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Printed March 2016

Chaparral Model 60 Infrasound Sensor Evaluation

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Abstract

Sandia National Laboratories has tested and evaluated an infrasound sensor, the Model 60 manufactured by Chaparral Physics, a Division of Geophysical Institute of the University of Alaska, Fairbanks. The purpose of the infrasound sensor evaluation was to determine a measured sensitivity, transfer function, power, self-noise, dynamic range, and seismic sensitivity. The Model 60 infrasound sensor is a new sensor developed by Chaparral Physics intended to be a small, rugged sensor used in more flexible application conditions.

ACKNOWLEDGMENTS

This work was funded by the United States Department of Energy Office of Nuclear Verification (NA-221).

We would like to thank Chaparral Physics for providing the Model 60 sensors to evaluate.

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NOMENCLATURE

dB	decibel
DOE	Department of Energy
LNM	Low Noise Model
PSD	Power Spectral Density
SNL	Sandia National Laboratories

1 INTRODUCTION

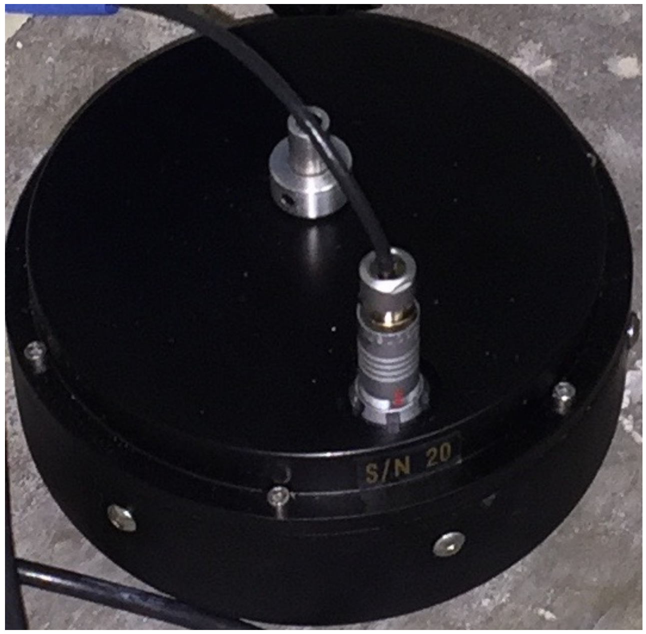

Figure 1 Chaparral Physics Model 60 Infrasound Sensor

Sandia National Laboratories has tested and evaluated an infrasound sensor, the Model 60 manufactured by Chaparral Physics, a Division of Geophysical Institute of the University of Alaska, Fairbanks.

2 TESTING OVERVIEW

2.1 Objectives

The objective of this work was to evaluate the overall technical performance of the Model 60 (M-60) infrasound sensor. Notable features of the M-60 include being low power and compact size. Basic infrasound sensor characterization includes determining sensitivity, linearity to pressure input, power, self-noise, dynamic range, seismic sensitivity, 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 MB2000 infrasound sensor, serving as a reference for this evaluation, had been previously compared and evaluated against a MB2005 infrasound sensor. 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 M-60 sensors was performed on August 21 – September 1, 2015 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 Power (IS-P)
- 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)
- Infrasound Sensor Seismic Sensitivity (IS-SEIS)

2.5 Test Configuration and System Specifications

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

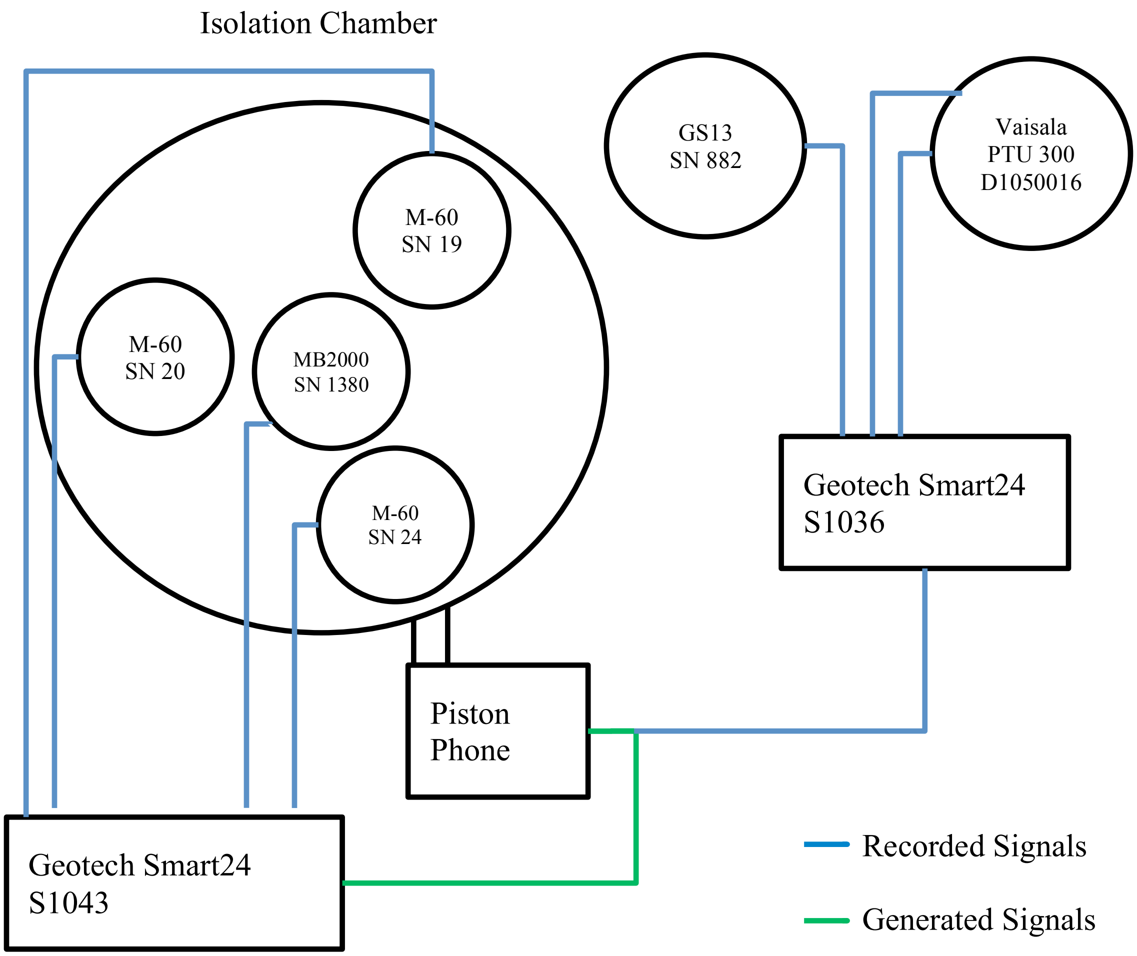

Figure 2 Test Configuration Diagram

Figure 3 M-60 infrasound sensors encapsulated in white foam jackets, the MB2000 reference sensor, and a Hyperion 5113GP (not utilized during this evaluation)

Figure 4 GS13 seismometer and Vaisala pressure & temperature reference

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, serials 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 M-60 sensor.

