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USGS VDP Infrasound Sensor Evaluation

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USGS VDP100 and VDP250 Infrasound Sensor Evaluations

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Abstract

Sandia National Laboratories has tested and evaluated two infrasound sensors, the model VDP100 and VDP250, built in-house at the USGS Cascades Volcano Observatory. The purpose of the infrasound sensor evaluation was to determine a measured sensitivity, self-noise, dynamic range and nominal transfer function. Notable features of the VDP sensors include novel and durable construction and compact size.

ACKNOWLEDGMENTS

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NOMENCLATURE

AVO	Alaska Volcano Observatory
dB	decibel
DOE	Department of Energy
FACT	Facility for the Acceptance, Calibration and Testing
IEEE	Institute of Electrical and Electronics Engineers
LANL	Los Alamos National Laboratory
LNM	Low Noise Model
PSD	Power Spectral Density
SNL	Sandia National Laboratories
USGS	United States Geological Survey

1 INTRODUCTION

Figure 1. USGS VDP100 model Infrasound Sensor

Sandia National Laboratories has tested and evaluated two infrasound sensors, the VDP100 and VDP250 sensor, built in-house at the USGS Cascades Volcano Observatory. Notable features of the VDP sensors include novel and durable construction and compact size, as the sensor is housed in a simple PVC pipe and cap housing.

2 TESTING OVERVIEW

2.1 Objectives

The objective of this work was to evaluate the overall technical performance of the VDP100 and VDP250 model infrasound sensors. Basic infrasound sensor characterization includes determining sensitivity, linearity to pressure input, self-noise, dynamic noise and nominal transfer function. The results of this evaluation were compared to relevant application requirements or specifications of the infrasound sensor provided by the manufacturer.

2.2 Test and Evaluation Background

Sandia National Laboratories (SNL), Ground-based Monitoring R&E Department has the long-standing capability of evaluating the performance of infrasound sensors for geophysical applications.

2.3 Standardization and Traceability

Most tests are based on the Institute of Electrical and Electronics Engineers (IEEE) Standard 1057 [Reference 1] for Digitizing Waveform Recorders and Standard 1241 for Analog to Digital Converters [Reference 2]. 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).

Prior to testing, the bit weights of the digitizers used in the tests were established by recording a known reference signal on each of the digitizer channels. The reference signal was simultaneously recorded on an Agilent 3458A high precision meter with a current calibration from Sandia's Primary Standards Laboratory in order to verify the amplitude of the reference signal. Thus, the digitizer bit weights are traceable to NIST.

The Vaisala PTU300 temperature and pressure sensor has a current calibration from Sandia's Primary Standards Laboratory in order to provide traceability in the measurements of ambient temperature and pressure.

The MB2005 infrasound sensor serves as a reference for this evaluation. The MB2005 had been evaluated in Los Alamos National Laboratories' calibrated reference chamber to determine its sensitivity.

2.4 Test and Evaluation Process

2.4.1 Infrasound Sensor Testing

Testing of the VDP sensors was performed on February 9 – February 16, 2016 at the Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) site, Albuquerque, NM.

2.4.2 General Infrasound Sensor Performance Tests

The tests that were conducted on the sensors were based on infrasound tests described in the test plan: *Test Definition and Test Procedures for the Evaluation of Infrasound Sensors*. For a thorough description of each test performed with details of test configuration layout, analysis description and methodology, and result definition, see Merchant 2011.

The tests selected provide a high level of characterization for an infrasound sensor.

Static Performance Tests

- Infrasound Sensor Isolation Noise (IS-IN)

Tonal Dynamic Performance Tests

- Infrasound Sensor Frequency/Amplitude Response Verification (IS-FAR)
- Infrasound Linearity Verification (IS-LV)

BroadBand Dynamic Performance Tests

- Infrasound Frequency Amplitude Phase Verification (IS-FAPV)
- Infrasound 2 Sensor Noise (IS-2SN)
- Infrasound 3 Sensor Noise (IS-3SN)

2.5 Test Configuration and System Specifications

The test configuration was setup consistent with the diagram and descriptions below.

