressure Driver	JL Audio 10w7ae	N/A	N/A
Environmental Monitor – Inside Thermal Chamber	Vaisala PTU300	J3040003	Ambient Temperature, Pressure, and Humidity

The thermal chamber is programmed to iterate through temperature cycles from -20 C 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 a minimum of 2 hours in order for the sensors for fully equilibrate. Near the end of each temperature step, a series of pressure tones at discrete frequencies are generated to measure the sensitivity of the sensor under test relative to the reference sensor. The calibration tones are performed while the temperature chamber is operating with sufficient amplitude to obtain the needed signal to noise ratio.

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

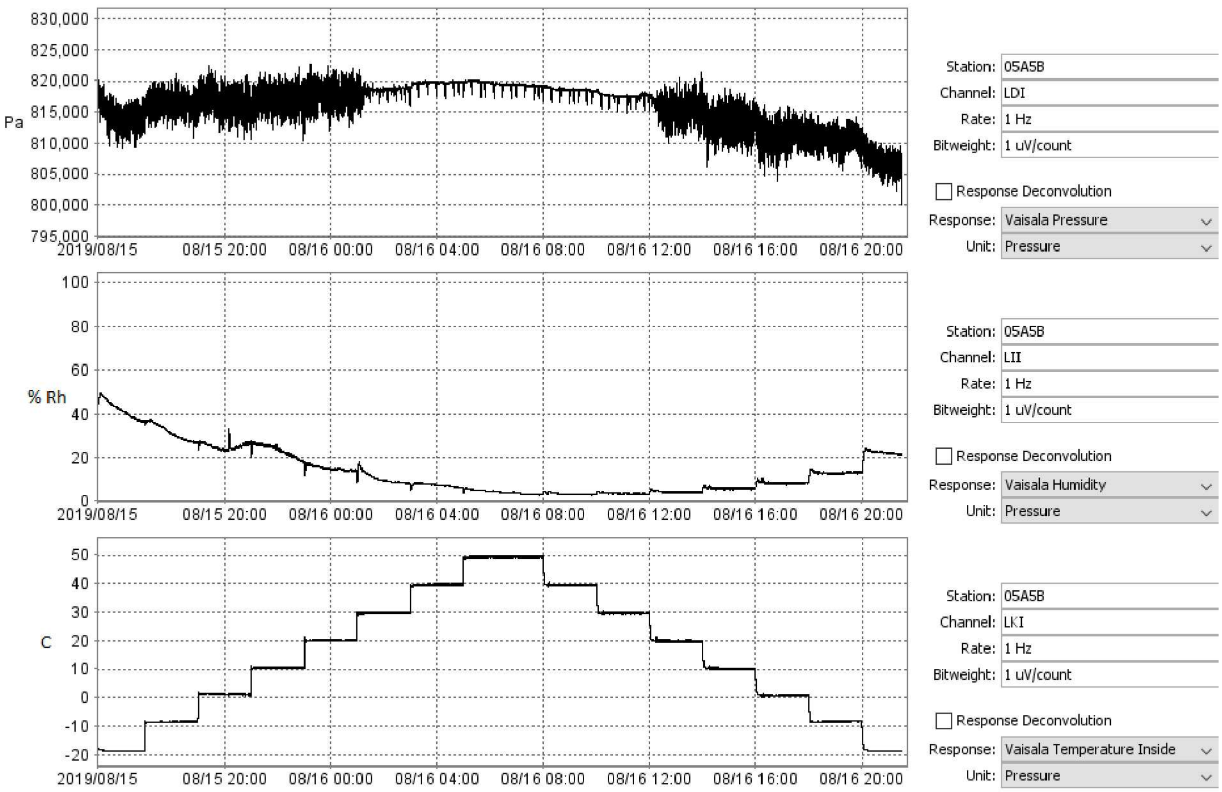


Figure 36 Environmental Conditions During Temperature Testing

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

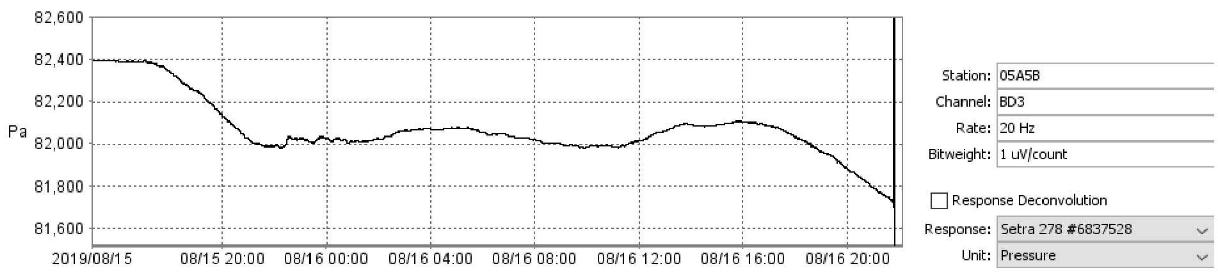


Figure 37 Static Pressure Within Manifold During Temperature Testing

As can be seen, the static pressure throughout the period of testing is within +/- 400 Pa. The B&K 4193 used as a reference has a pressure coefficient to its sensitivity of -0.005 dB/kPa. Therefore, the effect of the variability in static pressure is expected to add 0.023 % to the uncertainty of the results, which is far less than the measured variability due to temperature of the sensors under test.

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.

3.9.3 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.

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:

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

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

The sensor amplitude sensitivity in Volts / Pascal is computed:

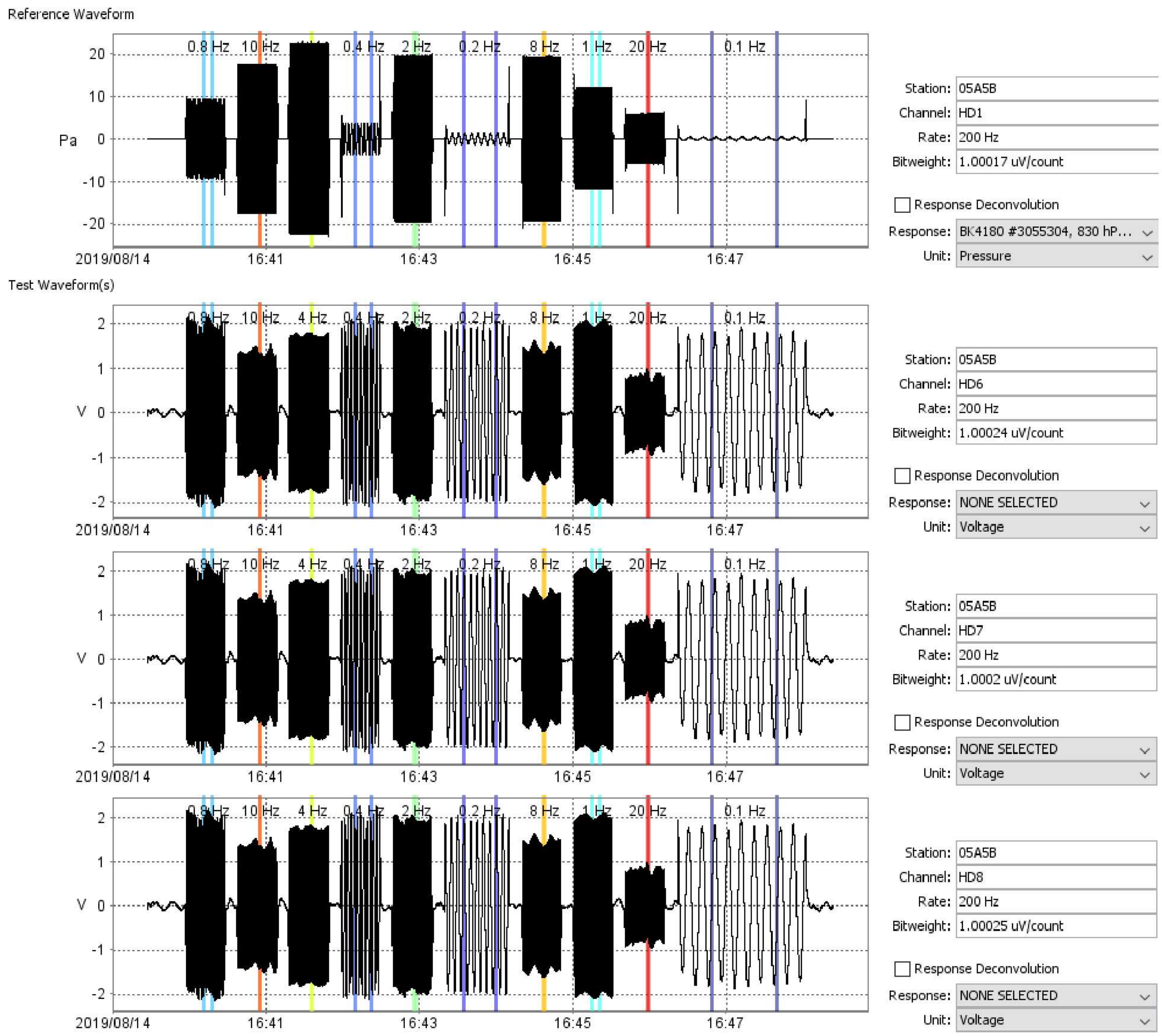
$$Sensitivity = \frac{V_{test}}{P_{ref}}$$

The percent change in sensitivity at each measurement is computed from a baseline sensitivity measurement:

$$Sensitivity\ Change = 100 * \frac{(Sensitivity - Sensitivity_{baseline})}{Sensitivity_{baseline}}$$

3.9.4 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.



The plots of the change in sensitivity over -20 C to +50 C and then from +50 C to -20 C at select frequencies are shown below:

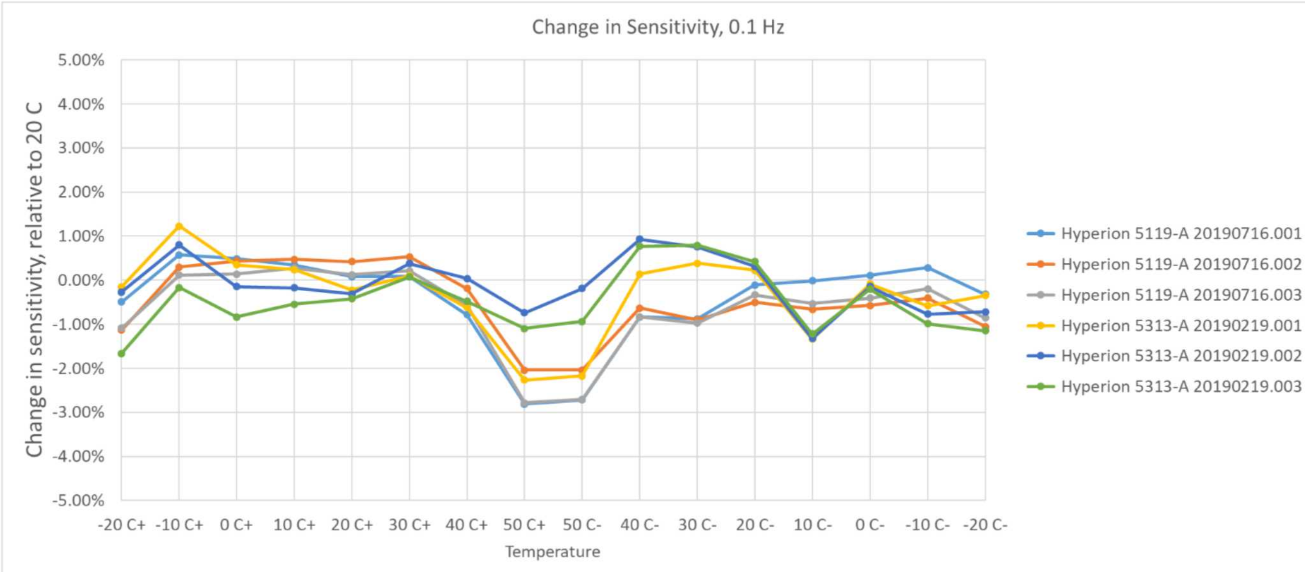


Figure 38 Sensitivity Variation with Static Temperature, 0.1 Hz

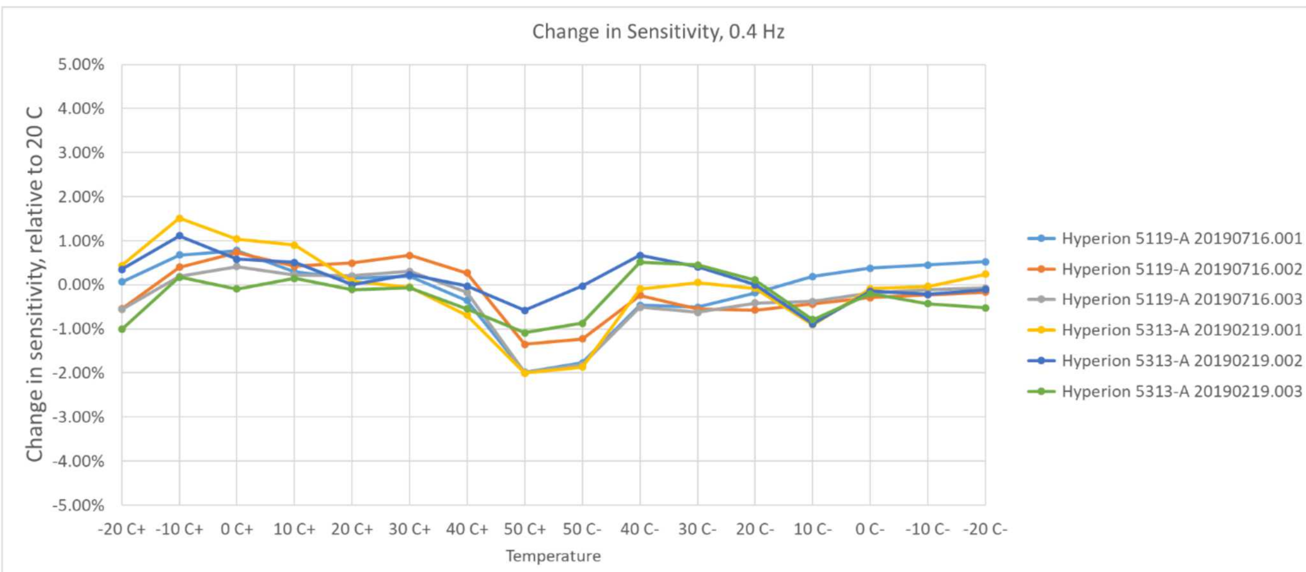


Figure 39 Sensitivity Variation with Static Temperature, 0.4 Hz

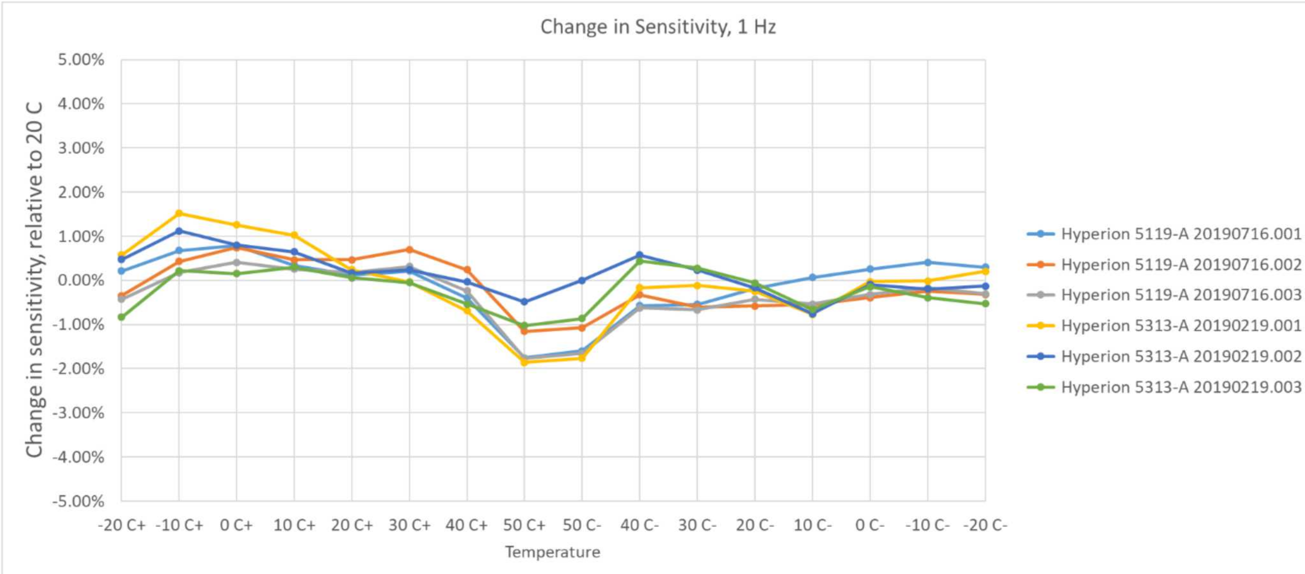


Figure 40 Sensitivity Variation with Static Temperature, 1 Hz

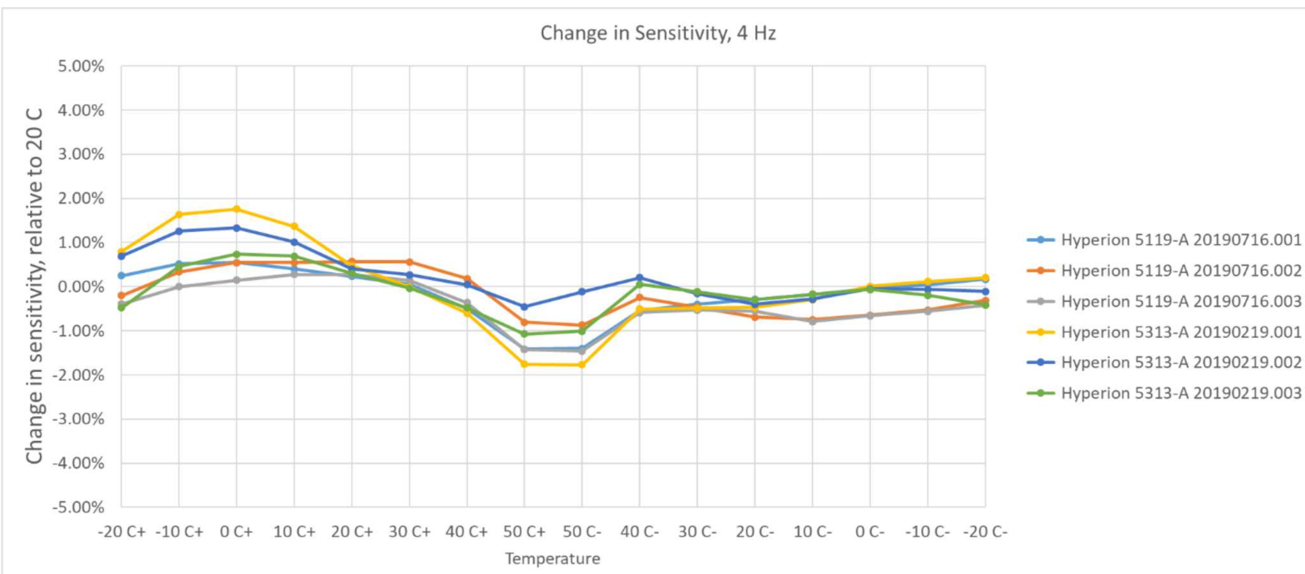


Figure 41 Sensitivity Variation with Static Temperature, 4 Hz

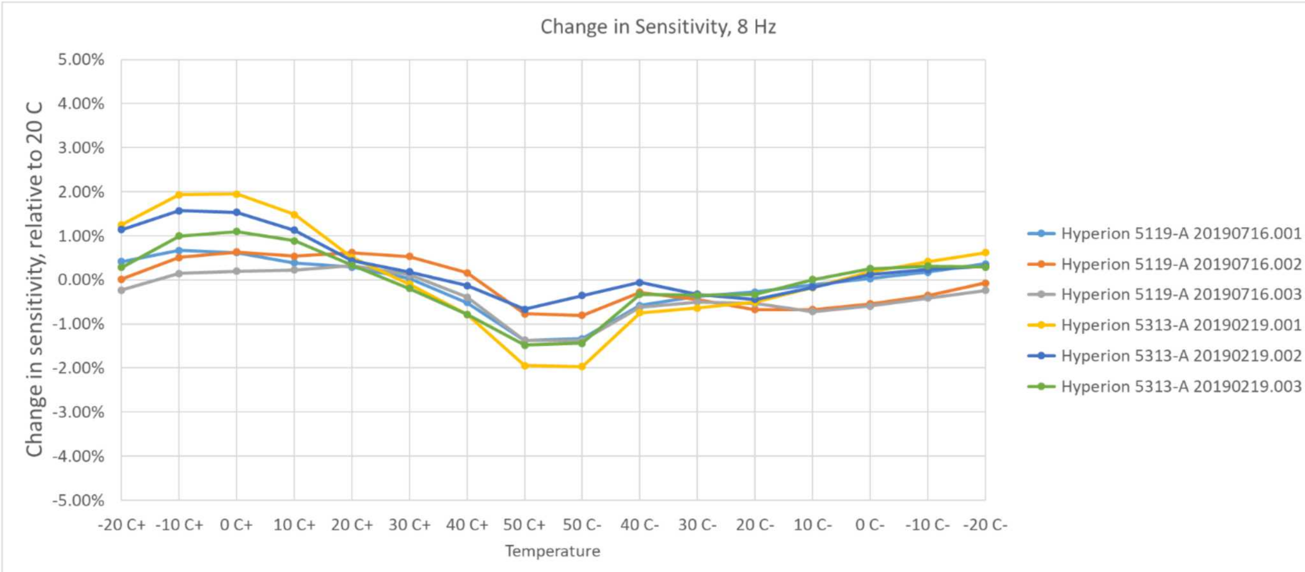


Figure 42 Sensitivity Variation with Static Temperature, 8 Hz

All of the measured variations in sensitivity with respect to static temperature were within 2% across 0.1 to 8 Hz and -20 C to 40 C with the majority of the variations observed within 1%. The most notable change occurred at temperatures of 50 C where the sensitivity changed by as much as 3% at 0.1 Hz.

The percent variations are calculated relative to an initial measurement at 20 C that was made just prior to starting the programmed set of steps within the thermal chamber. This ensures that the baseline is made when the sensors are fully stabilized to temperature.

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

Table 24 Static Temperature Variation: 5313A #20190219.001

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-20 C+	-0.15%	0.25%	0.44%	0.46%	0.58%	0.66%	0.79%	1.25%
-10 C+	1.23%	1.53%	1.51%	1.49%	1.52%	1.60%	1.63%	1.93%
0 C+	0.35%	0.83%	1.04%	1.12%	1.26%	1.55%	1.76%	1.95%
10 C+	0.24%	0.64%	0.90%	0.98%	1.03%	1.23%	1.36%	1.48%
20 C+	-0.22%	0.11%	0.08%	0.15%	0.24%	0.38%	0.47%	0.51%
30 C+	0.10%	-0.06%	-0.05%	-0.09%	-0.03%	0.01%	0.00%	-0.09%
40 C+	-0.62%	-0.71%	-0.69%	-0.73%	-0.69%	-0.61%	-0.60%	-0.78%
50 C+	-2.27%	-2.16%	-2.01%	-1.91%	-1.86%	-1.76%	-1.76%	-1.95%
50 C-	-2.17%	-1.99%	-1.86%	-1.82%	-1.77%	-1.73%	-1.77%	-1.97%
40 C-	0.14%	0.06%	-0.09%	-0.21%	-0.17%	-0.36%	-0.51%	-0.75%
30 C-	0.39%	0.19%	0.05%	-0.13%	-0.11%	-0.32%	-0.48%	-0.64%
20 C-	0.22%	-0.11%	-0.08%	-0.15%	-0.24%	-0.38%	-0.47%	-0.51%
10 C-	-1.34%	-1.13%	-0.91%	-0.85%	-0.77%	-0.49%	-0.30%	-0.18%
0 C-	-0.09%	-0.22%	-0.09%	-0.12%	-0.03%	-0.04%	0.01%	0.18%
-10 C-	-0.58%	-0.23%	-0.04%	-0.06%	-0.01%	0.05%	0.11%	0.42%
-20 C-	-0.35%	0.08%	0.24%	0.14%	0.20%	0.18%	0.20%	0.62%