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	Signal Generator Output
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	MB2000 SN1380
c2p / c2s	3.24779 uV/count	M-60 SN 19
c3p / c3s	3.26001 uV/count	M-60 SN 20
c4p / c4s	3.25306 uV/count	M-60 SN 24

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. The generated signals were synchronously recorded on channel 5 of the Geotech Smart24 S1036 digitizer.

2.5.4 Reference Sensors

Several references sensors were used throughout the test.

An MB2000 SN 1380 was co-located within the isolation chamber to provide a reference measurement for the testing of the M-60 sensors. An 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 transfer calibration was performed at the SNL FACT site to validate that the MB2000 sensitivity of 100 mV/Pa was consistent with the MB2005.

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.

A Geotech GS13 SN 882 vertical seismometer was co-located with the sensors just outside of the isolation chamber to provide a reference for ground motion. Coherence between the GS13 Seismometer and the infrasound sensors was used in determining the seismic sensitivity of the infrasound sensors.

2.5.5 Infrasound Sensor Configuration

The three infrasound sensors under evaluation were provided by Chaparral Physics. The infrasound sensors were stated to have an output sensitivity of 0.4 V/Pa and were designed for a differential output of 55 Pa, or 22 Volts, peak to peak. The nominal sensitivity was used in the processing and analysis of all sensor data. The frequency pass band is specified to be 0.03-245 Hz. The power input voltage range is 11.25 - 20 Volts DC.

2.5.6 Ambient Conditions

Testing of the Chaparral Physics Model 60 was conducted at Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) Site in Albuquerque, NM. 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.

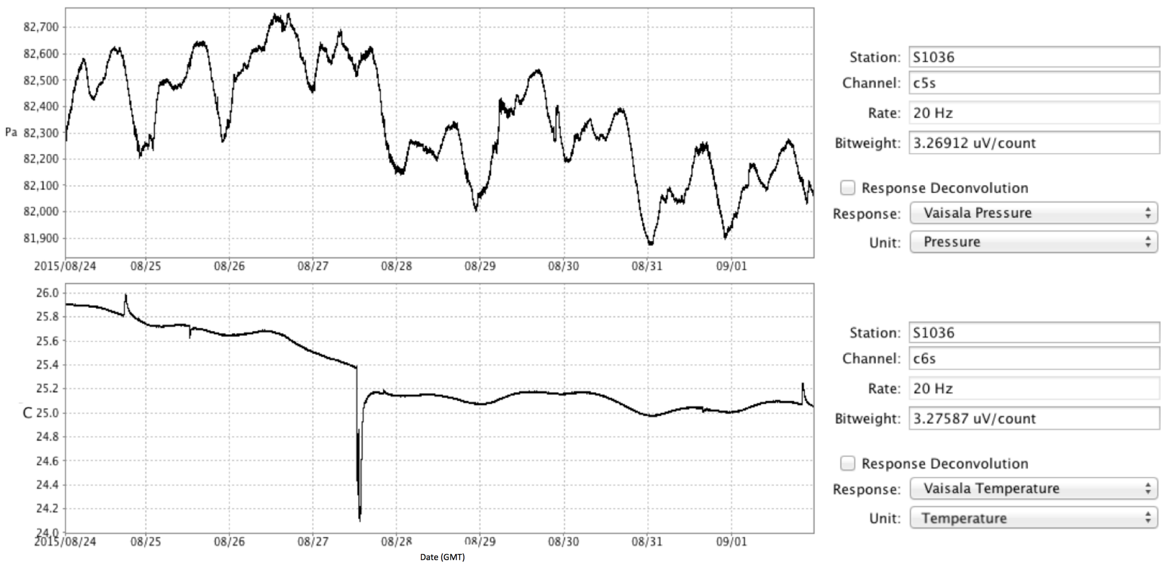

Figure 5 Ambient pressure and temperature

As may be seen in the plots, the mean atmospheric pressure during the testing was approximately 82,300 Pa with some variation in ambient pressure between 82,800 and 81,800 Pa during the days of testing.

While the ambient temperature in the FACT bunker gradually dropped over the week of testing, it is very stable during each individual night; nightly temperature variations were typically on the order of 0.1 degrees Celsius and the maximum nightly variation during the testing period was less than 0.2 degrees Celsius. During the day there were some significant variations in temperature due to entering and exiting the underground bunker where the testing was being performed.

3 EVALUATION

3.1 Power

Test description: Measure power consumption of an infrasound sensor under nominal application voltage requirements.

The manufacturer's specified input voltage range is 11.25 - 20 V DC. The evaluation of the Chaparral Model 60 sensors was performed at a nominal voltage of 14.09 V DC powered by a Protek 3032B DC Power Supply. Measurements of voltage and current were made with two hand-held Fluke multi-meters.

Table 3 Chaparral Model 60 Power Consumption

Sensor	Power Supply Voltage	Current	Power Consumption
M-60 SN 19	14.09 V	11.86 mA	0.1671 W
M-60 SN 20	14.09 V	12.28 mA	0.1730 W
M-60 SN 24	14.09 V	12.18 mA	0.1716 W

The observed power consumption of the Chaparral Physics M-60 was between approximately 167 mW and 173 mW at 14.09 V. The stated power consumption from the sensor specifications is less than 150 mW, 12 mA @ 12.6 V.

.

3.2 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 over night, and the data were collected and reviewed prior to processing.

For this test, a 12 hour time window was used on both of the sensors. The area between the red lines defines the time window used in the self-noise analysis.