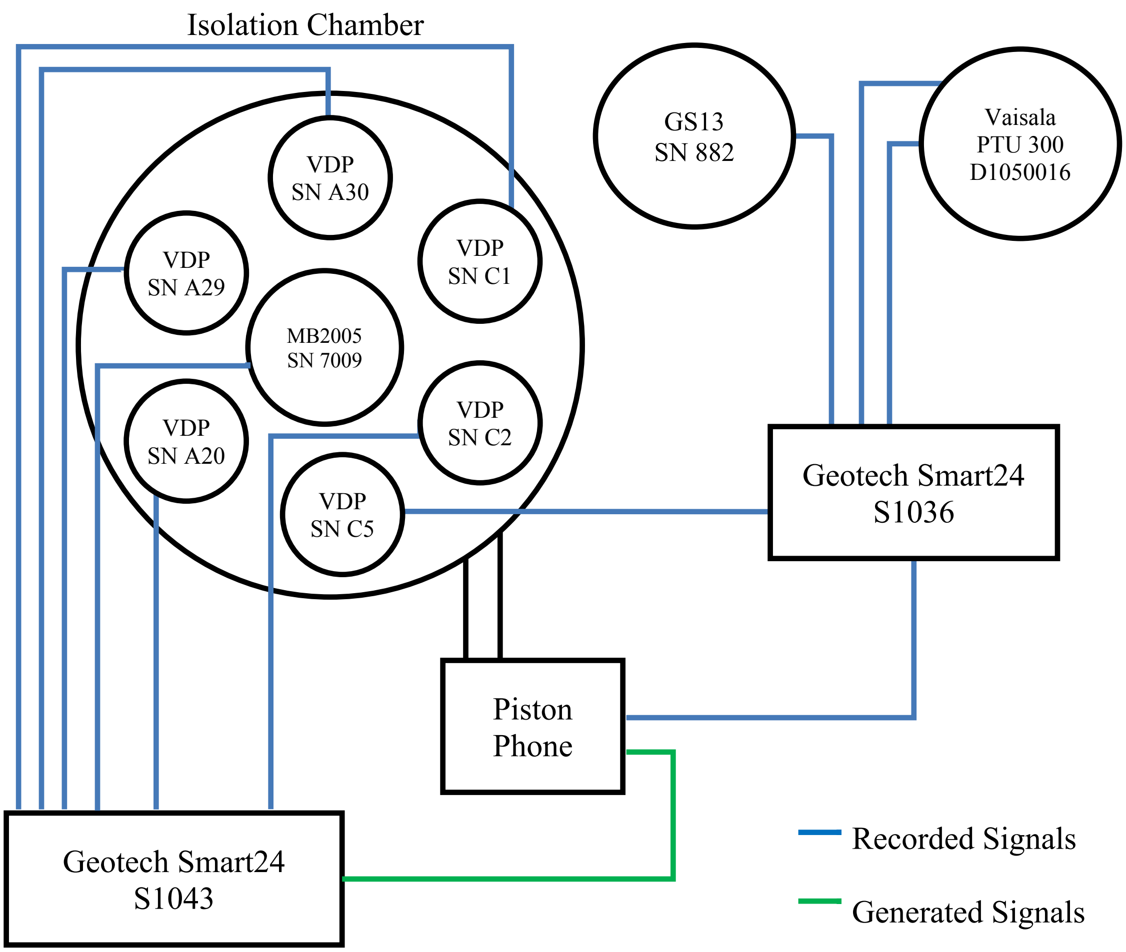

Figure 1. Test Configuration Diagram

Figure 2. The VDP100 and VDP250 model sensors placed inside the infrasound chamber

Figure 3 provides a view of the physical configuration of the sensors, including the MB2005 reference. A20, A29 and A30 are in the 7, 10 and 12 o'clock positions; C1, C2 and C5 are in the 2, 4 and 6 o'clock positions, respectively.

Figure 3. Vaisala pressure & temperature reference, Geotech SMART24 datalogger and a GS13 seismometer

2.5.1 Power

All of the sensors and digitizers within the testbed were powered by a Powertek DC Power Supply 3032A.

2.5.2 Data Recording

The data from the sensors used in this test were recorded on two Geotech Smart24 digitizers, serial numbers S1036 and S1043. The digitizer channels recording the pressure sensors have a nominal bit weight of 3.27 uV/count with a 40 Volt peak-to-peak input range. The digitizer channel recording the output of the GS13 Seismometer has a nominal bit weight of 0.409 uV/count with a 5 Volt peak-to-peak input range. The digitizers were configured to record each channel of data with a 100 Hz primary channel and a 20 Hz secondary channel. The majority of testing utilize the 100 Hz rate to more fully capture the pass band of the VDP sensors.

The digitizer bit weights were verified prior to testing using a precision DC source that was verified against an Agilent 3458A that has been calibrated by the SNL Primary Standards Lab to provide traceability. The measured bit weights, shown in the digitizer configuration tables below, were used for all collected sensor data.

Table 1. Geotech Smart24 Digitizer S1036 Configuration

Channel Name	Bit weight	Description
c1p / c1s	0.40956 uV/count	GS13 Vertical Seismometer
c4p / c4s	3.27691 uV/count	VDP250 SN C5
c5p / c5s	3.26912 uV/count	Vaisala Ambient Pressure
c6p / c6s	3.27587 uV/count	Vaisala Ambient Temperature

Table 2. Geotech Smart24 Digitizer S1043 Configuration

Channel Name	Bit weight	Description
c1p / c1s	3.26343 uV/count	MB2005 SN 7009
c2p / c2s	3.24779 uV/count	VDP100 SN A20
c3p / c3s	3.26001 uV/count	VDP100 SN A29
c4p / c4s	3.25306 uV/count	VDP100 SN A30
c5p / c5s	3.25293 uV/count	VDP250 SN C1
c6p / c6s	3.26842 uV/count	VDP250 SN C2

2.5.3 Signal Generation

The test signals were generated from the Geotech Smart24 S1043 calibrator. The generated signals could then be fed into a piston-phone and converted into a varying pressure into the isolation chamber.

2.5.4 *Reference Sensors*

Three references sensors were used throughout the test.

An MB2005, SN 7009, was co-located within the isolation chamber to provide a reference measurement for the testing of the USGS sensors. The MB2005 has been calibrated against the Los Alamos National Laboratory (LANL) calibration chamber and determined to have a sensitivity of 97 mV/Pa (Hart, 2012).

A Vaisala PTU300 SN D1050016 temperature and pressure sensor was recorded to provide a record of the ambient conditions throughout the testing. For each test, the ambient conditions from the Vaisala were recorded.

2.5.5 *Infrasound Sensor Configuration*

The 6 infrasound sensors, models VDP100 and VDP250, under evaluation were provided by United States Geological Survey (USGS), Alaska Volcano Observatory (AVO). The infrasound sensors were designed for a differential output of 100 Pa and 250 Pa. Sensor specific sensitivities were calculated and subsequently used in later testing and analysis of all sensor data.

2.5.6 Ambient Conditions

Testing of the USGS VDP infrasound sensors were conducted at Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) Site in Albuquerque, NM from February 9 – 16, 2016. The FACT site is at approximately 1830 meters in elevation.

The ambient pressure and temperature conditions were recorded throughout the test on the Vaisala PTU300 reference sensor. Plots of the recorded pressure and temperature are shown in the figure below. Note that local time in Albuquerque, NM was GMT - 6 during the testing.

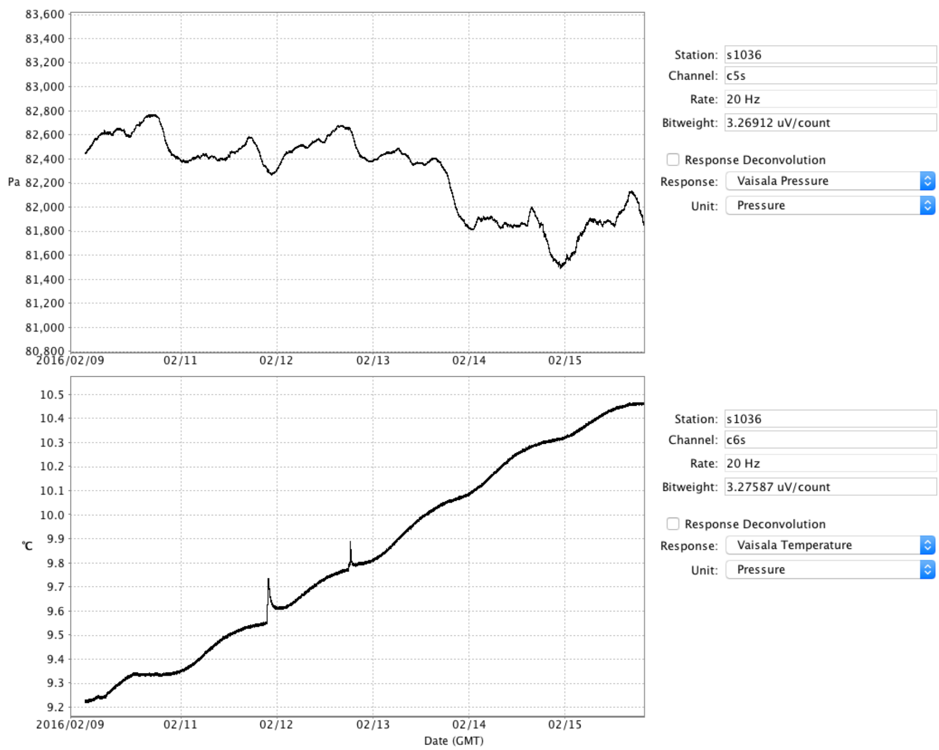

Figure 4. Ambient pressure and temperature

As may be seen in the plots, the mean atmospheric pressure during the testing was approximately 82,200 Pa with some variation in ambient pressure between 82,800 and 81,500 Pa during the days of testing.