Table 25 Static Temperature Variation: 5313A #20190219.002

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-20 C+	-0.27%	0.14%	0.35%	0.37%	0.47%	0.55%	0.69%	1.14%
-10 C+	0.80%	1.12%	1.11%	1.09%	1.12%	1.21%	1.26%	1.57%
0 C+	-0.14%	0.36%	0.58%	0.67%	0.80%	1.11%	1.33%	1.53%
10 C+	-0.18%	0.23%	0.51%	0.60%	0.65%	0.86%	1.01%	1.13%
20 C+	-0.31%	0.02%	0.00%	0.07%	0.17%	0.30%	0.40%	0.44%
30 C+	0.38%	0.22%	0.23%	0.19%	0.24%	0.28%	0.27%	0.18%
40 C+	0.04%	-0.05%	-0.03%	-0.08%	-0.03%	0.04%	0.04%	-0.13%
50 C+	-0.74%	-0.69%	-0.58%	-0.54%	-0.49%	-0.43%	-0.46%	-0.67%
50 C-	-0.19%	-0.08%	-0.03%	-0.05%	0.00%	-0.03%	-0.11%	-0.35%
40 C-	0.93%	0.84%	0.67%	0.55%	0.58%	0.37%	0.21%	-0.06%
30 C-	0.76%	0.55%	0.41%	0.22%	0.23%	0.01%	-0.16%	-0.33%
20 C-	0.31%	-0.02%	0.00%	-0.07%	-0.17%	-0.30%	-0.40%	-0.44%
10 C-	-1.32%	-1.11%	-0.89%	-0.83%	-0.75%	-0.48%	-0.29%	-0.17%
0 C-	-0.15%	-0.27%	-0.14%	-0.18%	-0.09%	-0.11%	-0.05%	0.12%
-10 C-	-0.77%	-0.42%	-0.22%	-0.25%	-0.20%	-0.13%	-0.06%	0.24%
-20 C-	-0.72%	-0.26%	-0.11%	-0.19%	-0.13%	-0.14%	-0.11%	0.31%

Table 26 Static Temperature Variation: 5313A #20190219.003

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-20 C+	-1.66%	-1.22%	-1.01%	-0.95%	-0.83%	-0.71%	-0.48%	0.28%
-10 C+	-0.17%	0.17%	0.17%	0.18%	0.22%	0.34%	0.46%	0.99%
0 C+	-0.83%	-0.33%	-0.10%	0.01%	0.15%	0.48%	0.74%	1.10%
10 C+	-0.55%	-0.13%	0.14%	0.24%	0.30%	0.52%	0.69%	0.89%
20 C+	-0.42%	-0.09%	-0.11%	-0.04%	0.06%	0.20%	0.30%	0.33%
30 C+	0.07%	-0.09%	-0.07%	-0.11%	-0.05%	-0.01%	-0.03%	-0.19%
40 C+	-0.48%	-0.57%	-0.55%	-0.59%	-0.54%	-0.46%	-0.48%	-0.79%
50 C+	-1.10%	-1.15%	-1.09%	-1.07%	-1.03%	-0.99%	-1.07%	-1.48%
50 C-	-0.93%	-0.89%	-0.87%	-0.90%	-0.87%	-0.89%	-1.01%	-1.44%
40 C-	0.77%	0.68%	0.52%	0.40%	0.43%	0.23%	0.05%	-0.32%
30 C-	0.79%	0.59%	0.45%	0.26%	0.28%	0.06%	-0.11%	-0.34%
20 C-	0.42%	0.09%	0.11%	0.04%	-0.06%	-0.20%	-0.30%	-0.33%
10 C-	-1.22%	-1.01%	-0.79%	-0.73%	-0.66%	-0.38%	-0.17%	0.01%
0 C-	-0.20%	-0.33%	-0.20%	-0.23%	-0.15%	-0.15%	-0.06%	0.25%
-10 C-	-0.99%	-0.64%	-0.43%	-0.44%	-0.39%	-0.31%	-0.19%	0.31%
-20 C-	-1.15%	-0.69%	-0.53%	-0.59%	-0.53%	-0.51%	-0.41%	0.29%

Table 27 Static Temperature Variation: 5119A, #20190716.001

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-20 C+	-0.50%	-0.04%	0.06%	0.17%	0.21%	0.14%	0.25%	0.42%
-10 C+	0.58%	0.60%	0.68%	0.62%	0.68%	0.54%	0.52%	0.67%
0 C+	0.48%	0.75%	0.78%	0.77%	0.78%	0.60%	0.55%	0.62%
10 C+	0.35%	0.21%	0.29%	0.81%	0.34%	0.42%	0.40%	0.38%
20 C+	0.08%	-0.20%	0.15%	0.02%	0.13%	0.17%	0.24%	0.29%
30 C+	0.08%	0.20%	0.19%	0.24%	0.21%	0.08%	0.05%	0.03%
40 C+	-0.78%	-0.49%	-0.35%	-0.34%	-0.40%	-0.48%	-0.49%	-0.52%
50 C+	-2.81%	-2.32%	-1.99%	-1.80%	-1.76%	-1.58%	-1.41%	-1.37%
50 C-	-2.71%	-1.99%	-1.77%	-1.72%	-1.59%	-1.50%	-1.40%	-1.34%
40 C-	-0.83%	-0.61%	-0.47%	-0.57%	-0.57%	-0.60%	-0.54%	-0.58%
30 C-	-0.88%	-0.73%	-0.51%	-0.54%	-0.55%	-0.46%	-0.40%	-0.37%
20 C-	-0.11%	-0.32%	-0.18%	-0.20%	-0.18%	-0.28%	-0.29%	-0.28%
10 C-	-0.01%	0.13%	0.19%	0.12%	0.07%	-0.11%	-0.17%	-0.11%
0 C-	0.11%	0.29%	0.38%	0.27%	0.26%	0.04%	-0.05%	0.03%
-10 C-	0.28%	0.40%	0.45%	0.30%	0.41%	0.12%	0.04%	0.18%
-20 C-	-0.32%	0.30%	0.52%	0.52%	0.30%	0.20%	0.17%	0.37%

Table 28 Static Temperature Variation, 5119A, #20190716.002

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-20 C+	-1.13%	-0.67%	-0.55%	-0.40%	-0.35%	-0.36%	-0.20%	0.02%
-10 C+	0.30%	0.32%	0.40%	0.36%	0.43%	0.32%	0.33%	0.51%
0 C+	0.44%	0.70%	0.73%	0.73%	0.75%	0.58%	0.55%	0.63%
10 C+	0.47%	0.34%	0.42%	0.93%	0.47%	0.55%	0.54%	0.54%
20 C+	0.42%	0.14%	0.49%	0.36%	0.46%	0.51%	0.57%	0.62%
30 C+	0.53%	0.67%	0.67%	0.72%	0.70%	0.58%	0.56%	0.53%
40 C+	-0.19%	0.12%	0.27%	0.29%	0.24%	0.18%	0.19%	0.16%
50 C+	-2.04%	-1.63%	-1.35%	-1.18%	-1.16%	-0.98%	-0.80%	-0.77%
50 C-	-2.04%	-1.40%	-1.23%	-1.20%	-1.08%	-0.98%	-0.87%	-0.80%
40 C-	-0.63%	-0.40%	-0.24%	-0.33%	-0.33%	-0.33%	-0.24%	-0.28%
30 C-	-0.90%	-0.76%	-0.55%	-0.59%	-0.60%	-0.52%	-0.46%	-0.45%
20 C-	-0.50%	-0.71%	-0.58%	-0.59%	-0.58%	-0.68%	-0.69%	-0.67%
10 C-	-0.66%	-0.51%	-0.44%	-0.49%	-0.55%	-0.70%	-0.75%	-0.67%
0 C-	-0.57%	-0.38%	-0.29%	-0.39%	-0.39%	-0.59%	-0.65%	-0.55%
-10 C-	-0.41%	-0.28%	-0.22%	-0.35%	-0.24%	-0.49%	-0.53%	-0.36%
-20 C-	-1.05%	-0.40%	-0.17%	-0.12%	-0.32%	-0.35%	-0.32%	-0.07%

Table 29 Static Temperature Variation, 5119A, #20190716.003

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-20 C+	-1.09%	-0.65%	-0.56%	-0.47%	-0.43%	-0.50%	-0.39%	-0.23%
-10 C+	0.11%	0.12%	0.19%	0.12%	0.18%	0.03%	0.00%	0.14%
0 C+	0.14%	0.40%	0.42%	0.40%	0.40%	0.21%	0.15%	0.20%
10 C+	0.28%	0.15%	0.22%	0.73%	0.26%	0.32%	0.28%	0.23%
20 C+	0.13%	-0.15%	0.20%	0.07%	0.18%	0.22%	0.28%	0.33%
30 C+	0.21%	0.33%	0.31%	0.35%	0.32%	0.18%	0.14%	0.12%
40 C+	-0.57%	-0.29%	-0.17%	-0.18%	-0.24%	-0.34%	-0.36%	-0.39%
50 C+	-2.78%	-2.30%	-1.98%	-1.80%	-1.76%	-1.59%	-1.42%	-1.37%
50 C-	-2.71%	-2.01%	-1.81%	-1.77%	-1.65%	-1.56%	-1.46%	-1.38%
40 C-	-0.84%	-0.64%	-0.51%	-0.62%	-0.62%	-0.65%	-0.58%	-0.62%
30 C-	-0.97%	-0.84%	-0.62%	-0.66%	-0.67%	-0.58%	-0.53%	-0.50%
20 C-	-0.33%	-0.55%	-0.42%	-0.45%	-0.43%	-0.54%	-0.55%	-0.54%
10 C-	-0.53%	-0.41%	-0.38%	-0.47%	-0.54%	-0.73%	-0.79%	-0.72%
0 C-	-0.40%	-0.24%	-0.19%	-0.31%	-0.32%	-0.56%	-0.66%	-0.59%
-10 C-	-0.19%	-0.12%	-0.11%	-0.28%	-0.18%	-0.48%	-0.56%	-0.42%
-20 C-	-0.86%	-0.27%	-0.07%	-0.08%	-0.30%	-0.40%	-0.42%	-0.24%

3.10 Static Pressure Sensitivity 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.

3.10.1 Measurand

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

3.10.2 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.

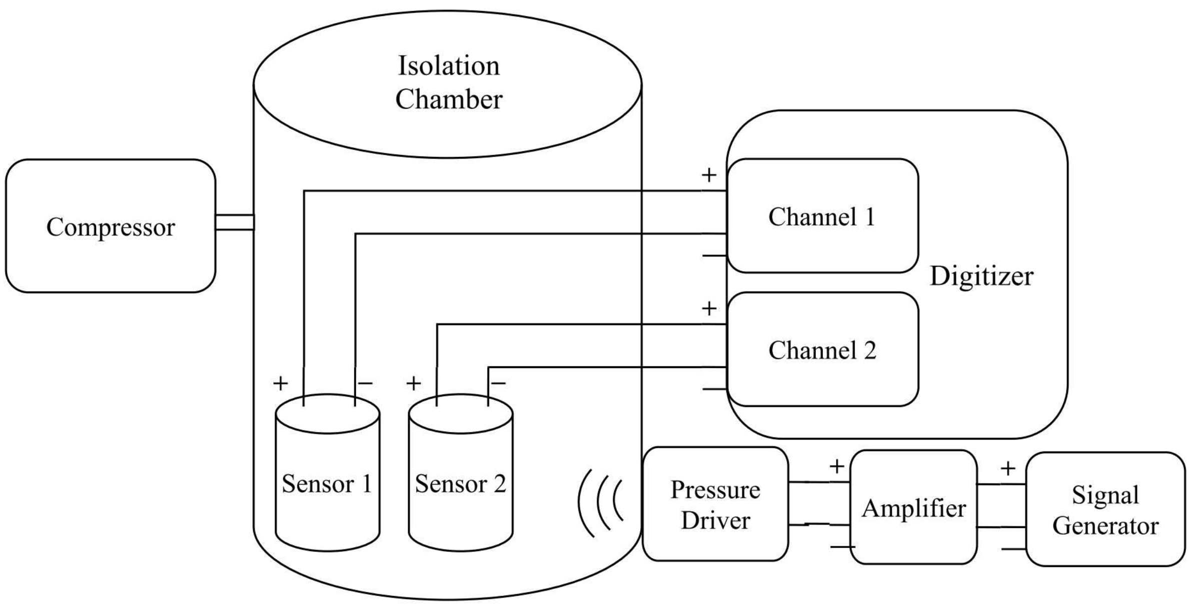


Figure 43 Sensitivity Variation with Static Pressure Configuration Diagram

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.

Figure 44 Sensitivity Variation with Static Pressure Configuration Picture

Table 30 Static Pressure Sensitivity Testbed Equipment

	Manufacturer / Model	Serial Number	Nominal Configuration
Reference Sensor	SNL	Laser speaker #1	0.92881 mV/Pa at 1 Hz, 1000 hPa, 23 C
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	0.25 Hz and 1 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 1000 hPa. In the case of the 5313A sensors, an external solenoid was fitted to the back-volume vent screw and the solenoid was remotely opened to equalize the pressure in the sensor back-volume. In the case of the 5119A sensors, they were powered off, which causes the integrated microvalve to the sensor back-volume to open and the pressure to equalize, and then powered on, which causes the integrated micro-valve to close.