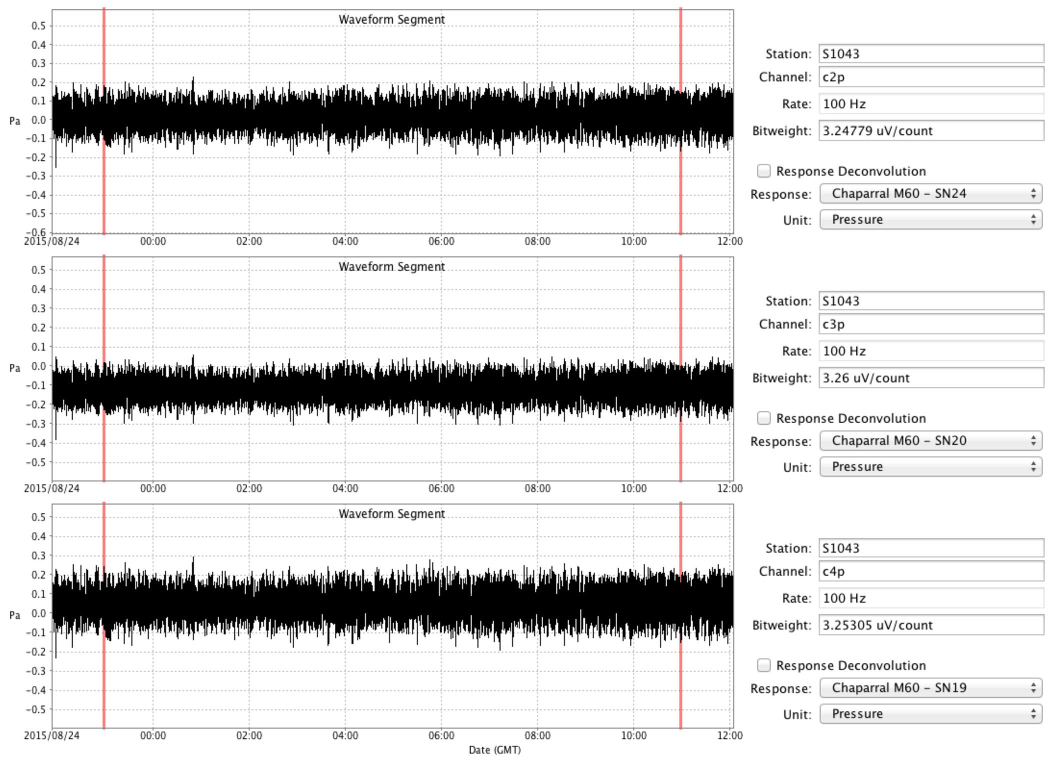

Figure 6 Chaparral Physics Model 60 isolation time series

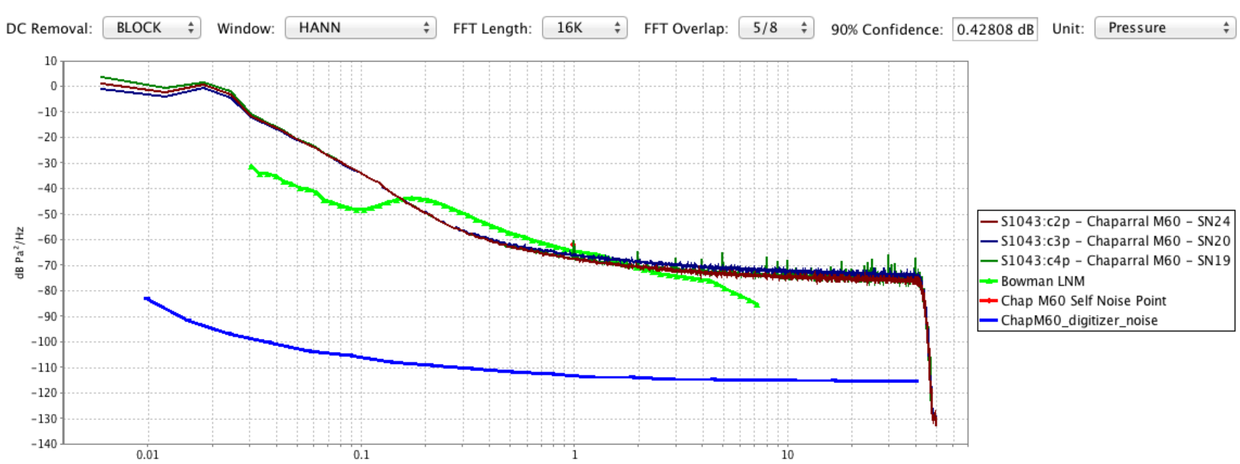

Figure 7 Chaparral Physics Model 60 isolation power spectra

Even with the presence of the isolation chamber to attenuate signals, there remains some coherent signal between the M-60 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 M-60 sensors to compute their incoherent noise, using a noise model that is able to uniquely identify the noise of each sensor. The M-60 noise and the Bowman Low Noise Model (LNM) are shown on the plot below.

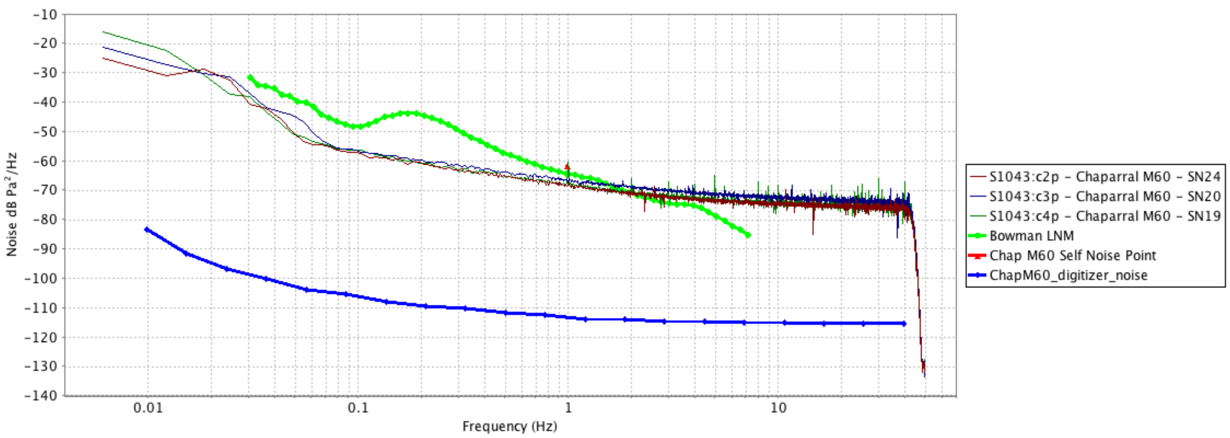

Figure 8 Chaparral Physics Model 60 isolation incoherent self-noise

Chaparral Physics provides two values regarding self-noise: 3 mPa and 0.8 mPa, over 0.1 Hz to 40 Hz and 0.5 Hz to 2 Hz, respectively The M-60 evaluated self-noise is below the Bowman LNM for frequencies below approximately 2 Hz and is lower than the manufacturer specified self-noise of -62 dB, relative to 1 Pa^2/Hz.

Table 4 Chaparral M-60 RMS Noise

Waveform	0.1 Hz - 40 Hz	0.5 Hz - 2 Hz
S1043:c2p - Chaparral M-60 SN 24	0.0013 Pa rms	0.0004 Pa rms
S1043:c3p - Chaparral M-60 SN 20	0.0016 Pa rms	0.0006 Pa rms
S1043:c4p - Chaparral M-60 SN 19	0.0014 Pa rms	0.0005 Pa rms
Manufacturer Specification	<0.003 Pa rms	< 0.0008 Pa rms

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 3.2 Isolation Noise, which is believed to be the best estimate of self-noise available, the RMS noise and dynamic range using the M-60 11 V peak clip level at 1 Hz are:

Table 5 Chaparral M-60 Dynamic Range

Waveform	0.1 Hz - 40 Hz	0.5 Hz - 2 Hz
S1043:c2p - Chaparral M-60 SN 24	83.67 dB	92.70 dB
S1043:c3p - Chaparral M-60 SN 20	81.74 dB	90.89 dB
S1043:c4p - Chaparral M-60 SN 19	83.28 dB	91.21 dB
Manufacturer Specification	88 db (no frequency range provided)	

Over the narrow pass band (0.5 Hz - 2 Hz) utilized in the self noise specification suggested by Chaparral Physics, the evaluated dynamic range is greater than what is listed in the sensor's specifications, however over the broad pass band (0.1 Hz - 40 Hz) over which self noise is specified the evaluated dynamic range is less than the 88 dB described in Chaparral Physics' specifications.

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 response at multiple frequencies and amplitudes using a variable frequency, variable amplitude piston-phone acoustic signal generator.