While the ambient temperature in the FACT bunker gradually rose over the week of testing, the total change in temperature over the time period are less than 1.25° C. Diurnal variations are more of an increase or decrease in the rate of temperature increase during the time period rather than a increase and decrease in temperature. During the day there were some temperature transients due to entering and exiting the underground bunker where the testing was being performed.

3 EVALUATION

3.1 Isolation Noise

Test Description: The purpose of the isolation noise test is to provide an environment that is free from the influence of atmospheric background, allowing for the evaluation of the sensors' electronics and transducer noise under conditions of minimal excitation. The sensors were isolated by placing them inside the 330L chamber with their inlets open. This test was run overnight, and the data were collected and reviewed prior to processing.

For this test, an eleven hour time window was used on each model of sensor. The area between the red lines defines the time window used in the self-noise analysis.

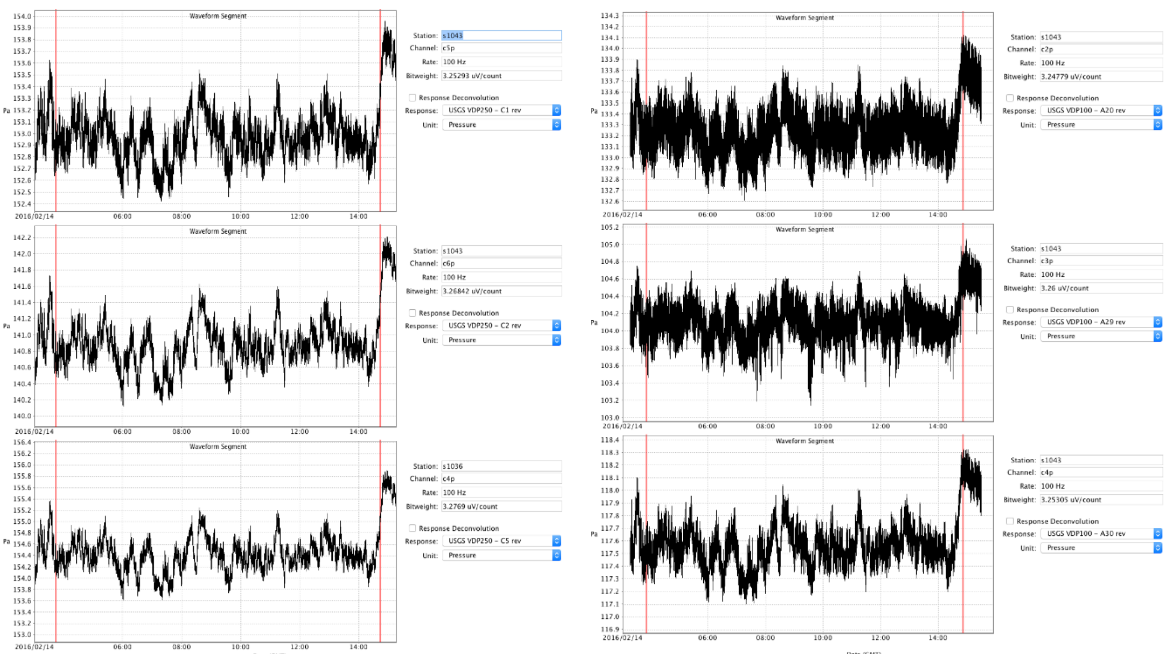

Figure 5. Isolation time series: VDP100 sensors left, VDP250 right

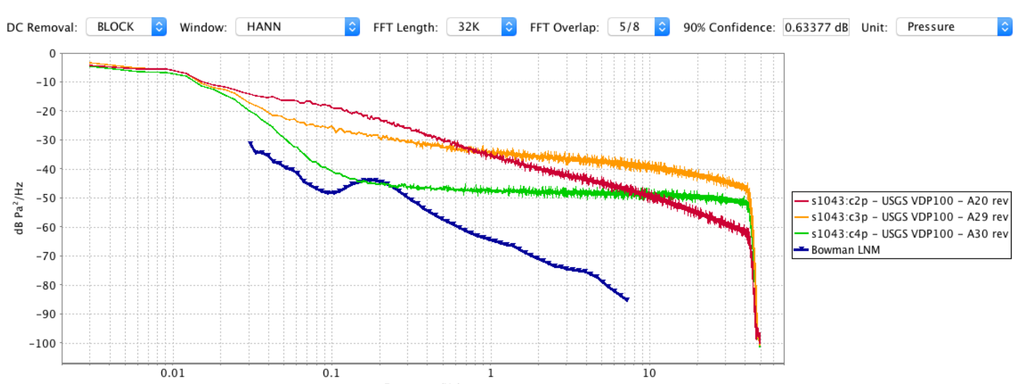

Figure 6. VDP100 sensor isolation power spectra

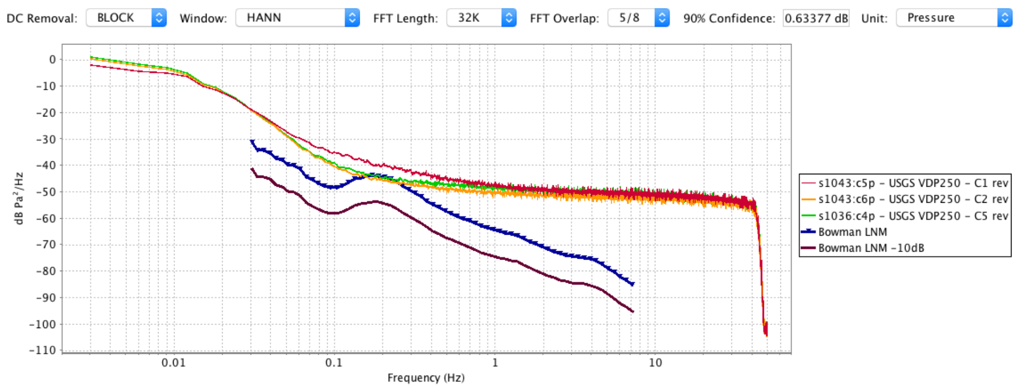

Figure 7. VDP250 sensor isolation power spectra

There clearly is an issue with the response of sensor A20 and possibly A29, as is evident when viewing their power spectra in Figure 6. The broad, high amplitude spectra exhibited by sensor A20 appears, after further investigation, to be the expression in the frequency domain of transient, box-car-like signals in the time-series, see the top plot of Figure 8 below. Sensor A29 also exhibits similar, but at lower amplitudes, the second plot of Figure 8.