The static pressure was then increased to +50 hPa (1050 hPa), relative to the initial static pressurization, and then decreased in 5 hPa steps to -50 hPa (950 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 5 minutes before the sensitivity of each sensor under test was evaluated against the reference sensor at selected frequencies between 0.1 and 8 Hz. Note that the back-volumes of the sensors under test were not re-vented at each pressurization step.

In this test, the laser measurement of the speaker displacement was used as the reference to measure the induced pressure inside of the chamber. Corrections to the sensitivity of the laser reference were performed to account for the different static pressure level at each step, according to the ideal gas law. The results are reported as a percent change in each sensor's sensitivity relative to the initial sensitivity measured at 1000 hPa.

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.

3.10.3 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.

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:

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

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

The sensor amplitude sensitivity in Volts / Pascal is computed:

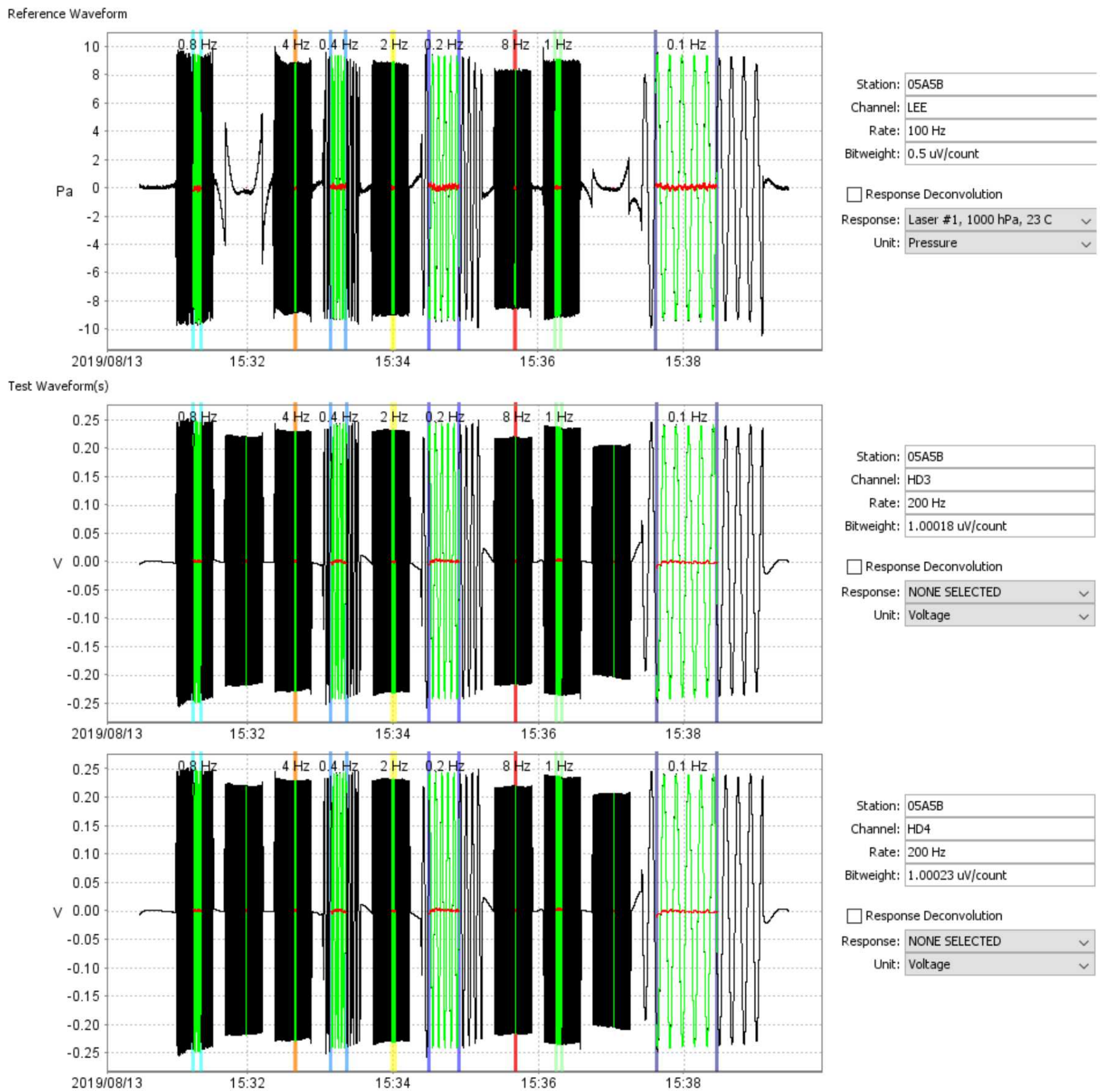
$$Sensitivity = \frac{V_{test}}{P_{ref}}$$

The percent change in sensitivity at each measurement is computed from a baseline sensitivity measurement:

$$Sensitivity\ Change = 100 * \frac{\left(Sensitivity - Sensitivity_{baseline}\right)}{Sensitivity_{baseline}}$$

3.10.4 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.



The plots of the change in sensitivity over +/- 50 hPa at select frequencies are shown below:

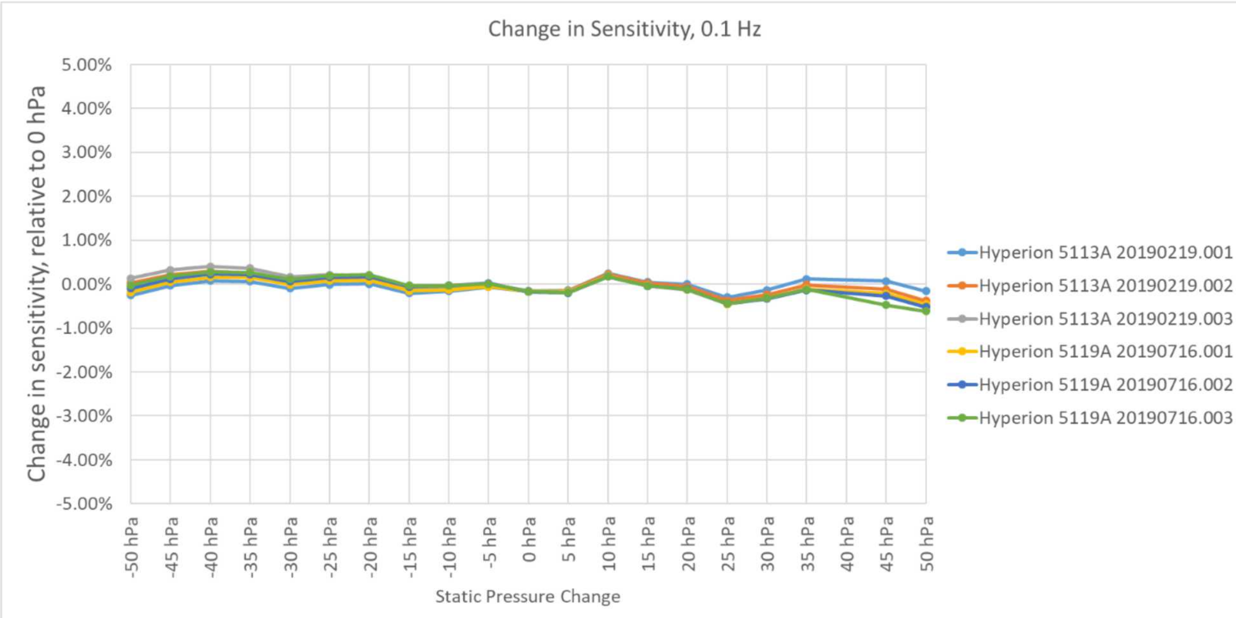


Figure 45 Sensitivity Variation with Static Pressure, 0.1 Hz

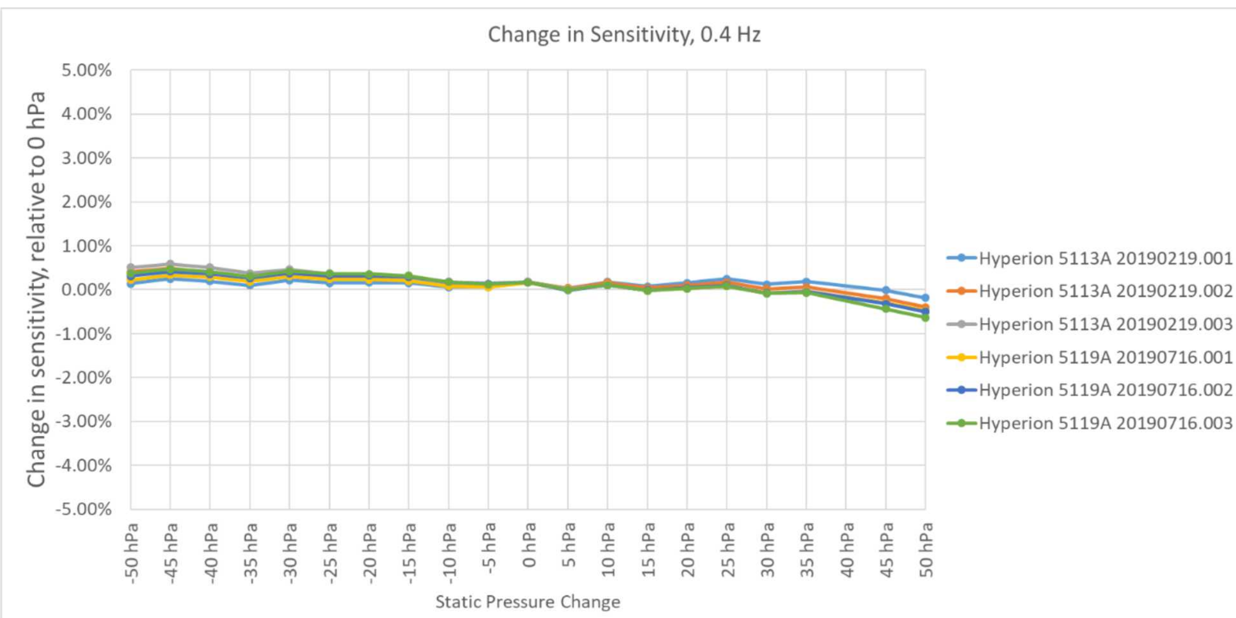


Figure 46 Sensitivity Variation with Static Pressure, 0.4 Hz

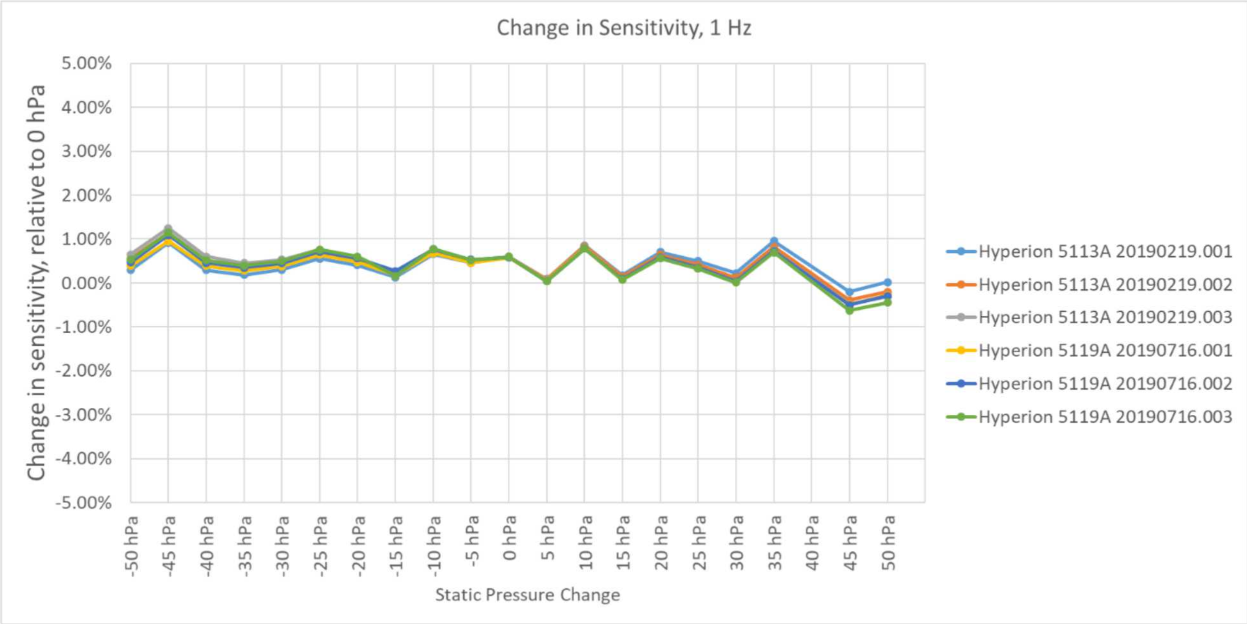


Figure 47 Sensitivity Variation with Static Pressure, 1 Hz

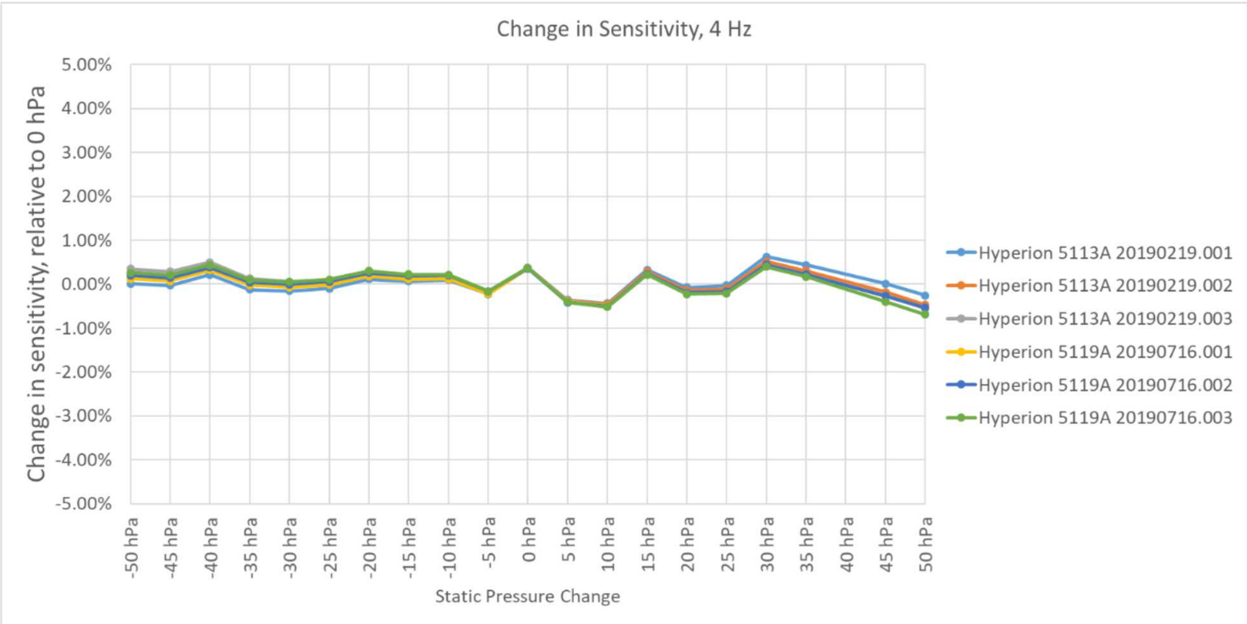


Figure 48 Sensitivity Variation with Static Pressure, 4 Hz

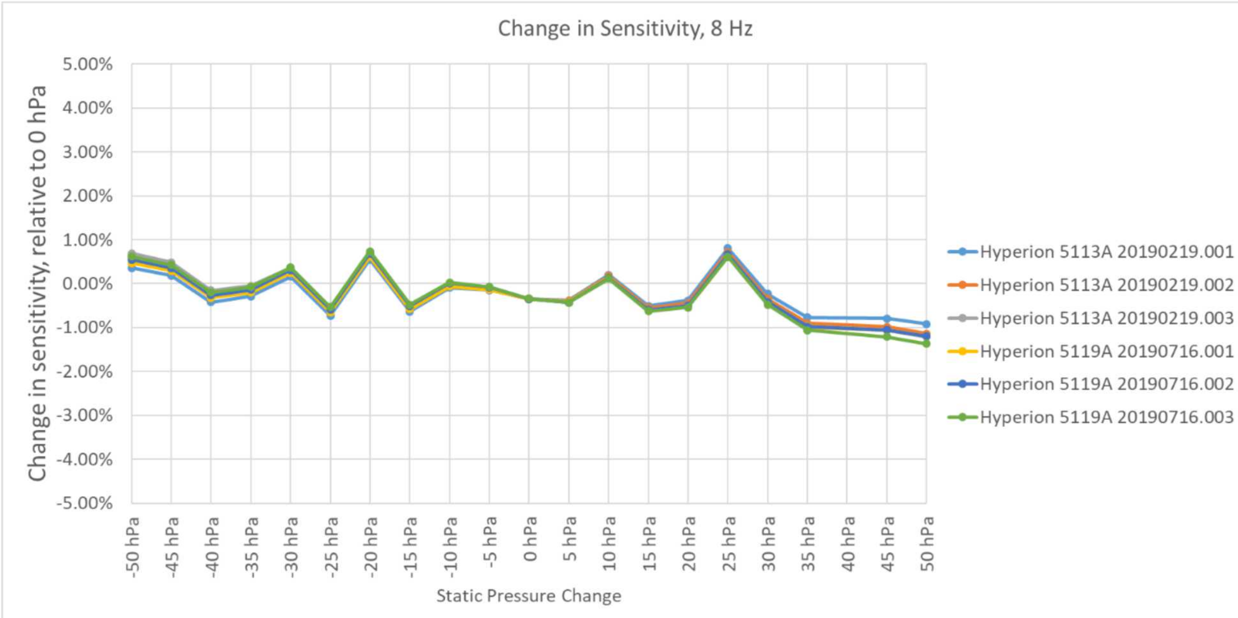


Figure 49 Sensitivity Variation with Static Pressure, 8 Hz

All of the measured variations in sensitivity with respect to static pressure were within approximately +/- 1% across 0.1 to 8 Hz and -50 to 50 hPa at 23 C. It does appear that the variations between individual sensors were largely correlated, which is more pronounced at higher frequencies, representing the underlying uncertainty in the output of the reference laser measurement.

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

Table 31 Static Pressure Variation: 5313A #20190219.001

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-50 hPa	-0.25%	-0.01%	0.14%	-0.17%	0.29%	-0.30%	0.01%	0.36%
-45 hPa	-0.03%	0.21%	0.25%	-0.09%	0.92%	0.32%	-0.03%	0.19%
-40 hPa	0.08%	0.01%	0.19%	0.00%	0.30%	-0.38%	0.22%	-0.42%
-35 hPa	0.06%	0.25%	0.10%	0.06%	0.19%	0.19%	-0.12%	-0.29%
-30 hPa	-0.09%	0.02%	0.21%	-0.45%	0.30%	0.14%	-0.16%	0.16%
-25 hPa	-0.01%	0.18%	0.16%	-0.10%	0.56%	-0.04%	-0.10%	-0.73%
-20 hPa	0.01%	0.13%	0.16%	0.03%	0.41%	-0.14%	0.11%	0.54%
-15 hPa	-0.21%	0.05%	0.15%	0.04%	0.13%	-0.10%	0.06%	-0.63%
-10 hPa	-0.16%	0.05%	0.06%	-0.21%	0.66%	0.30%	0.10%	-0.09%
-5 hPa	-0.06%	0.04%	0.06%	-0.22%	0.46%	-0.05%	-0.22%	-0.14%
0 hPa	-0.16%	0.10%	0.17%	0.05%	0.60%	0.22%	0.37%	-0.34%
5 hPa	-0.15%	0.02%	0.04%	-0.04%	0.09%	-0.19%	-0.36%	-0.38%
10 hPa	0.24%	0.06%	0.17%	0.04%	0.86%	-0.06%	-0.43%	0.20%
15 hPa	0.05%	0.14%	0.08%	-0.11%	0.18%	0.26%	0.32%	-0.51%
20 hPa	0.00%	0.13%	0.15%	0.16%	0.70%	-0.17%	-0.08%	-0.39%
25 hPa	-0.30%	0.12%	0.25%	-0.12%	0.50%	-0.38%	-0.03%	0.81%
30 hPa	-0.13%	0.30%	0.12%	0.11%	0.23%	-0.02%	0.62%	-0.24%
35 hPa	0.11%	0.31%	0.19%	0.05%	0.96%	-0.60%	0.44%	-0.77%
45 hPa	0.07%	-0.03%	-0.01%	0.06%	-0.20%	-0.61%	0.01%	-0.79%
50 hPa	-0.16%	-0.11%	-0.18%	-0.10%	0.02%	-0.10%	-0.26%	-0.92%

Table 32 Static Pressure Variation: 5313A #20190219.002

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-50 hPa	0.03%	0.27%	0.41%	0.10%	0.55%	-0.05%	0.27%	0.61%
-45 hPa	0.21%	0.44%	0.48%	0.14%	1.14%	0.54%	0.19%	0.40%
-40 hPa	0.29%	0.21%	0.40%	0.20%	0.49%	-0.19%	0.41%	-0.24%
-35 hPa	0.25%	0.43%	0.28%	0.24%	0.36%	0.36%	0.05%	-0.13%
-30 hPa	0.07%	0.18%	0.37%	-0.30%	0.45%	0.29%	-0.01%	0.30%
-25 hPa	0.13%	0.32%	0.29%	0.03%	0.68%	0.08%	0.03%	-0.61%
-20 hPa	0.12%	0.24%	0.27%	0.14%	0.51%	-0.04%	0.21%	0.64%
-15 hPa	-0.13%	0.12%	0.22%	0.11%	0.20%	-0.03%	0.13%	-0.57%
-10 hPa	-0.12%	0.09%	0.10%	-0.17%	0.70%	0.34%	0.14%	-0.05%
-5 hPa	-0.04%	0.06%	0.08%	-0.20%	0.47%	-0.03%	-0.21%	-0.13%
0 hPa	-0.16%	0.10%	0.18%	0.05%	0.60%	0.22%	0.37%	-0.34%
5 hPa	-0.15%	0.01%	0.03%	-0.04%	0.08%	-0.20%	-0.37%	-0.39%
10 hPa	0.23%	0.05%	0.16%	0.02%	0.84%	-0.08%	-0.46%	0.17%
15 hPa	0.02%	0.11%	0.04%	-0.14%	0.14%	0.23%	0.28%	-0.55%
20 hPa	-0.05%	0.07%	0.10%	0.10%	0.64%	-0.23%	-0.14%	-0.45%
25 hPa	-0.37%	0.04%	0.17%	-0.20%	0.42%	-0.46%	-0.11%	0.72%
30 hPa	-0.23%	0.19%	0.02%	0.01%	0.12%	-0.13%	0.52%	-0.35%
35 hPa	-0.01%	0.18%	0.06%	-0.08%	0.83%	-0.73%	0.31%	-0.91%
45 hPa	-0.12%	-0.22%	-0.20%	-0.13%	-0.39%	-0.80%	-0.18%	-0.98%
50 hPa	-0.38%	-0.33%	-0.40%	-0.32%	-0.20%	-0.32%	-0.47%	-1.14%

Table 33 Static Pressure Variation: 5313A #20190219.003

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-50 hPa	0.14%	0.37%	0.51%	0.19%	0.65%	0.05%	0.35%	0.69%
-45 hPa	0.32%	0.55%	0.59%	0.24%	1.25%	0.64%	0.28%	0.48%
-40 hPa	0.40%	0.32%	0.50%	0.30%	0.60%	-0.09%	0.50%	-0.16%
-35 hPa	0.36%	0.53%	0.38%	0.33%	0.46%	0.45%	0.13%	-0.06%
-30 hPa	0.17%	0.27%	0.46%	-0.22%	0.53%	0.37%	0.06%	0.36%
-25 hPa	0.21%	0.40%	0.36%	0.10%	0.76%	0.15%	0.09%	-0.56%
-20 hPa	0.19%	0.30%	0.33%	0.20%	0.57%	0.02%	0.26%	0.69%
-15 hPa	-0.07%	0.18%	0.27%	0.16%	0.24%	0.02%	0.17%	-0.53%
-10 hPa	-0.07%	0.13%	0.14%	-0.13%	0.73%	0.38%	0.17%	-0.03%
-5 hPa	-0.01%	0.09%	0.10%	-0.18%	0.50%	-0.01%	-0.19%	-0.11%
0 hPa	-0.15%	0.10%	0.18%	0.05%	0.60%	0.22%	0.37%	-0.34%
5 hPa	-0.17%	-0.01%	0.01%	-0.07%	0.06%	-0.22%	-0.39%	-0.41%
10 hPa	0.19%	0.00%	0.11%	-0.02%	0.80%	-0.12%	-0.49%	0.14%
15 hPa	-0.04%	0.05%	-0.02%	-0.20%	0.08%	0.17%	0.23%	-0.60%
20 hPa	-0.13%	0.00%	0.02%	0.03%	0.57%	-0.29%	-0.20%	-0.51%
25 hPa	-0.45%	-0.04%	0.08%	-0.28%	0.34%	-0.54%	-0.18%	0.66%
30 hPa	-0.32%	0.10%	-0.07%	-0.08%	0.04%	-0.21%	0.44%	-0.41%
35 hPa	-0.11%	0.08%	-0.04%	-0.17%	0.74%	-0.82%	0.22%	-0.98%
45 hPa	-0.22%	-0.32%	-0.30%	-0.23%	-0.49%	-0.89%	-0.26%	-1.05%
50 hPa	-0.48%	-0.43%	-0.50%	-0.42%	-0.30%	-0.41%	-0.56%	-1.21%