A sequence of tones, covering the combination of frequencies in Table 6 and amplitudes in Table 7 below, 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 15 cycles of each tone were recorded; however, only approximately 10 cycles were used to perform the sine fits.

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 V	1.559 Pa
1.5 V	2.452 Pa
2 V	3.344 Pa
2.5 V	4.020 Pa
3 V	4.695 Pa

Table 7 Piston-phone Tone Frequencies

Frequencies
0.01 Hz
0.02 Hz
0.03 Hz
0.04 Hz
0.08 Hz
0.1 Hz
0.2 Hz
0.4 Hz
0.8 Hz
1 Hz
2 Hz
4 Hz
8 Hz
10 Hz

The sequences of 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.

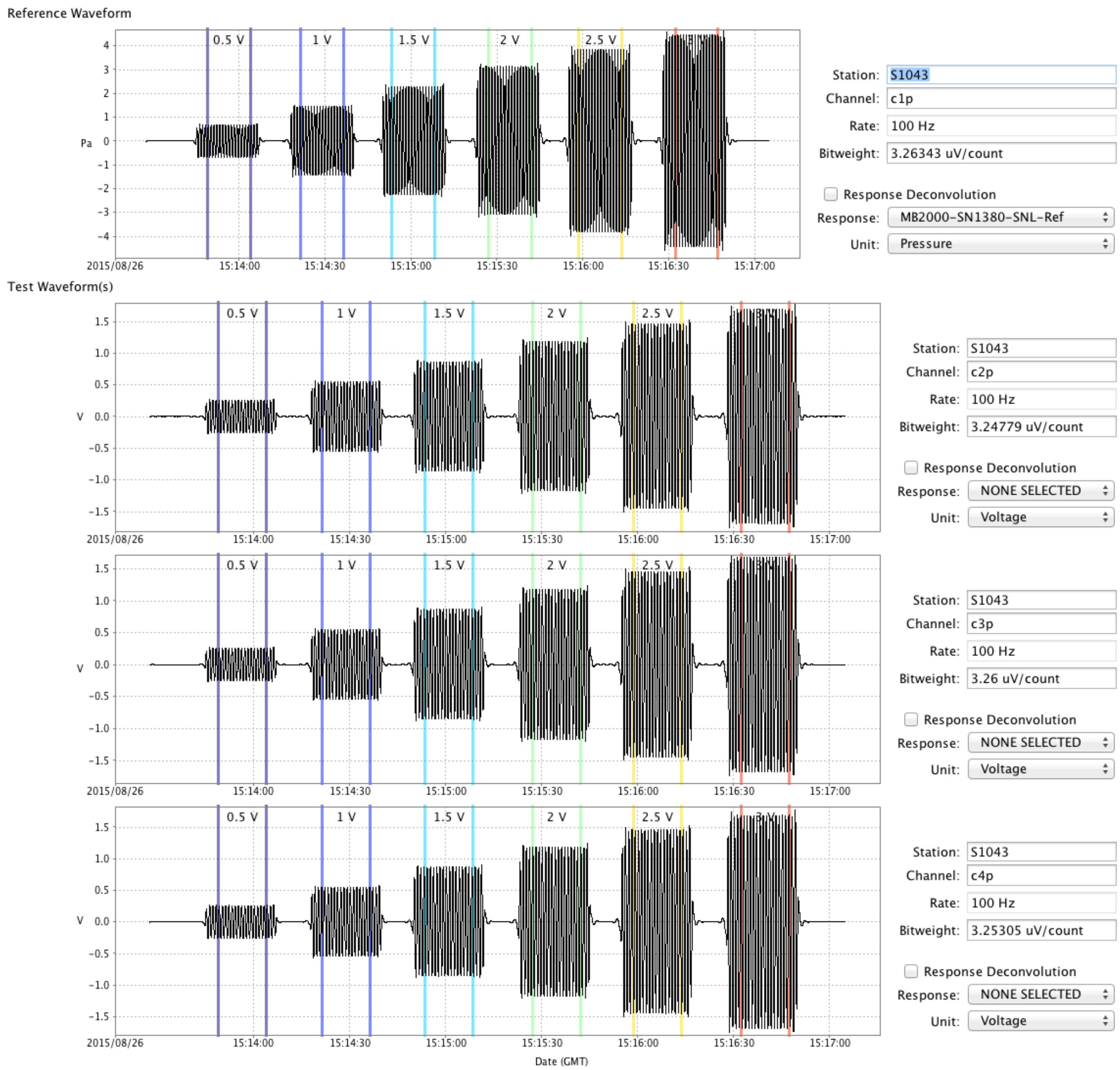

Figure 9 Piston-phone tone time series for 1 Hz

The pressure measurement for each of the tones was observed on the MB2000 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. For the lower frequency sines (0.01, 0.02, 0.03, 0.04 and 0.08 Hz) the 100 sps data were down-sampled to 20 sps and reduced-length windows were used to further improve sine fits (recall the infra-sound chamber poorly isolates below frequencies of approximately 1 Hz). The time windows use to perform the sine fits were set to capture the portion of the tone with the least variation in peak amplitude.

Table 8 Piston-phone Sensitivities at Selected Pressures for M-60 SN 19

Freq. (Hz)	Nominal Sensitivity (0.4 V/Pa @ 1 Hz)	0.7244 Pa	1.559 Pa	2.452 Pa	3.344 Pa	4.020 Pa	4.695 Pa
0.01	0.2336 V/Pa	0.1054* V/Pa	0.1056* V/Pa	0.1054 V/Pa	0.1054 V/Pa	0.1052 V/Pa	0.1052 V/Pa
0.02	0.3244 V/Pa	0.2292 V/Pa	0.2269 V/Pa	0.2281 V/Pa	0.2271 V/Pa	0.2275 V/Pa	0.2276 V/Pa
0.03	0.3597 V/Pa	0.2908* V/Pa	0.2911 V/Pa	0.2902 V/Pa	0.2904 V/Pa	0.2901 V/Pa	0.2905 V/Pa
0.04	0.3756 V/Pa	0.3218 V/Pa	0.3215 V/Pa	0.3215 V/Pa	0.3218 V/Pa	0.3216 V/Pa	0.3217 V/Pa
0.08	0.3934 V/Pa	0.3600 V/Pa	0.3599 V/Pa	0.3599 V/Pa	0.3599 V/Pa	0.3599 V/Pa	0.3598 V/Pa
0.1	0.3958 V/Pa	0.3696 V/Pa	0.3694 V/Pa	0.3697 V/Pa	0.3695 V/Pa	0.3694 V/Pa	0.3695 V/Pa
0.2	0.3990 V/Pa	0.3755 V/Pa	0.3754 V/Pa	0.3754 V/Pa	0.3754 V/Pa	0.3753 V/Pa	0.3754 V/Pa
0.4	0.3998 V/Pa	0.3774 V/Pa	0.3779 V/Pa	0.3778 V/Pa	0.3779 V/Pa	0.3778 V/Pa	0.3778 V/Pa
0.8	0.4000 V/Pa	0.3791 V/Pa	0.3791 V/Pa	0.3792 V/Pa	0.3790 V/Pa	0.3791 V/Pa	0.3790 V/Pa
1	0.4000 V/Pa	0.3795 V/Pa	0.3793 V/Pa	0.3793 V/Pa	0.3792 V/Pa	0.3790 V/Pa	0.3791 V/Pa
2	0.4000 V/Pa	0.3792 V/Pa	0.3796 V/Pa	0.3792 V/Pa	0.3791 V/Pa	0.3794 V/Pa	0.3793 V/Pa
4	0.4000 V/Pa	0.3781 V/Pa	0.3786 V/Pa	0.3783 V/Pa	0.3786 V/Pa	0.3784 V/Pa	0.3784 V/Pa
8	0.4000 V/Pa	0.3759 V/Pa	0.3764 V/Pa	0.3764 V/Pa	0.3790 V/Pa	0.3758 V/Pa	0.3762 V/Pa
10	0.4000 V/Pa	0.3736 V/Pa	0.3742 V/Pa	0.3735 V/Pa	0.3745 V/Pa	0.3737 V/Pa	0.3737 V/Pa