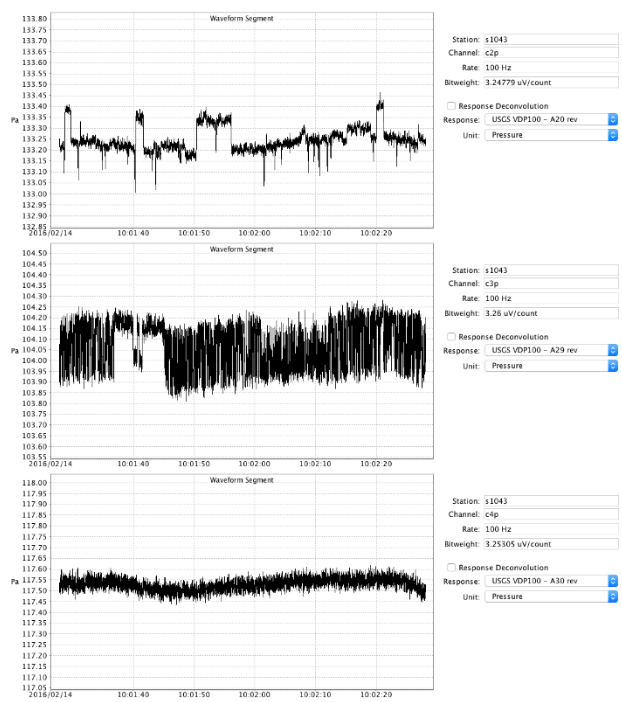

Figure 8. Time-series plot of sensors A20, A29 and A30 data

Even with the presence of the isolation chamber to attenuate signals, there remains some coherent signal between the VDP sensors. This is a known limitation of the existing infrasound chamber. Therefore, the 3-Channel Sleeman coherence technique was applied to the power spectra of the VDP sensors to compute their incoherent noise, using a noise model that is able to uniquely identify the noise of each sensor. The VDP noise and the Bowman Low Noise Model (LNM) are shown in the plot below.

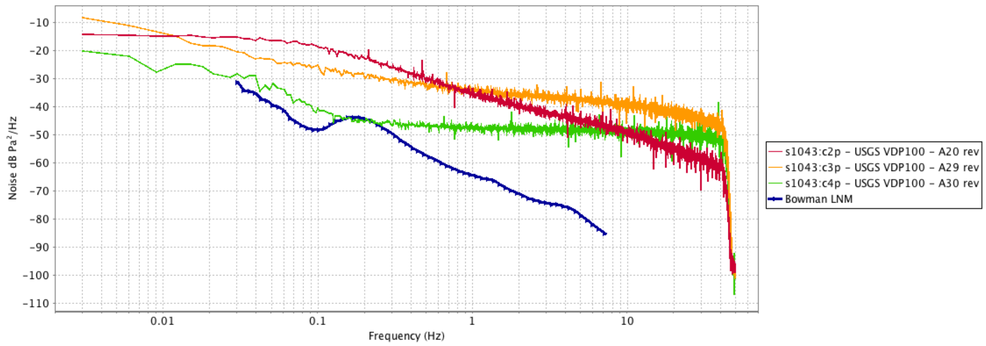

Figure 9. VDP100 sensor isolation incoherent self-noise

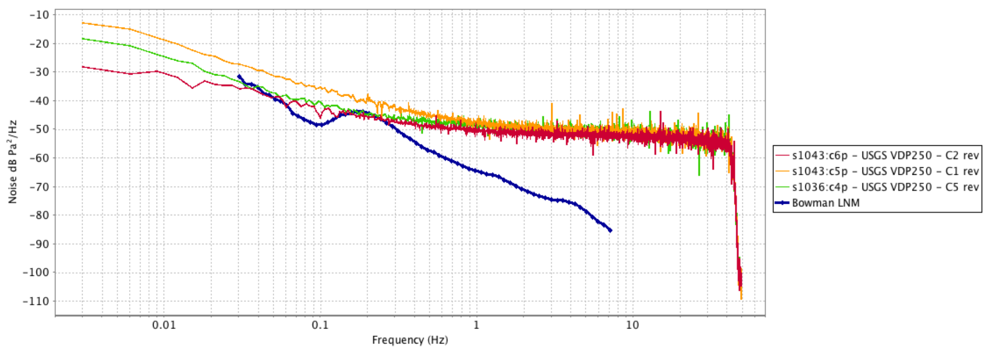

Figure 10. VDP250 sensor isolation incoherent self-noise

We evaluated sensor self-noise over two bands, 0.1 Hz to 40 Hz and 0.5 Hz to 2 Hz. Both the VDP100 (specifically A30) and VDP250 model sensors have self-noise that generally exceeds the Bowman low noise model, except perhaps in the vicinity of 0.15 Hz to 0.2 Hz, where the self-noise of sensors A30 and C5 are less than 2 dB below the Bowman LNM and sensor C2 is slightly more than 2 dB over the Bowman LNM in this frequency range.

Table 3. VDP 100 and VDP250 sensor RMS noise

Waveform	0.1 Hz - 40 Hz	0.5 Hz - 2 Hz
s1043:c2p - USGS VDP100 - A20 rev	0.04768 Pa rms	0.0207 Pa rms
s1043:c3p - USGS VDP100 - A29 rev	0.06192 Pa rms	0.02294 Pa rms
s1043:c4p - USGS VDP100 - A30 rev	0.02092 Pa rms	0.00506 Pa rms
s1043:c6p - USGS VDP250 - C2 rev	0.01382 Pa rms	0.00361 Pa rms
s1043:c5p - USGS VDP250 - C1 rev	0.01686 Pa rms	0.00492 Pa rms
s1036:c4p - USGS VDP250 - C5 rev	0.01592 Pa rms	0.00446 Pa rms

3.2 Full Scale

Test Description: The purpose of the full scale test is to determine the maximum signal amplitude that may be measured by the sensor without clipping. To test this quantity the piston phone was connected directly to each individual sensor, as shown in Figure 11, and increasing pressure changes were presented to the sensors. The clip level was measured for each sensor, averaging the measurements over 5 cycles taken from the middle of the recorded sine calibration signal.