Table 34 Static Pressure Variation: 5119A #20190716.001

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-50 hPa	-0.18%	0.07%	0.22%	-0.07%	0.39%	-0.20%	0.12%	0.47%
-45 hPa	0.04%	0.29%	0.34%	0.00%	0.95%	0.42%	0.08%	0.29%
-40 hPa	0.16%	0.09%	0.29%	0.09%	0.39%	-0.29%	0.32%	-0.32%
-35 hPa	0.15%	0.33%	0.19%	0.15%	0.27%	0.28%	-0.02%	-0.20%
-30 hPa	-0.01%	0.11%	0.30%	-0.36%	0.38%	0.23%	-0.07%	0.25%
-25 hPa	0.08%	0.27%	0.24%	-0.02%	0.64%	0.04%	-0.01%	-0.65%
-20 hPa	0.09%	0.20%	0.23%	0.11%	0.48%	-0.07%	0.18%	0.62%
-15 hPa	-0.15%	0.10%	0.20%	0.09%	0.18%	-0.05%	0.12%	-0.58%
-10 hPa	-0.13%	0.07%	0.08%	-0.19%	0.68%	0.33%	0.13%	-0.06%
-5 hPa	-0.06%	0.04%	0.06%	-0.22%	0.46%	-0.05%	-0.22%	-0.14%
0 hPa	-0.17%	0.08%	0.16%	0.03%	0.58%	0.21%	0.36%	-0.35%
5 hPa	-0.17%	-0.02%	0.00%	-0.08%	0.05%	-0.23%	-0.40%	-0.42%
10 hPa	0.19%	0.00%	0.11%	-0.03%	0.79%	-0.12%	-0.50%	0.14%
15 hPa	-0.03%	0.05%	-0.02%	-0.20%	0.08%	0.17%	0.23%	-0.60%
20 hPa	-0.12%	0.00%	0.02%	0.03%	0.57%	-0.29%	-0.20%	-0.51%
25 hPa	-0.45%	-0.04%	0.08%	-0.28%	0.33%	-0.54%	-0.18%	0.65%
30 hPa	-0.32%	0.10%	-0.08%	-0.09%	0.03%	-0.22%	0.43%	-0.42%
35 hPa	-0.11%	0.07%	-0.05%	-0.18%	0.72%	-0.83%	0.21%	-0.99%
45 hPa	-0.22%	-0.32%	-0.30%	-0.23%	-0.49%	-0.90%	-0.26%	-1.06%
50 hPa	-0.46%	-0.40%	-0.47%	-0.39%	-0.28%	-0.39%	-0.53%	-1.19%

Table 35 Static Pressure Variation: 5119A #20190716.002

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-50 hPa	-0.09%	0.16%	0.31%	0.01%	0.47%	-0.12%	0.20%	0.55%
-45 hPa	0.12%	0.36%	0.41%	0.08%	1.09%	0.49%	0.15%	0.36%
-40 hPa	0.23%	0.16%	0.36%	0.17%	0.46%	-0.21%	0.38%	-0.26%
-35 hPa	0.22%	0.40%	0.26%	0.22%	0.35%	0.35%	0.04%	-0.14%
-30 hPa	0.06%	0.18%	0.37%	-0.29%	0.45%	0.30%	0.00%	0.31%
-25 hPa	0.15%	0.35%	0.32%	0.06%	0.71%	0.12%	0.06%	-0.58%
-20 hPa	0.17%	0.29%	0.32%	0.19%	0.56%	0.01%	0.26%	0.69%
-15 hPa	-0.05%	0.20%	0.30%	0.19%	0.27%	0.04%	0.20%	-0.51%
-10 hPa	-0.03%	0.17%	0.18%	-0.10%	0.77%	0.41%	0.20%	0.01%
-5 hPa	0.02%	0.12%	0.13%	-0.15%	0.53%	0.02%	-0.16%	-0.09%
0 hPa	-0.17%	0.09%	0.17%	0.04%	0.59%	0.21%	0.36%	-0.35%
5 hPa	-0.20%	-0.04%	-0.01%	-0.09%	0.04%	-0.25%	-0.41%	-0.43%
10 hPa	0.17%	-0.01%	0.10%	-0.04%	0.78%	-0.13%	-0.51%	0.13%
15 hPa	-0.04%	0.05%	-0.01%	-0.20%	0.09%	0.17%	0.23%	-0.60%
20 hPa	-0.11%	0.02%	0.04%	0.04%	0.58%	-0.28%	-0.19%	-0.50%
25 hPa	-0.44%	-0.03%	0.10%	-0.27%	0.35%	-0.53%	-0.17%	0.66%
30 hPa	-0.33%	0.10%	-0.07%	-0.08%	0.04%	-0.21%	0.44%	-0.41%
35 hPa	-0.13%	0.06%	-0.05%	-0.18%	0.73%	-0.82%	0.22%	-0.98%
45 hPa	-0.27%	-0.36%	-0.32%	-0.25%	-0.51%	-0.90%	-0.26%	-1.06%
50 hPa	-0.52%	-0.44%	-0.50%	-0.40%	-0.30%	-0.40%	-0.53%	-1.19%

Table 36 Static Pressure Variation: 5119A #20190716.003

	0.1 Hz	0.2 Hz	0.4 Hz	0.8 Hz	1.0 Hz	2.0 Hz	4.0 Hz	8.0 Hz
-50 hPa	-0.03%	0.22%	0.37%	0.08%	0.53%	-0.06%	0.26%	0.62%
-45 hPa	0.18%	0.42%	0.47%	0.14%	1.14%	0.55%	0.21%	0.43%
-40 hPa	0.28%	0.21%	0.41%	0.22%	0.51%	-0.16%	0.44%	-0.20%
-35 hPa	0.26%	0.45%	0.31%	0.27%	0.39%	0.40%	0.09%	-0.08%
-30 hPa	0.11%	0.23%	0.42%	-0.24%	0.50%	0.35%	0.05%	0.37%
-25 hPa	0.20%	0.39%	0.36%	0.11%	0.76%	0.16%	0.11%	-0.53%
-20 hPa	0.21%	0.33%	0.36%	0.23%	0.60%	0.06%	0.30%	0.73%
-15 hPa	-0.03%	0.22%	0.32%	0.21%	0.16%	0.07%	0.22%	-0.48%
-10 hPa	-0.03%	0.17%	0.18%	-0.09%	0.78%	0.42%	0.22%	0.02%
-5 hPa	0.01%	0.11%	0.12%	-0.15%	0.52%	0.02%	-0.16%	-0.08%
0 hPa	-0.17%	0.09%	0.17%	0.05%	0.59%	0.22%	0.37%	-0.34%
5 hPa	-0.19%	-0.02%	0.00%	-0.08%	0.05%	-0.24%	-0.41%	-0.43%
10 hPa	0.17%	-0.01%	0.10%	-0.04%	0.78%	-0.13%	-0.51%	0.11%
15 hPa	-0.04%	0.05%	-0.02%	-0.21%	0.07%	0.16%	0.21%	-0.63%
20 hPa	-0.12%	0.01%	0.03%	0.02%	0.57%	-0.31%	-0.22%	-0.54%
25 hPa	-0.45%	-0.04%	0.08%	-0.29%	0.32%	-0.56%	-0.21%	0.61%
30 hPa	-0.32%	0.10%	-0.09%	-0.10%	0.01%	-0.25%	0.39%	-0.48%
35 hPa	-0.12%	0.06%	-0.07%	-0.21%	0.69%	-0.86%	0.17%	-1.06%
45 hPa	-0.48%	-0.46%	-0.44%	-0.36%	-0.63%	-1.03%	-0.40%	-1.21%
50 hPa	-0.62%	-0.56%	-0.63%	-0.54%	-0.45%	-0.55%	-0.69%	-1.36%

3.11 Response to Vertical Acceleration

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

3.11.1 Measurand

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

3.11.2 Configuration

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

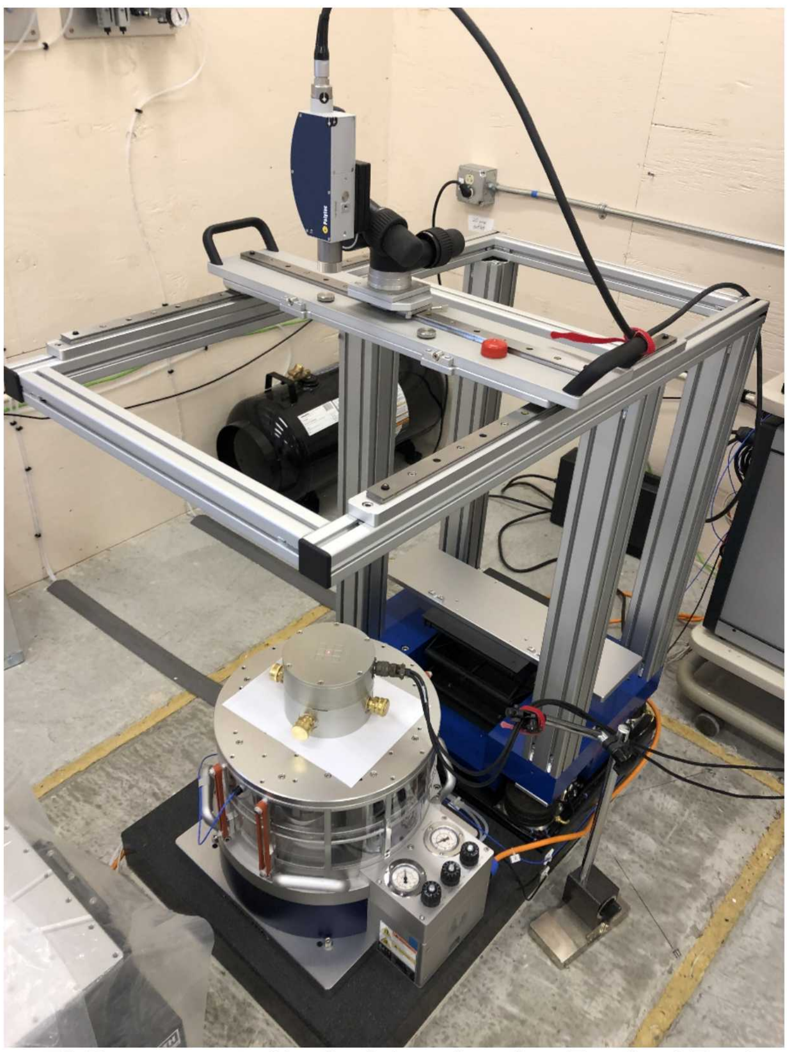


Figure 50 Response to Vertical Acceleration Testbed Equipment

Table 37 Response to Vertical Acceleration Testbed Equipment

	Manufacturer / Model	Serial #
Calibration System	Spektra SE-13	#6

The Spektra SE-13 Seismic Calibration system provides integrated control, data acquisition, and analysis systems in order 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 pressure and improve the signal to noise ratio.