*** Signal to noise ratios were below 20 dB for these measurements; sine fits used to calculate these sensitivities were less than ideal.**

Table 9 Piston-Phone Sensitivities at Selected Pressures for M-60 SN 20

Freq. (Hz)	Nominal Sensitivity (0.4 V/Pa @ 1 Hz)	0.7244 Pa	1.559 Pa	2.452 Pa	3.344 Pa	4.020 Pa	4.695 Pa
0.01	0.2336 V/Pa	0.0861* V/Pa	0.0867* V/Pa	0.0866 V/Pa	0.0866 V/Pa	0.0864 V/Pa	0.0862 V/Pa
0.02	0.3244 V/Pa	0.2022 V/Pa	0.2045 V/Pa	0.2034 V/Pa	0.2032 V/Pa	0.2034 V/Pa	0.2031 V/Pa
0.03	0.3597 V/Pa	0.2717* V/Pa	0.2718 V/Pa	0.2712 V/Pa	0.2710 V/Pa	0.2709 V/Pa	0.2713 V/Pa
0.04	0.3756 V/Pa	0.3074 V/Pa	0.3074 V/Pa	0.3076 V/Pa	0.3077 V/Pa	0.3075 V/Pa	0.3076 V/Pa
0.08	0.3934 V/Pa	0.3541 V/Pa	0.3540 V/Pa	0.3539 V/Pa	0.3538 V/Pa	0.3538 V/Pa	0.3538 V/Pa
0.1	0.3958 V/Pa	0.3609 V/Pa	0.3608 V/Pa	0.3607 V/Pa	0.3607 V/Pa	0.3607 V/Pa	0.3607 V/Pa
0.2	0.3990 V/Pa	0.3713 V/Pa	0.3713 V/Pa	0.3713 V/Pa	0.3712 V/Pa	0.3712 V/Pa	0.3713 V/Pa
0.4	0.3998 V/Pa	0.3757 V/Pa	0.3758 V/Pa	0.3756 V/Pa	0.3757 V/Pa	0.3756 V/Pa	0.3756 V/Pa
0.8	0.4000 V/Pa	0.3781 V/Pa	0.3779 V/Pa	0.3778 V/Pa	0.3778 V/Pa	0.3778 V/Pa	0.3778 V/Pa
1	0.4000 V/Pa	0.3779 V/Pa	0.3783 V/Pa	0.3782 V/Pa	0.3782 V/Pa	0.3781 V/Pa	0.3781 V/Pa
2	0.4000 V/Pa	0.3789 V/Pa	0.3789 V/Pa	0.3784 V/Pa	0.3786 V/Pa	0.3787 V/Pa	0.3787 V/Pa
4	0.4000 V/Pa	0.3776 V/Pa	0.3780 V/Pa	0.3776 V/Pa	0.3780 V/Pa	0.3778 V/Pa	0.3778 V/Pa
8	0.4000 V/Pa	0.3757 V/Pa	0.3757 V/Pa	0.3759 V/Pa	0.3772 V/Pa	0.3754 V/Pa	0.3757 V/Pa
10	0.4000 V/Pa	0.3736 V/Pa	0.3742 V/Pa	0.3735 V/Pa	0.3745 V/Pa	0.3737 V/Pa	0.3737 V/Pa

*** Signal to noise ratios were below 20 dB for these measurements; sine fits used to calculate these sensitivities were less than ideal.**

Table 10 Piston-Phone Sensitivities at Selected Pressures for M-60 SN 24

Freq (Hz)	Nominal Sensitivity (0.4 V/Pa @ 1 Hz)	0.7244 Pa	1.559 Pa	2.452 Pa	3.344 Pa	4.020 Pa	4.695 Pa
0.01	0.2336 V/Pa	0.1434* V/Pa	0.1441* V/Pa	0.1440 V/Pa	0.1439 V/Pa	0.1438 V/Pa	0.1437 V/Pa
0.02	0.3244 V/Pa	0.2662 V/Pa	0.2673 V/Pa	0.2663 V/Pa	0.2664 V/Pa	0.2665 V/Pa	0.2663 V/Pa
0.03	0.3597 V/Pa	0.3169* V/Pa	0.3172 V/Pa	0.3166 V/Pa	0.3167 V/Pa	0.3165 V/Pa	0.3168 V/Pa
0.04	0.3756 V/Pa	0.3394 V/Pa	0.3395 V/Pa	0.3394 V/Pa	0.3395 V/Pa	0.3395 V/Pa	0.3396 V/Pa
0.08	0.3934 V/Pa	0.3657 V/Pa	0.3656 V/Pa	0.3656 V/Pa	0.3656 V/Pa	0.3656 V/Pa	0.3656 V/Pa
0.1	0.3958 V/Pa	0.3656 V/Pa	0.3655 V/Pa	0.3655 V/Pa	0.3654 V/Pa	0.3654 V/Pa	0.3654 V/Pa
0.2	0.3990 V/Pa	0.3742 V/Pa	0.3741 V/Pa	0.3742 V/Pa	0.3741 V/Pa	0.3741 V/Pa	0.3741 V/Pa
0.4	0.3998 V/Pa	0.3780 V/Pa	0.3780 V/Pa	0.3778 V/Pa	0.3779 V/Pa	0.3778 V/Pa	0.3778 V/Pa
0.8	0.4000 V/Pa	0.3801 V/Pa	0.3799 V/Pa	0.3798 V/Pa	0.3798 V/Pa	0.3798 V/Pa	0.3798 V/Pa
1	0.4000 V/Pa	0.3799 V/Pa	0.3802 V/Pa	0.3802 V/Pa	0.3801 V/Pa	0.3801 V/Pa	0.3800 V/Pa
2	0.4000 V/Pa	0.3807 V/Pa	0.3808 V/Pa	0.3803 V/Pa	0.3804 V/Pa	0.3806 V/Pa	0.3805 V/Pa
4	0.4000 V/Pa	0.3794 V/Pa	0.3798 V/Pa	0.3795 V/Pa	0.3798 V/Pa	0.3796 V/Pa	0.3797 V/Pa
8	0.4000 V/Pa	0.3773 V/Pa	0.3776 V/Pa	0.3776 V/Pa	0.3796 V/Pa	0.3770 V/Pa	0.3773 V/Pa
10	0.4000 V/Pa	0.3750 V/Pa	0.3757 V/Pa	0.3751 V/Pa	0.3760 V/Pa	0.3751 V/Pa	0.3752 V/Pa

*** Signal to noise ratios were below 20 dB for these measurements; sine fits used to calculate these sensitivities were less than ideal.**

The average sensitivities across the evaluated pressures at 1 Hz and the differences are shown in the table below.