Figure 11. Sensor A20 directly connected to piston phone

The measured clip level of the 1 Hz sinusoid varied appreciably more for the A model sensor than the C model sensor as illustrated in the table below.

Table 4. Measured Clip Level at 1 Hz

Sensor	Average Clip Level	Individual Sensor Measured Clip Level	Difference of Individual Clip Level from Average Clip Level
VDP100 A20	1.505 V	1.421 V	5.56%
VDP100 A29		1.545 V	2.66%
VDP100 A30		1.550 V	2.98%
VDP250 C1	2.465 V	2.479 V	0.579%
VDP250 C2		2.454 V	0.462%
VDP250 C5		2.453 V	0.070%

3.3 Dynamic Range

Test Description: The purpose of the dynamic range test is to determine the ratio between the largest and smallest possible signals that may be observed on the sensor. We define dynamic range as the ratio between the RMS of a full-scale sinusoid at the calibration frequency, typically 1 Hz, and the RMS noise present in the self-noise of the sensor across an application pass band.

Using the sensor self-noise estimate obtained from 3.1, which is believed to be the best estimate of self-noise available, and the average clip levels from 3.2, the dynamic ranges are:

Table 5. VDP100 and VDP 250 dynamic range

Waveform	0.1 Hz - 40 Hz	0.5 Hz - 2 Hz
s1043:c2p - USGS VDP100 - A20 rev	67.27 dB	74.52 dB
s1043:c3p - USGS VDP100 - A29 rev	64.36 dB	72.98 dB
s1043:c4p - USGS VDP100 - A30 rev	73.75 dB	86.09 dB
s1043:c5p - USGS VDP250 - C1 rev	76.04 dB	86.74 dB
s1043:c6p - USGS VDP250 - C2 rev	77.76 dB	89.42 dB
s1036:c4p - USGS VDP250 - C5 rev	76.73 dB	87.78 dB

The VDP sensors, specifically A30 and the VDP250 models, exhibit similar dynamic ranges over the narrow range of 0.5 Hz to 2 Hz, ranging from 86.1 dB to 89.4 dB (excluding sensors A20 and A29 due to the aforementioned noise). Dynamic ranges of sensors A20 and A29 are approximately 15 dB less than that of the other sensors, almost certainly due to the aforementioned noise. Over the broad range, from 0.1 Hz to 40 Hz, the VDP250 model sensors have an appreciably higher dynamic range (2.3 dB to 4 dB) over sensor A20.

3.4 Frequency Amplitude Response Verification

Test description: The purpose of the infrasound sensor frequency/amplitude response verification test is to determine or verify the infrasound sensor amplitude at a specific frequency, in this case 1 Hz.

A sequence of tones, over the amplitudes listed in Table 6, were generated by the calibration output channel of a Smart24 testbed digitizer. The tones were fed into a piston-phone infrasound source attached to the 330L test chamber. Approximately 25 cycles of each tone were recorded; however, only approximately 15 cycles were used to perform the sine fits.

Three iterations of the test were conducted. The tones were run overnight or during the early morning hours to ensure data were collected when temperature variations, wind, and other man-made noise sources were minimal. The average values of the sensitivities computed from these three test iterations are presented in Table 7.

Table 6. Piston-phone Tone Amplitudes

Amplitudes (Volts) into piston-phone	Approximate pressure (at 1 Hz) within the chamber
0.5 V	0.7244 Pa
1.0 V	1.559 Pa
1.5 V	2.452 Pa
2.0 V	3.344 Pa
2.5 V	4.020 Pa
3.0 V	4.695 Pa