3.11.3 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:

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

3.11.4 Result

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

Table 38 Response to Vertical Acceleration: Hyperion 5313A

Frequency	Hyperion 5313A 20190219.001		Hyperion 5313A 20190219.002		Hyperion 5313A 20190219.003		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
0.50 Hz	1.991	-176.67	2.315	-175.95	4.673	-178.94	3%	2 deg
0.63 Hz	1.968	-178.21	2.334	-177.75	4.701	-179.43	3%	2 deg
0.79 Hz	1.952	-179.01	2.317	-178.40	4.700	179.86	3%	2 deg
1.00 Hz	1.938	-179.56	2.316	-178.78	4.686	179.88	3%	2 deg
1.26 Hz	1.923	179.76	2.305	-178.92	4.676	179.65	3%	2 deg
1.59 Hz	1.921	179.60	2.302	-179.37	4.666	179.50	3%	2 deg
2.00 Hz	1.910	179.54	2.304	-179.54	4.658	179.38	3%	2 deg
2.51 Hz	1.904	179.33	2.288	-179.66	4.641	179.29	3%	2 deg
3.16 Hz	1.894	179.13	2.290	179.90	4.627	179.28	2%	1.5 deg
3.98 Hz	1.884	178.75	2.272	179.74	4.608	179.23	2%	1.5 deg
5.01 Hz	1.884	178.40	2.294	179.46	4.583	179.13	2%	1.5 deg
6.31 Hz	1.874	178.54	2.279	179.52	4.575	178.94	2%	1.5 deg
7.94 Hz	1.859	178.47	2.301	179.35	4.565	178.99	2%	1.5 deg
10.00 Hz	1.864	178.37	2.280	179.39	4.529	179.11	1%	1 deg

Table 39 Response to Vertical Acceleration: Hyperion 5119A

Frequency	Hyperion 5119A 20190716.001		Hyperion 5119A 20190716.002		Hyperion 5119A 20190716.003		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
0.50 Hz	1.036	-164.22	0.273	118.90*	0.658	-155.87	3%	2 deg
0.63 Hz	0.968	-165.69	0.546	10.20	0.604	-162.62	3%	2 deg
0.79 Hz	0.924	-170.89	0.791	14.97	0.538	-165.88	3%	2 deg
1.00 Hz	0.888	-173.23	0.951	16.42	0.513	-169.90	3%	2 deg
1.26 Hz	0.870	-174.25	1.060	16.07	0.476	-170.91	3%	2 deg
1.59 Hz	0.862	-174.79	1.142	16.08	0.466	-170.43	3%	2 deg
2.00 Hz	0.860	-174.90	1.220	15.86	0.465	-170.08	3%	2 deg
2.51 Hz	0.863	-174.99	1.282	15.93	0.462	-169.32	3%	2 deg
3.16 Hz	0.868	-174.93	1.343	15.77	0.462	-168.06	2%	1.5 deg
3.98 Hz	0.877	-174.64	1.398	15.57	0.472	-166.89	2%	1.5 deg
5.01 Hz	0.889	-174.82	1.456	15.33	0.485	-165.10	2%	1.5 deg
6.31 Hz	0.901	-174.68	1.521	15.25	0.501	-163.08	2%	1.5 deg
7.94 Hz	0.914	-174.64	1.588	15.07	0.525	-161.05	2%	1.5 deg
10.00 Hz	0.931	-174.59	1.653	14.82	0.556	-158.98	1%	1 deg

* This reading at 0.5 Hz had very poor signal quality, indicating a poor fit for sine approximation.

The Hyperion design cancels out the effects of vertical acceleration from its pressure output by summing the output of pressure transducers that are in opposite vertical orientations from one another. So, the residual vertical acceleration, in both amplitude and phase, depends on how well matched the individual pressure transducers are. Generally, the phase is expected to be either in-phase (0 degrees) or out-of-phase (+/- 180 degrees), depending on which pressure transducer has the largest contribution.

The measured frequency response was flat with sensitivities ranging from 0.513 to 4.686 mV/(m/s^2) at 1 Hz. This low level of sensitivity to vertical acceleration is consistent with manufacturer's specification and the sensor design having the capability to differentially cancel the effects of vertical acceleration.

4 SUMMARY

Power Consumption
The Hyperion sensors consumed between 31.6 and 33.5 mW for the 5313A model and between 232 and 256 mW for the 5119A model, consistent with the manufacturer's specifications.

Sensitivity
The Hyperion sensors were found to have sensitivity values that were consistent with the manufacturer's datasheets at 0.25 Hz and 1 Hz to within 2% and 0.5% for the 5313A and 5119A models, respectively. The phase was consistent with the response model for all the sensors to within 0.5 degrees at 0.25 Hz and within 0.25 degrees at 1 Hz.

Sensitivity vs Input Amplitude
The sensitivities of all the Hyperion sensors did not change significantly with respect to an increased dynamic input pressure level ranging from 2 Pa to 17 Pa.

Full Scale
All the Hyperion sensors had a full-scale exceeding the manufacturer's specification of +/- 100 Pa.

Self-Noise
The self-noise levels of the Hyperion sensors were at or below the spectral noise model provided by Hyperion. Their self-noise was consistently below the Bowman Low-Noise-Model by more than 15 dB across 0.02 Hz to 4 Hz and below the IMS requirement at 1 Hz by 25 dB to 30 dB.

Dynamic Range
The measured dynamic ranges were between 109.28 dB and 115.42 dB across 0.02 Hz to 4 Hz, exceeding the IMS minimum requirement of 108 dB.

Frequency Response
The Hyperion sensors all demonstrated a frequency response that matched their nominal model.

Passband
The Hyperion sensors all had a measured passband from between 0.0159 Hz and 0.0163 Hz on the low end and exceeding the upper evaluation range of 10 Hz on the high end, covering the IMS passband of 0.02 Hz to 4 Hz.

Static Temperature Sensitivity Variation
The Hyperion sensor sensitivity was observed to vary by less than 2% across the range of -20 C to 40 C temperatures. Sensitivity changed by as much as 3% at temperatures of 50 C at 0.1 Hz.

Static Pressure Sensitivity Variation
The Hyperion sensor sensitivity was observed to vary by less than 1% across the range of -50 to 50 hPa static pressure level changes.

Response to Vertical Acceleration

The measured response to vertical acceleration on all six Hyperion sensors was flat across 0.5 to 10 Hz with sensitivities ranging from 0.513 to 4.686 mV/(m/s^2). These values are low, consistent with the Hyperion 5000 series design to cancel out vertical acceleration.

REFERENCES

1. Hart, Darren M, Rod Whitaker and Harold Parks, 2012, Validating Infrasound sensor Performance: Requirements, Specifications, and Calibration, The Journal of the Acoustical Society of America, 09/2012; 132(3):2048. DOI:10.1121/1.4755531. 164th meeting of the Acoustical Society of America.

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

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

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

5. Kromer, Richard P., Hart, Darren M. and J. Mark Harris (2007), *Test Definition for the Evaluation of Infrasound Sensors Version 1.0*, SAND2007-5038.

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

7. Sleeman, R., Wettum, A., Trampert, J. (2006), *Three-Channel Correlation Analysis: A New Technique to Measure Instrumental Noise of Digitizers and Seismic Sensors*, Bulletin of the Seismological Society of America, Vol. 96, No. 1, pp. 258-271, February 2006.

APPENDEX A: TEST REFERENCES

Guralp Affinity #405A5B Bit weights

The Guralp Affinity #405A5B used for data collected was calibrated against a reference meter Agilent 3458A #MY45048372 just prior to use in the data collection for this test. The digitizer bit weights were calculated use a stable positive and negative DC Source, simultaneously recorded on both the digitizer and Agilent meter.   The bit weights used in this test were determined to be:

Table 40 Guralp Affinity #405A5B Channel bit weights

Digitizer Channel	Bitweights
Channel 1	1.00017 uV/count
Channel 2	1.00019 uV/count
Channel 3	1.00018 uV/count
Channel 4	1.00023 uV/count
Channel 5	1.00025 uV/count
Channel 6	1.00024 uV/count
Channel 7	1.0002 uV/count
Channel 8	1.00025 uV/count

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

B&K 4193 #2812287 Response

The response model for the reference B&K 4193, #2812287 was determined by direct comparison with SNL's calibrated Setra 278 # 6837528 and MB2005 # NV7009 just prior to the testing of the sensors in this report.

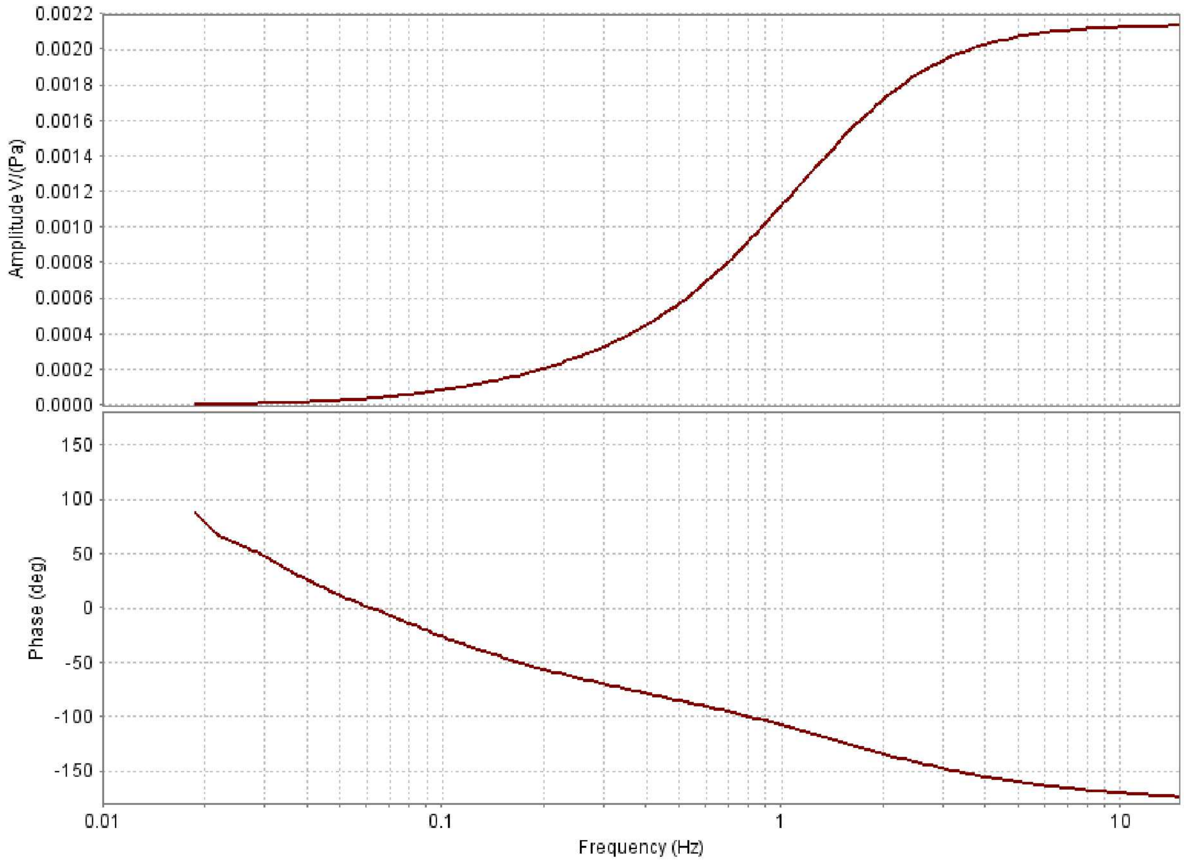


Figure 51 B&K 4193 #2812287 Response

The sensitivity of the B&K 4193 was determined to be 2.117 mV/Pa at conditions of 23 C and 830 hPa.

Setra 278 #6937528 Calibration

The Setra 278 #6937528 pressure sensor was used to transfer calibrations from SNL's PSL to the B&K 4193 #2812287 and SNL's Laser pistonphone by direct comparison prior to the evaluation. The SNL PSL's calibration certificate for the Setra 278 sensor is shown below.