Table 11 Piston-Phone Average Sensitivities

Sensor	Sensitivity at 1 Hz	Difference of Mean from Nominal Sensitivity at 1 Hz	Maximum Difference from Mean at 1 Hz across 0.7244 – 4.695 Pa
M-60 SN 19	0.379 mV/Pa	-5.3% (-0.46 dB)	-0.065% (-0.0056 dB)
M-60 SN 20	0.378 mV/Pa	-5.5% (-0.49 dB)	-0.065% (-0.0057 dB)
M-60 SN 24	0.380 mV/Pa	-5.1% (-0.44 dB)	-0.061% (-0.0053 dB)

The sensitivities at 1.0 Hz of the M-60 sensors were observed to be between 0.378 and 0.380 mV/Pa. The observed sensitivity values differed from the nominal sensitivity, provided on the manufacturer's preliminary data sheet, by between 5.1% (0.44 dB) and 5.5% (0.49 dB). All sensors were flat across the 0.7244 – 4.695 Pa amplitude range to within +/- 0.07% (0.006 dB). The variation in sensitivity observed across frequency is consistent, perhaps slightly better than, the magnitude response roll off (at the low frequency corner analyzed) provided by the manufacturer with the reduction in sensitivity by half below 0.02 Hz. Signal-to-noise ratios at the lowest frequencies evaluated are significantly lower than that of 1 Hz sine. Therefore, one must appropriately weigh the significance of the observed lower corner frequency observation.

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 with a known instrument response model (MB2000 serial number 1380) 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 6.82 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 0.568 dB.

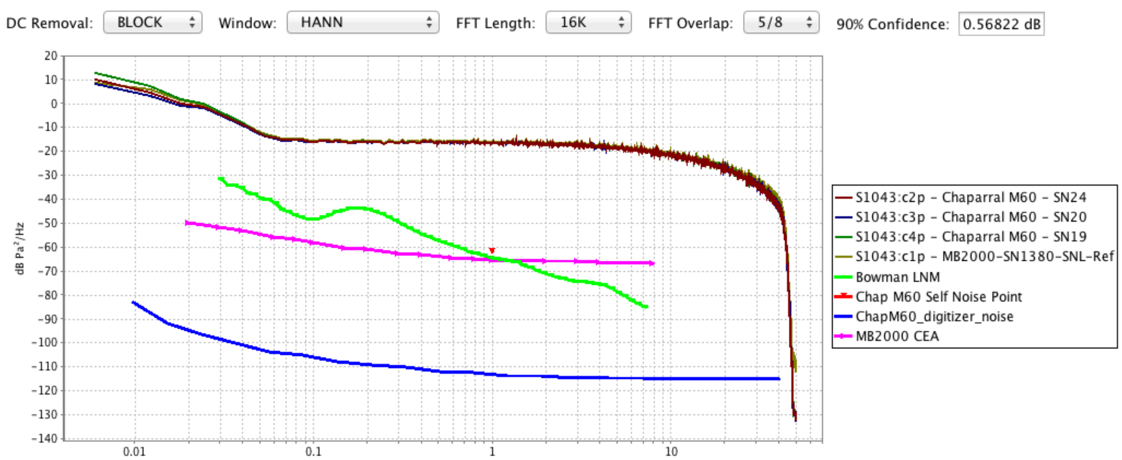

Figure 10 Piston-phone white noise power spectra

The PSDs show good broadband agreement with the MB2000 reference sensor from 0.1 to 40 Hz. 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 MB2000 and each of the M-60 sensors under evaluation are plotted below.