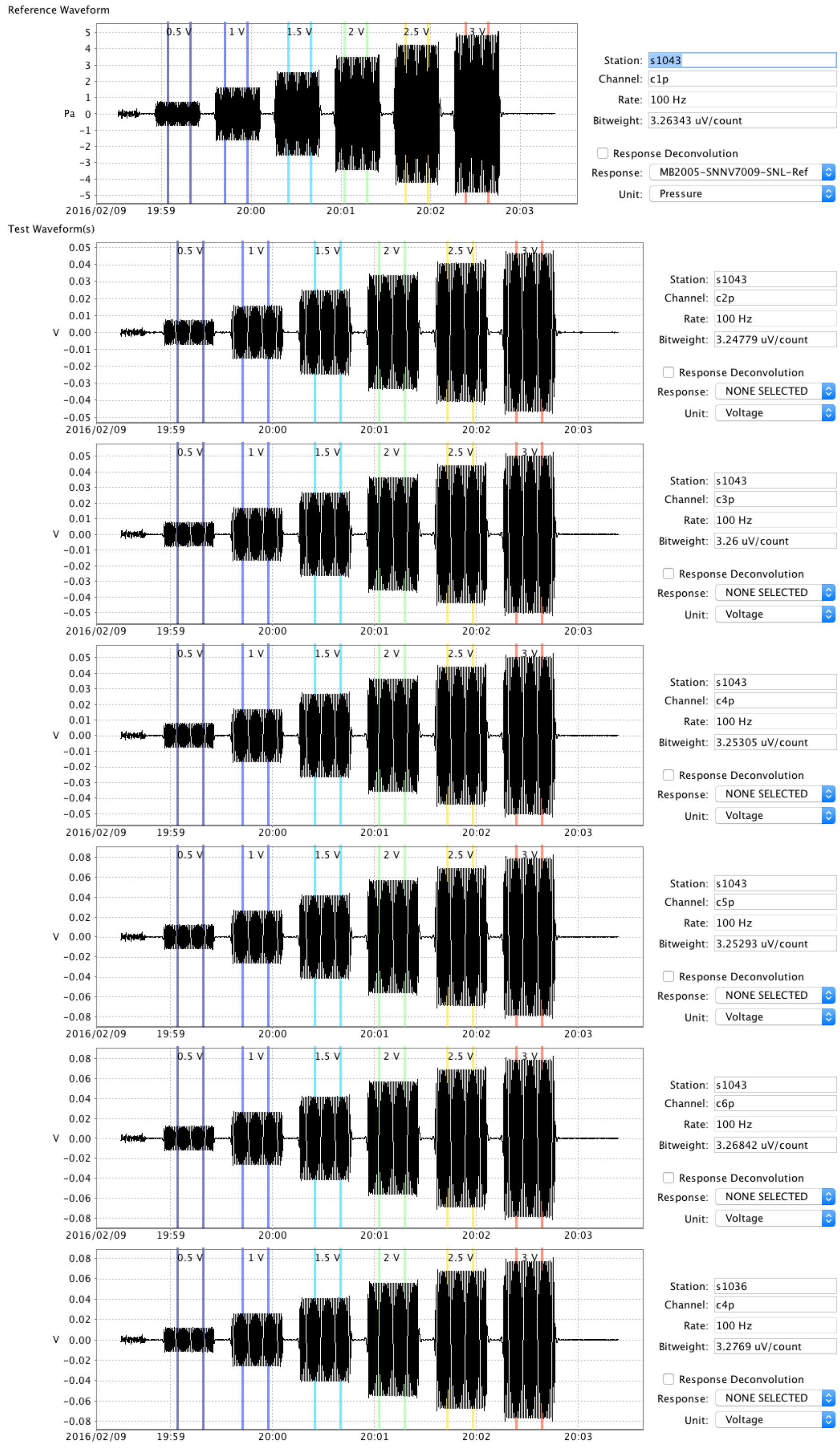

Figure 11. 1 Hz Piston-phone tone time series

The pressure measurement for each of the tones was observed on the MB2005 reference sensor. The reference pressure measurement was then compared to the peak voltages observed on each of the sensors under test to compute that sensor's sensitivity in Volts/Pascal. A Butterworth band-pass filter centered on the frequency of the sine was applied to the waveform data to remove frequency content outside of the tone so as to improve the performance of the sine fit algorithm. The time windows used to perform the sine fits were set to capture the portion of the tone with the least variation in peak amplitude.

Table 7. Average Piston-phone Sensitivities as Observed at Selected Pressures

Sensor	0.7244 Pa	1.559 Pa	2.452 Pa	3.344 Pa	4.020 Pa	4.695 Pa
A20	9.668 mV/Pa	9.627 mV/Pa	9.66 mV/Pa	9.660 mV/Pa	9.668 mV/Pa	9.658 mV/Pa
A29	10.43 mV/Pa	10.41 mV/Pa	10.41 mV/Pa	10.41 mV/Pa	10.41 mV/Pa	10.41 mV/Pa
A30	10.44 mV/Pa	10.45 mV/Pa	10.44 mV/Pa	10.44 mV/Pa	10.44 mV/Pa	10.44 mV/Pa
C1	16.31 mV/Pa	16.31 mV/Pa	16.30 mV/Pa	16.30 mV/Pa	16.30 mV/Pa	16.30 mV/Pa
C2	16.35 mV/Pa	16.34 mV/Pa	16.33 mV/Pa	16.33 mV/Pa	16.33 mV/Pa	16.33 mV/Pa
C5	15.92 mV/Pa	15.94 mV/Pa	15.97 mV/Pa	15.98 mV/Pa	15.97 mV/Pa	15.95 mV/Pa

Table 8. Average Sensitivity of each Model Sensor

Sensor Model	Average Sensitivity over all sensors/amplitudes
VDP100	10.17 mV/Pa
VDP250	16.20 mv/Pa

Differences of sensor-specific mean from model-specific mean are shown below. Notice sensor A20 has the largest difference from the respective average of either model average.

Table 9. Average Sensitivities Based Upon Piston-Phone Source

Sensor	Mean Sensitivity at 1 Hz, across all amplitudes	Difference of Sensor-Specific Mean from Model Mean Sensitivity at 1 Hz	Maximum Difference from Sensor-Specific Mean at 1 Hz across 0.7244 – 4.695 Pa
VDP100 A20	9.658 mV/Pa	-5.044% (-0.45 dB)	0.5665% (0.049 dB)
VDP100 A29	10.41 mV/Pa	2.380% (0.20 dB)	0.2696% (0.023 dB)
VDP100 A30	10.44 mV/Pa	2.664% (0.23 dB)	0.1118% (0.0097 dB)
VDP250 C1	16.30 mV/Pa	0.6478% (0.056 dB)	0.08314% (0.0072 dB)
VDP250 C2	16.34 mV/Pa	0.8622% (0.075 dB)	0.1269% (0.011 dB)
VDP250 C5	15.95 mV/Pa	-1.51% (-0.13 dB)	-0.3070% (-0.027 dB)

The mean observed sensitivities at 1.0 Hz of the VDP100 and VDP250 model sensors fall be between 9.658 mV/Pa and 10.44 mV/Pa and 15.95 mV/Pa and 16.33 mV/Pa, respectively. The mean observed sensitivities of the VDP100 model sensors varies significantly more than that of the VDP250 model sensors; sensor A20 varied as much as -5.04% (-0.45 dB) from the mean, whereas the VDP250 model sensor sensitivities varied no more than 1.51% (0.13 dB).

All sensors were flat across the 0.7244 – 4.695 Pa amplitude range; the VDP100 sensors to within 0.57% (0.049 dB), and the VDP250 sensors 0.31% (0.027 dB).

3.5 Frequency Amplitude Phase Verification

Test description: The purpose of the infrasound sensor frequency/amplitude/phase response verification test is to determine or verify the infrasound sensor frequency/amplitude/phase response at all frequencies using a variable amplitude, variable frequency piston-phone acoustic signal generator and a characterized reference infrasound sensor.

A sensor, MB2005 serial number 7009, with a known instrument response model was used as a reference for this test. A white noise signal with an amplitude of 1.0 Volts was generated by the calibration output channel of a Smart24 testbed digitizer. This white noise signal was fed into a piston-phone infrasound source attached to the 330L infrasound test chamber for 6.5 hours.

The data from the reference sensor and the sensors under test were corrected for their respective instrument response models, scaling the records to pressure (Pa) and correcting for amplitude and phase. If all of the instrument response models perfectly represent the reference sensor and the sensors under test, then the plots of relative magnitude and phase should be perfectly flat lines at 0 dB and 0 degrees, respectively. The extents to which the relative magnitude and phase are zero represent how consistent the sensors are with their responses and serves to validate the pass band of the sensor.

The coherence was computed using the technique described by Holcomb (1989) under the distributed noise model assumption. The spectra (power spectral density estimates or PSDs) were computed using block-by-block DC removal, Hann windowing, 16K FFT length and 5/8 window overlap. With the amount of data processed this provided a 90% confidence interval of 0.827 dB.