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

CALIBRATION
NVLAP LAB CODE 105002-0

Calibration Certificate
Document #: 6676085_11766071

Item Identification

Asset Number	6676085
Description	Transducer,Pressure,Diaphragm
Model	278
Serial #	6937528
Manufacturer	Setra Systems Inc
Customer Asset Id	
Purchase Order	N/A
Customer	Ground-Based Monitoring R&E 06752
Custodian	Slad, George William
Location	SNLNM/TA1/823/2444
Date of Receipt	May 28, 2019
Dates Tested (Start – End)	June 27, 2019 - June 27, 2019
Date Approved	July 10, 2019
Calibration Expiration Date	July 10, 2020

Calibration Description

Calibration Lab	PSL-PRESSURE
Calibration Procedure, rev.	PSL-PVL-CP-6210-001-V01, 10K Bench, High Pressure Calibration System
Temperature	23 ± 3 deg C
Humidity	40 ± 10 %RH
Barometric Pressure	NA mmHg
As Found Condition	PASS
As Left Condition	PASS-ADJ
Software Used	COMPASS 5.0.25
Tamper Seal	None

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6676085_11766071

PRIMARY STANDARDS
LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

CALIBRATION
NVLAP LAB CODE 105002-0

Calibration Results: As Found

DUT Full Scale Pressure (mbar)	1100	Pressure Coefficients	
DUT Full Scale Output (V)	5.0051	a	b
Previous Tolerance (%FS)	0.60	**499.716**	**119.929**

To calculate pressure, P (mbar), in terms of the DUT output, X (V), us the following equation:
P = 499.72669 + 119.91766 * X

Pressure Measurement Mode: Absolute					
Reference Pressure "P"	DUT Raw	DUT Corrected using previous fit	Error	Previous Tolerance ±	Status
mbar	V	mbar	% Full Scale	% Full Scale	Pass/Fail
505.0	0.0410	504.6	-0.03	0.60	Pass
600.0	0.8371	600.1	0.01	0.60	Pass
700.0	1.6716	700.2	0.02	0.60	Pass
750.0	2.0884	750.2	0.02	0.60	Pass
800.0	2.5049	800.1	0.01	0.60	Pass
840.0	2.8380	840.1	0.01	0.60	Pass
900.0	3.3377	900.0	0.00	0.60	Pass
950.0	3.7542	949.9	0.00	0.60	Pass
1000.0	4.1710	999.9	-0.01	0.60	Pass
1100.0	5.0051	1100.0	0.00	0.60	Pass
1100.0	5.0051	1100.0	0.00	0.60	Pass
1000.0	4.1710	999.9	-0.01	0.60	Pass
950.0	3.7542	950.0	0.00	0.60	Pass
900.0	3.3377	900.0	0.00	0.60	Pass
840.0	2.8381	840.1	0.01	0.60	Pass
800.0	2.5050	800.1	0.01	0.60	Pass
750.0	2.0885	750.2	0.02	0.60	Pass
700.0	1.6717	700.2	0.02	0.60	Pass
600.0	0.8371	600.1	0.01	0.60	Pass
505.0	0.0411	504.6	-0.03	0.60	Pass

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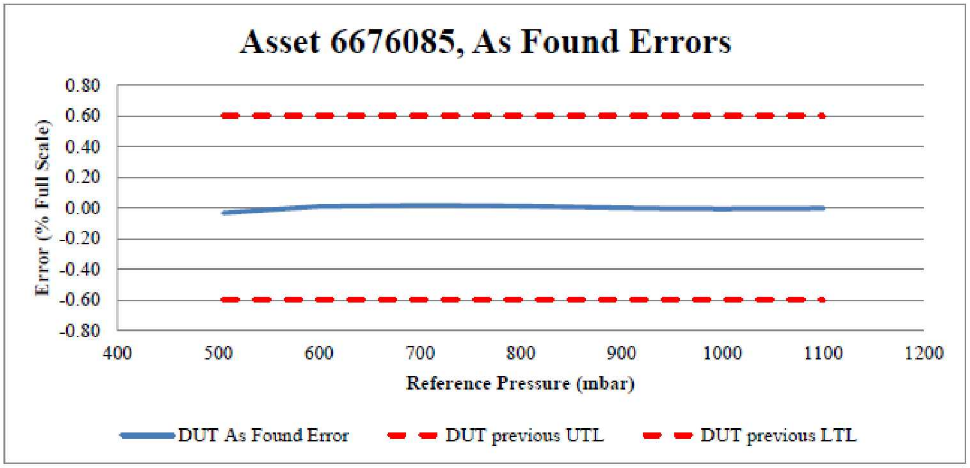
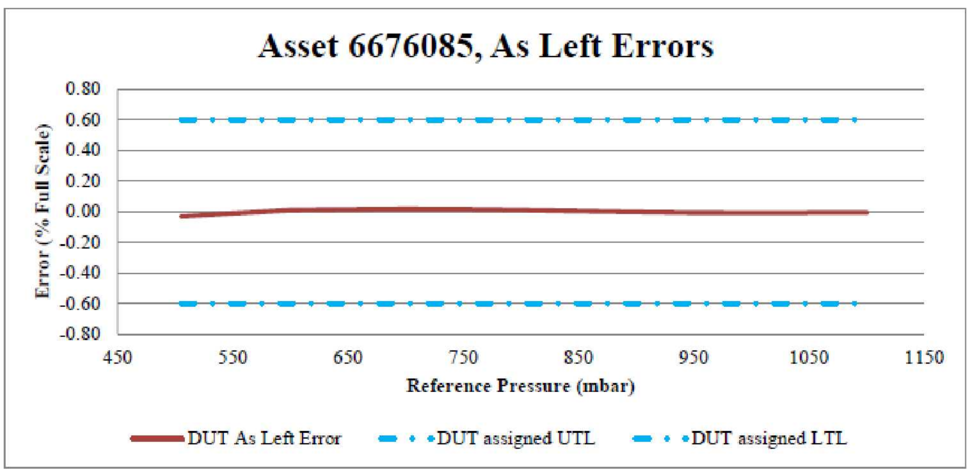
CALIBRATION
NVLAP LAB CODE 105002-0





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LABORATORY
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CALIBRATION
NVLAP LAB CODE 105002-0

As Left

DUT Full Scale Pressure (mbar)	1100	Pressure Coefficients	
DUT Full Scale Output (V)	5.0051	a	b
Assigned Tolerance (%FS)	0.60	**499.727**	**119.918**

To calculate pressure, P (mbar), in terms of the DUT output, X (V), us the following equation:
P = 499.727 + 119.918 * X

Pressure Measurement Mode: Absolute					
Reference Pressure "P"	DUT Raw	DUT Corrected using new fit	Error	Assigned Tolerance ±	Status
mbar	V	mbar	% Full Scale	% Full Scale	Pass/Fail
505.0	0.0410	504.6	-0.03	0.60	Pass
600.0	0.8371	600.1	0.01	0.60	Pass
700.0	1.6716	700.2	0.02	0.60	Pass
750.0	2.0884	750.2	0.01	0.60	Pass
800.0	2.5049	800.1	0.01	0.60	Pass
840.0	2.8380	840.1	0.00	0.60	Pass
900.0	3.3377	900.0	0.00	0.60	Pass
950.0	3.7542	949.9	-0.01	0.60	Pass
1000.0	4.1710	999.9	-0.01	0.60	Pass
1100.0	5.0051	1099.9	-0.01	0.60	Pass
1100.0	5.0051	1099.9	-0.01	0.60	Pass
1000.0	4.1710	999.9	-0.01	0.60	Pass
950.0	3.7542	949.9	-0.01	0.60	Pass
900.0	3.3377	900.0	0.00	0.60	Pass
840.0	2.8381	840.1	0.01	0.60	Pass
800.0	2.5050	800.1	0.01	0.60	Pass
750.0	2.0885	750.2	0.02	0.60	Pass
700.0	1.6717	700.2	0.02	0.60	Pass
600.0	0.8371	600.1	0.01	0.60	Pass
505.0	0.0411	504.7	-0.03	0.60	Pass

PRIMARY STANDARDS
LABORATORY

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CALIBRATION
NVLAP LAB CODE 105002-0

Calibration Method

This device was tested using a comparison technique. The standard used to determine the reference pressure was a Quartz-Reference Pressure Transducer (Q-RPT) Pressure Controller/Calibrator. This transfer standard was calibrated by Sandia National Laboratories Primary Standards Lab with Deadweight Piston Gauges using a coverage factor of k=2.

Calibration Note

This device was found to meet the requested tolerance of ± 0.6% of full scale from 500 mbar to 1100 mbar, with a Test Uncertainty Ratio (TUR) of > 4:1. This device is expected to remain within the stated measurement tolerance through the calibration interval.

Equipment (Standard) Used

Asset #	Description	Model #	Expires
6651361	System,Data,Acquisition	34970A	May 16, 2020
6654883	Supply,Power,DC	6633B	August 24, 2019
6652763	Calibrator,Pressure	PPC4 A700K/A100K	July 20, 2019

PRIMARY STANDARDS LABORATORY

Sandia National Laboratories, Albuquerque, New Mexico 87185-0665

CALIBRATION
NVLAP LAB CODE 105002-0

Traceability

Values and the associated uncertainties reported are traceable to the SI through one of more of the following:

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

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NOTE 3: The results reported above relate only to the items tested or calibrated.

NOTE 4: The Decision Rule for the As-Found condition is Simple Acceptance, where the measured value is within the previous certification limits.

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Authorization

Calibrated By:

Kothmann, Diana
Metrologist

Approved By:

Vanderburg, Timothy A.
QA Representative

End-of-Document

Hyperion 5000 Response

The nominal response models for the Hyperion 5313A and 5119A sensors were provided by the manufacturer at the time of evaluation.

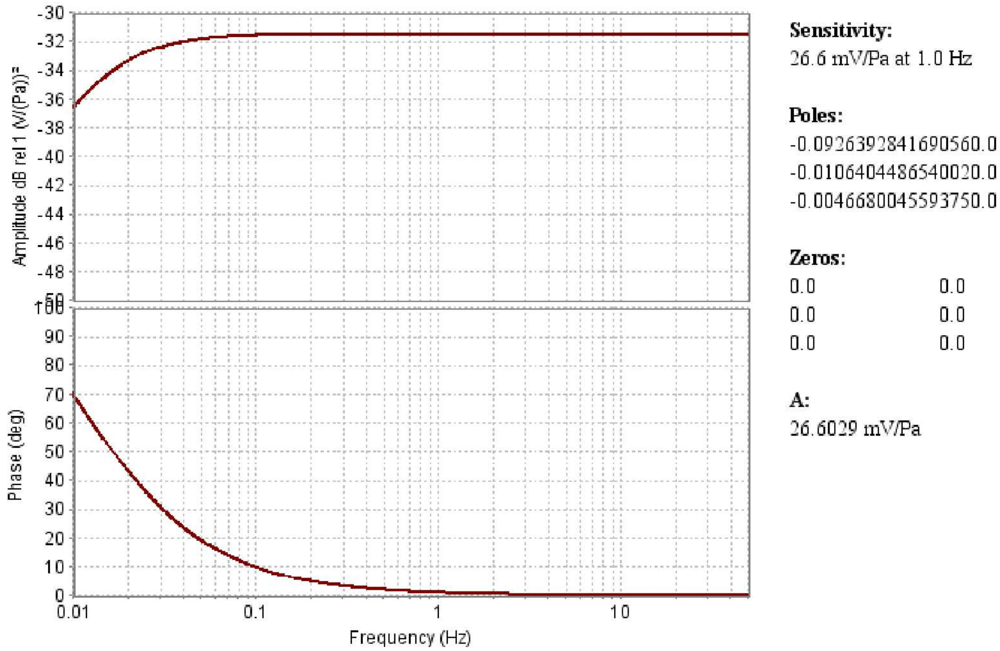

Figure 52 Hyperion 5313A, 26.6 mV/Pa Nominal Response

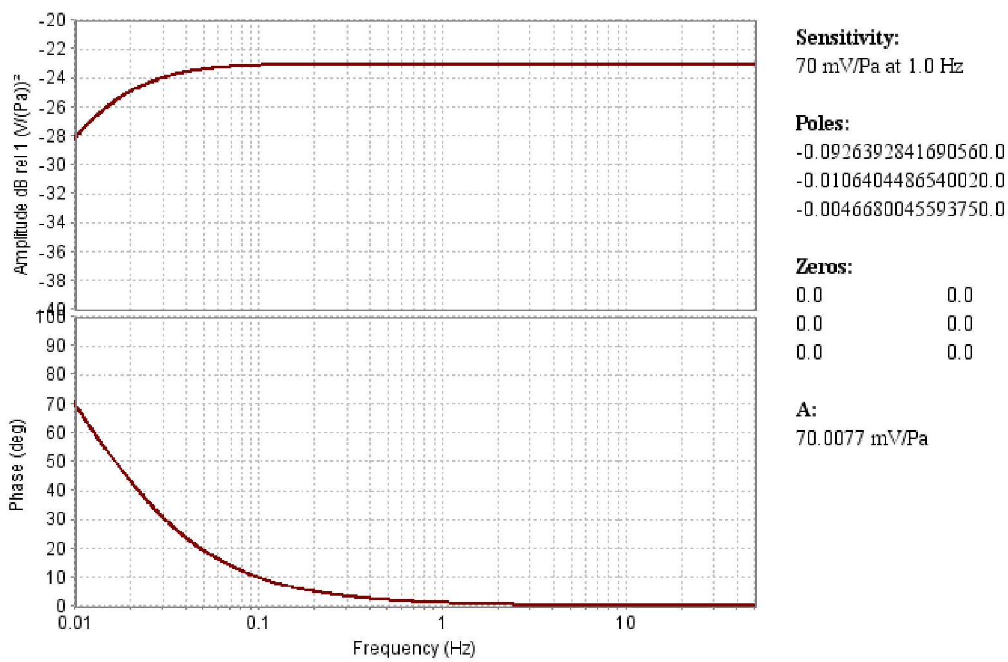

Figure 53 Hyperion 5119A, 70 mV/Pa Nominal Response

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