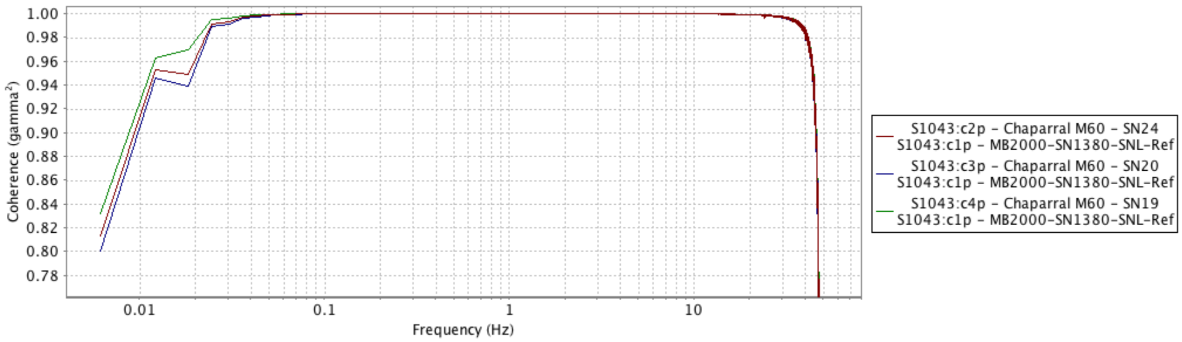

Figure 11 Piston-phone white noise coherence

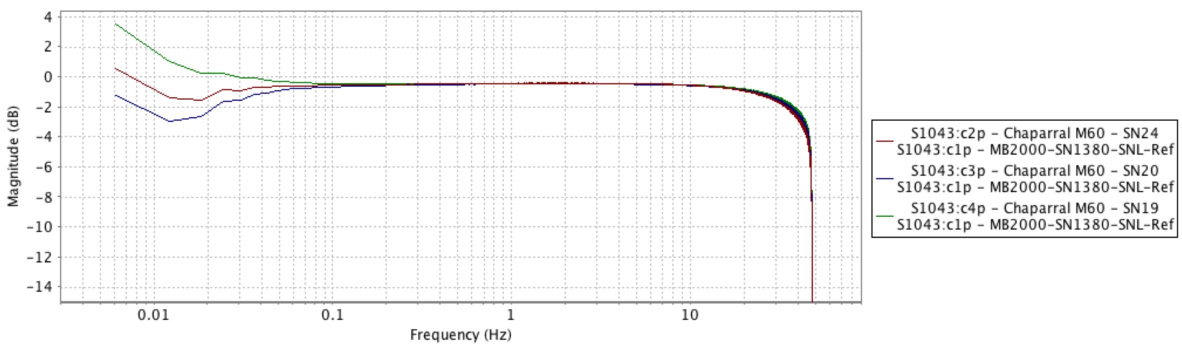

Figure 12 Piston-phone white noise relative magnitude

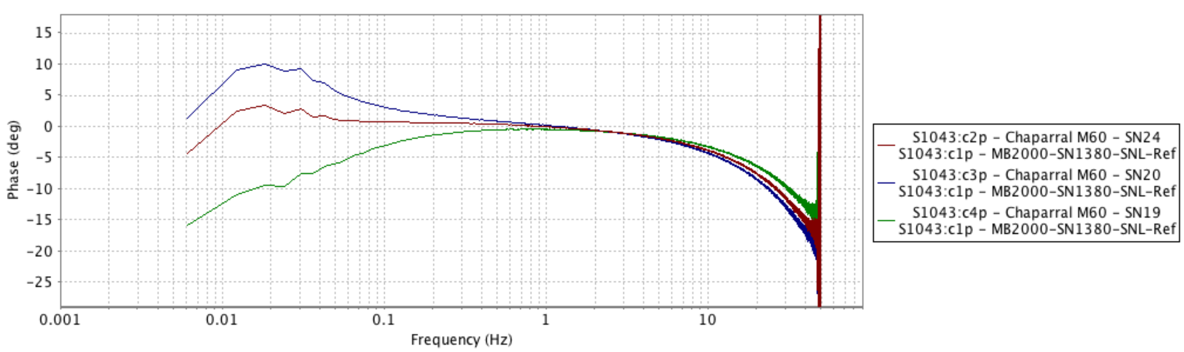

Figure 13 Piston-phone white noise relative phase

The variation in magnitude and phase between the outputs of the MB2000 reference and each of the Chaparral M-60 sensors are described in the table below. There is sufficient coherence between the Chaparral M-60 and the MB2000 reference to be able to comment on the relative response over 0.03 to 40 Hz.

Table 12 Piston-phone White Noise Relative Magnitude and Phase, 0.1 Hz and 40 Hz

	Magnitude	**Phase**
M-60 SN 19	-0.060 dB / 0.018 dB	+ 2.42 deg / -1.79 deg
M-60 SN 20	-0.113 dB / 0.080 dB	- 6.19 deg / 4.12 deg
M-60 SN 24	-0.053 dB / -0.218 dB	+ 3.77 deg / -2.36 deg

The theoretical response models for the MB2000 and Chaparral have a 3 dB low frequency corner at 0.01 Hz and 0.03 Hz, respectively. There is general agreement between the response-corrected relative magnitude from 0.1 Hz to 10 Hz. The frequency band over which there is agreement in response-corrected relative phase however, is more narrow, from 0.3 Hz to 3 Hz.

3.6 Dynamic Noise

Test Description: The purpose of the dynamic noise test is to evaluate the sensors' electronics and transducer noise under conditions of significant excitation. The sensors were isolated by placing them inside the 330L chamber with their inlets open. This test was run over night, and the data were collected and reviewed prior to processing.

A band-width limited white noise signal was generated by a Smart24 testbed digitizer with an amplitude of 1.0 Volts. This white noise signal was fed into a piston-phone infrasound source attached to the 330L infrasound test chamber.

The data from the reference sensors 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.

The coherence was computed using the technique described by Sleeman (2006). 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 0.570 dB.

Plots of the time series, power spectral density, and incoherent noise are shown below.