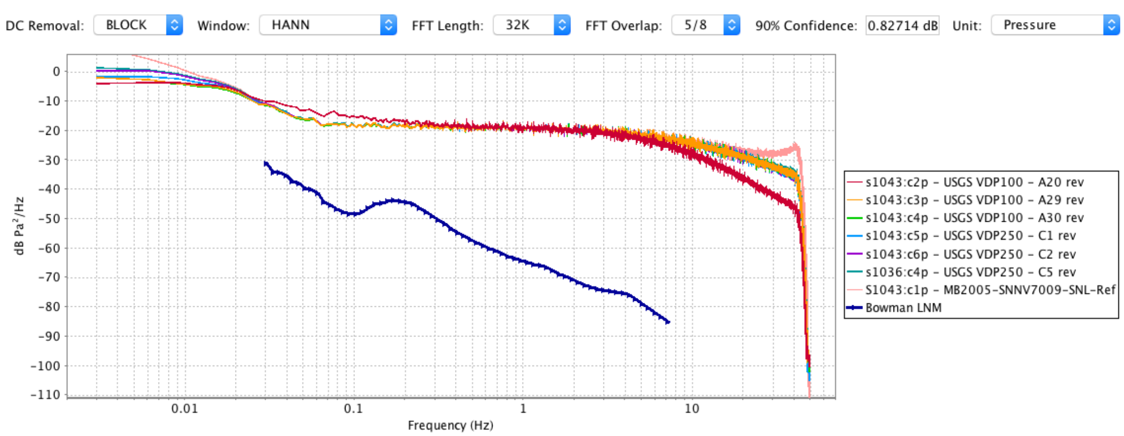

Figure 12. Piston-phone white noise power spectra

The PSDs of 5 of the 6 sensors (excluding sensor A20) show good broadband agreement with the MB2005 reference sensor from 0.09 Hz to 11 Hz, below and above which there is a gradual degradation in agreement through 0.02 Hz and 25 Hz, respectively, beyond which agreement is poor. To interpret the test results we need to review the coherence, relative gain, and relative phase. The computed mean-squared coherence values, relative gain, and relative phase between the reference MB2005 and each of the VDP sensors under evaluation are plotted below.

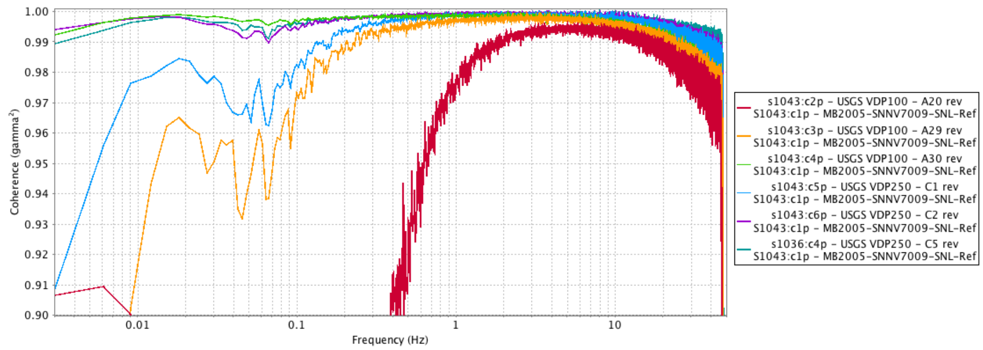

Figure 13. Piston-phone white noise coherence

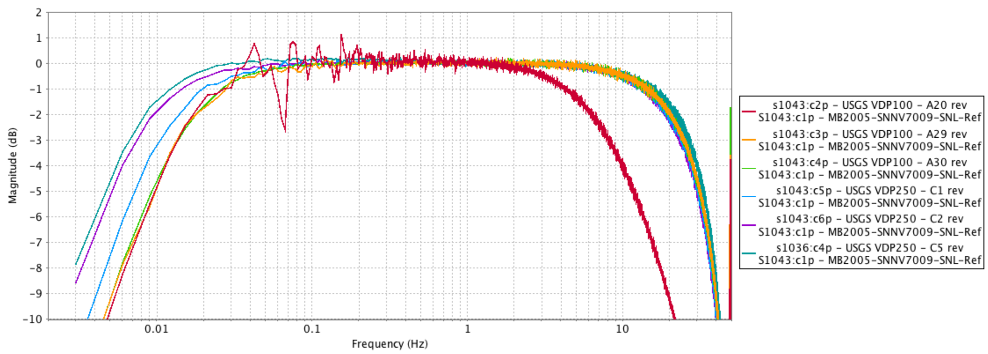

Figure 14. Piston-phone white noise relative magnitude

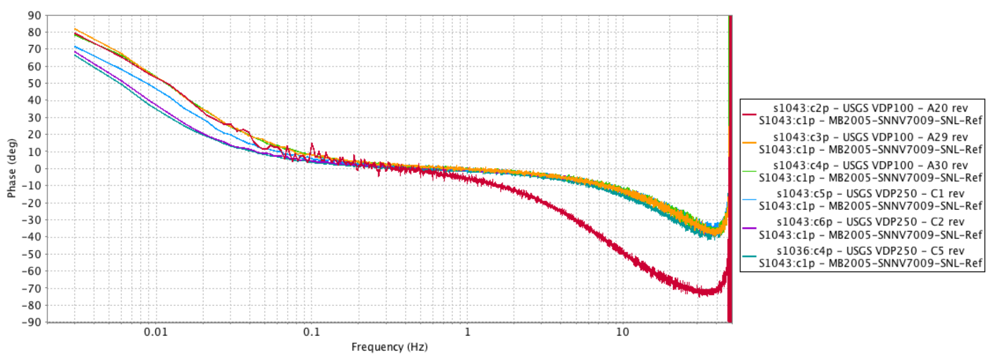

Figure 15. Piston-phone white noise relative phase

Coherence between the MB2005 reference sensor and the sensors under test varies across serial numbers and model; in the best case, sensor A30 has good coherence from 0.005 Hz to 15 Hz. Excluding sensor A20, the remainder of the sensors have good coherence from as low 0.12 Hz to as high as 28 Hz.

The variation in magnitude and phase between the outputs of the MB2005 reference and each of the VDP sensors are described in the table below. There is sufficient coherence between sensors C2 and C5 and the MB2005 reference to be able to comment on the relative response over 0.01

to 20 Hz; A30 over 0.01 to 10 Hz. Insufficient coherence between the reference sensor and A20, A29 and C5 limits comment at frequencies 0.1 Hz and 10 Hz.

Table 10. Piston-phone White Noise Relative Magnitude and Phase, 0.01 Hz and 10 Hz

Sensor	**Magnitude**	**Phase**
VDP100 A20	-4.98 dB* / -3.97 dB*	+53.4 deg* / -49.0 deg*
VDP100 A29	-5.03 dB* / -0.518 dB*	+53.9 deg* / 13.0 deg*
VDP100 A30	-4.74 dB / -0.502 dB	+ 53.9 deg / -12.8 deg
VDP250 C1	-3.33 dB* / -0.505 dB*	+47.0 deg* / -12.4 deg*
VDP250 C2	-1.96 dB / -0.535 dB	+37.3 deg / -13.0 deg
VDP250 C5	-1.54 dB / -0.440 dB	+35.0 deg / -16.0 deg

*Insufficient coherence at the stated frequencies requires caution when interpreting results.

The widest range over which the VDP sensors and references sensor have general agreement in relative magnitude (within 0.5 dB) is 0.02 Hz to 10 Hz; regarding relative phase, the widest band over which there is general agreement (within 5 deg) is 0.07 Hz to 4 Hz. The frequency range over which there is broad agreement varies significantly by individual sensor, specifically at the lowest frequencies; the variability does not correlate with sensor type.

Table 11. Low and High Frequency Response Limits (-3 dB)*

Sensor	Low Frequency Corner	High Frequency Corner
A20	0.011 Hz*	8.1 Hz
A29	0.014 Hz*	24.3 Hz*
A30	0.014 Hz	24.3 Hz*
C1	0.011 Hz*	23.7 Hz*
C2	0.008 Hz*	23.6 Hz*
C5	0.007 Hz*	26.5 Hz*

*Corner frequencies listed exceed the low or high frequency limit at which coherence is less than 0.995.

Excluding sensor A20, the remaining sensors have similar low and high corner frequencies; averaging at 0.011 Hz and 24.5 Hz. The measured corner frequencies, in most cases, exceed the low and high frequency band limits of high coherence.

4 EVALUATION SUMMARY

Isolation Noise:
The VDP100 and VDP250 measured self-noise varied significantly. One of three VDP100 sensors had self-noise below the Bowman LNM over a narrow frequency band, 0.15 Hz to 0.22 Hz. The VDP250 sensor fared slightly better with two of three sensors, falling below the Bowman LNM between 0.15 Hz and 0.24 Hz. The measured sensor self-noise of the VDP100 and VDP250 varied between 0.021 Pa rms to 0.061 Pa rms and 0.014 Pa rms and 0.017 Pa rms, respectively, over the broad frequency range of 0.1 Hz to 40 Hz. Over the narrow frequency band, 0.5 Hz to 2 Hz, the noise of the VDP100 and VDP250 ranged from 0.005 Pa rms to 0.023 Pa rms and 0.004 Pa rms to 0.005 Pa rms, respectively.

Full Scale
The average observed clip level of the VDP100 is 1.505 V. The VDP250 average observed clip level is 2.465 V. Observed clip levels varied more for the VDP100 sensors than the VDP250, 5.56% vs. 0.579%, respectively.

Dynamic Range:
The observed dynamic range, over 0.1 – 40 Hz, of the VDP100 and VDP250 sensors varied from 64.4 to 73.8 dB and 76.0 dB to 77.8 dB, respectively. Over the range of 0.5 Hz – 2 Hz, the VDP100 and VDP250 ranged from 73.0 dB to 86.1 dB and 86.7 dB to 89.4 dB, respectively.

Frequency Amplitude Response Verification:
The observed sensitivity at 1 Hz of the VDP100 and VDP250 sensors were 10.17 mV/Pa and 16.20 mV/Pa, respectively. Sensitivities varied more widely for the VDP100 than the VDP250, 5.0% versus 0.86%. All sensors, excluding sensor A20, were flat between approximately 0.011 Hz and 24.5 Hz.

Frequency Amplitude Phase Verification:
Broadband measurements of a white noise source indicate the VDP100 and VDP250 sensors have a response that is flat over varying frequency ranges for each sensor type. At best, relative magnitude is flat (within 0.5 db) from 0.02 Hz to 10 Hz; regarding relative phase the response is flat (within 5 deg) from 0.07 Hz to 4 Hz.

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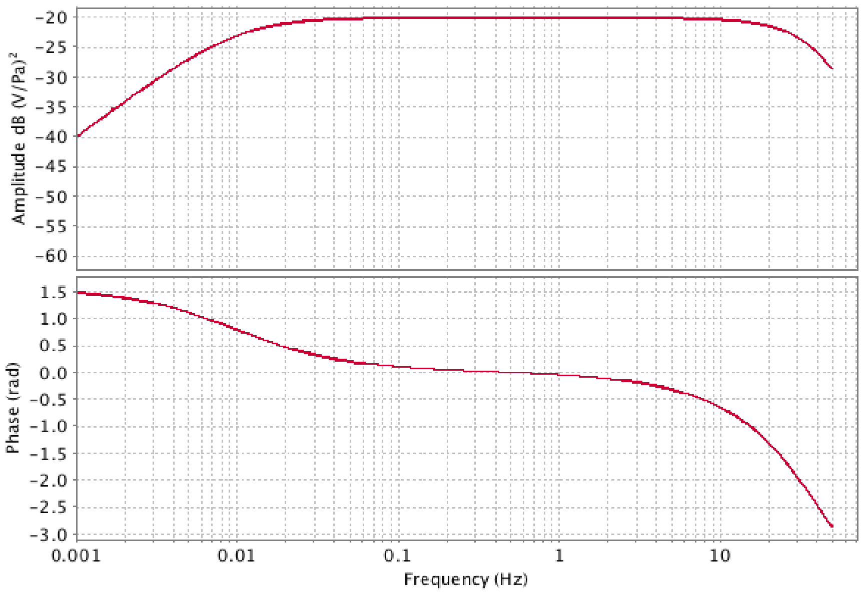
APPENDIX

MB2005 Response

The MB2005 response used has the standard poles and zeros provided by CEA. The sensitivity of the instrument is 97 mV/Pa.



Sensitivity:
97 mV/Pa at 1.0 Hz

Poles:

-206.69	0.0
-177.7	177.8
-177.7	-177.8
-4.3	819.6
-4.3	-819.6
-4.0	1116.7
-4.0	-1116.7
-0.0628	0.0

Zeros:

-468820.0	0.0
0.0	0.0

A:
2.2647053E6 MV/Pa

Figure 16. MB2005 Response

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