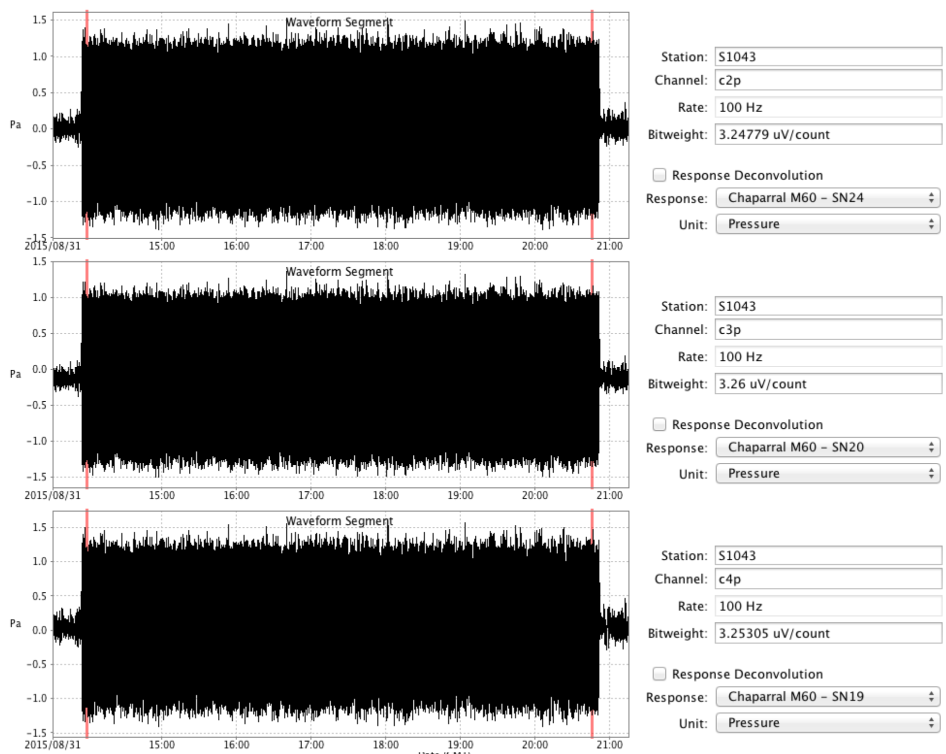

Figure 14 Chaparral M-60 dynamic noise time series

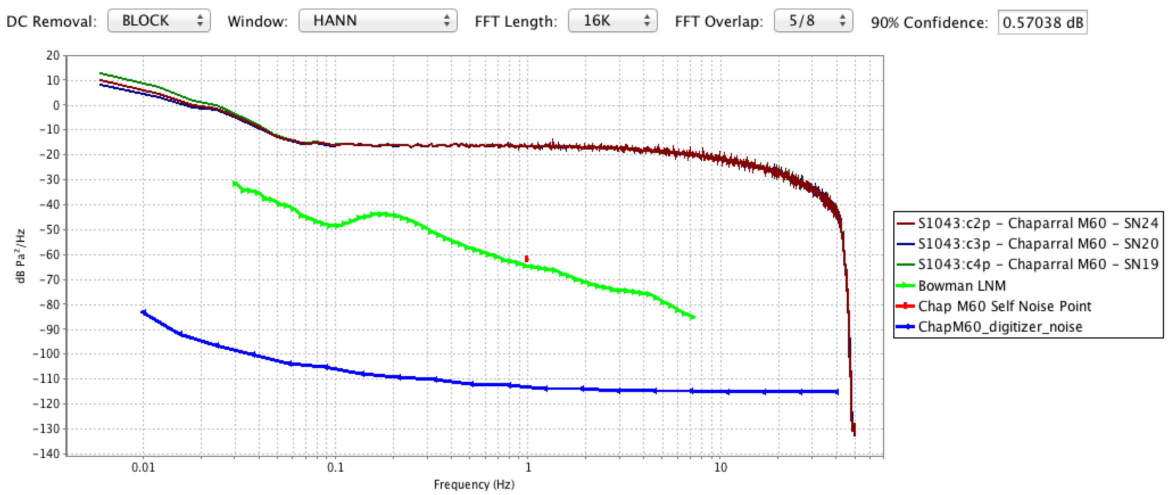

Figure 15 Chaparral M-60 dynamic noise power spectra

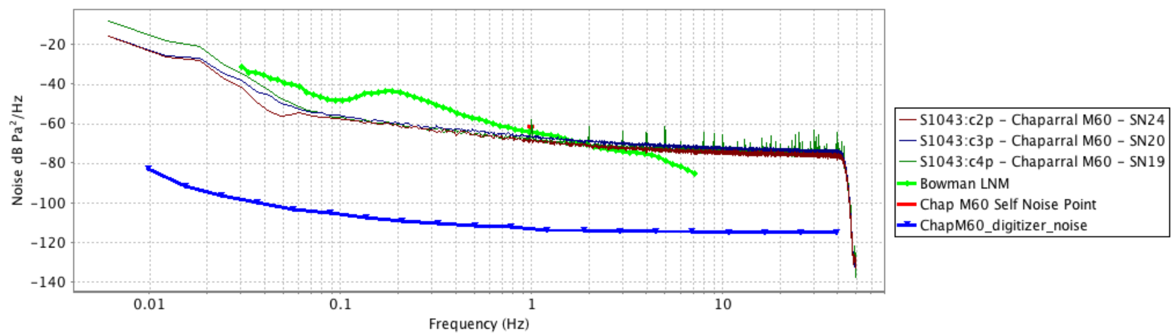

Figure 16 Chaparral M-60 dynamic noise incoherent noise

We observe that the M-60 self-noise, represented by the incoherent noise in Figure 16, is ~4-6 dB lower than the specification provided by Chaparral Physics, -62 db at 1 Hz. Sensor SN 20 shows an approximately 2 dB higher self noise from 0.5 Hz to 40 Hz. While the dynamic self-noise of the sensors is higher than the Bowman Low Noise Model at frequencies greater than 1.6 Hz, over the bands of 0.1 Hz to 40 Hz and 0.5 to 2.0 Hz, all sensors under test exhibited dynamic self-noise less than that specified by the manufacturer. It is noteworthy that the dynamic self noise is equivalent to that of the isolation test evaluated self-noise.

3.7 Seismic Sensitivity

Test description: The purpose of the seismic sensitivity test is to evaluate and determine the infrasound sensors sensitivity to ground motion. The sensors were isolated by placing them inside the 330L chamber with their inlets open. Isolating the sensors from the ambient pressure will serve to minimize signals that may mask the outputs due to ground motion. A GS13 short-period seismometer was co-located with the infrasound sensors just outside of the isolation chamber to provide a reference.

The M-60 sensors were removed from their encapsulating foam jackets (see Figure 3) and placed directly on the concrete pier. A vehicle was then driven around the FACT site bunker for approximately 20 minutes to generate the desired ground motion.

There were no visible effects from the vehicle driving around the bunker in the M-60 time-series. To qualitatively illustrate this point the time-series were band-pass filtered in the dominant frequency band of the vehicle-generated noise (10 Hz to 40 Hz), with a 3 pole Butterworth band pass filter. Notice there is no obvious similarity in the signals recorded.

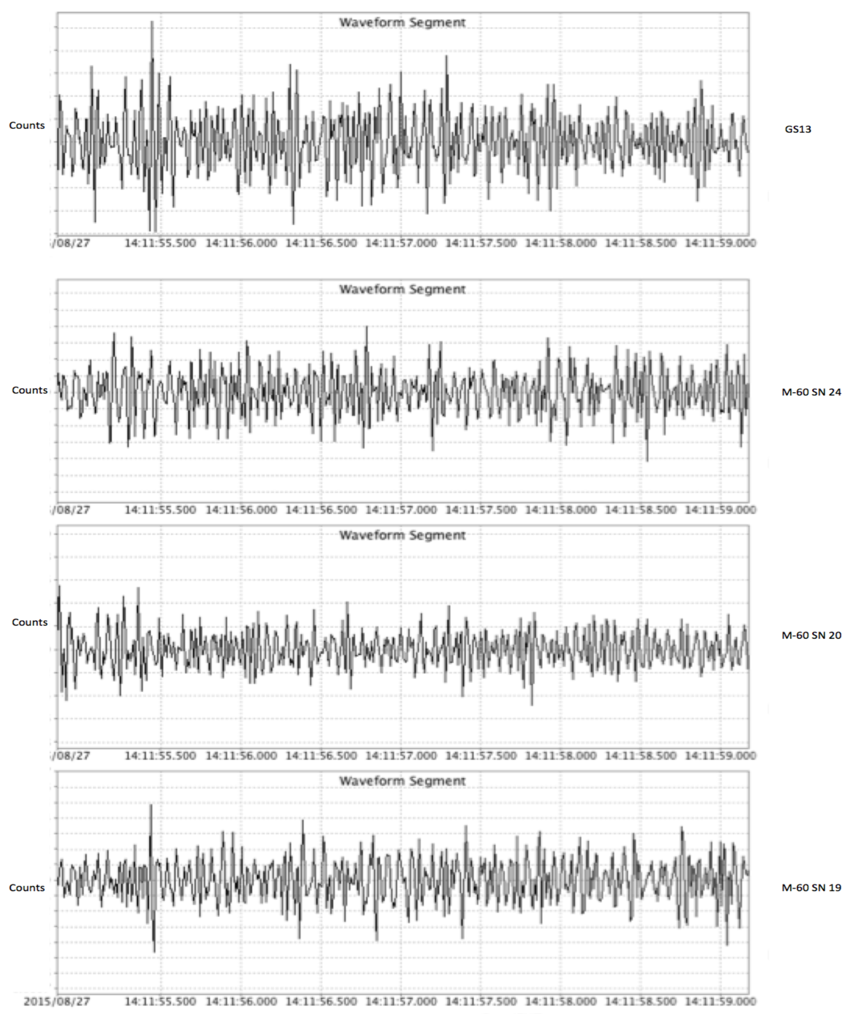

Figure 17 Seismic and infrasound time series band pass filtered 10 Hz - 40 Hz

A review of the coherence (gamma^2) below, of unfiltered data, shows coherence is less than 0.13 between the GS-13 and the M-60. It is clear from the lack of coherence that the time-series would not exhibit any similarity.

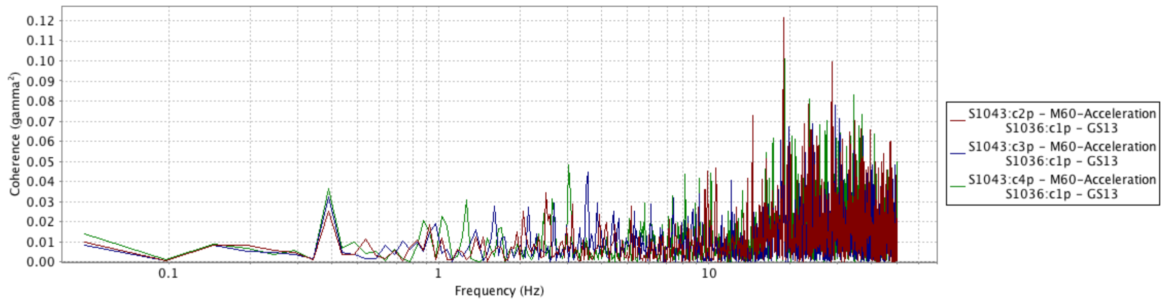

Figure 18 Seismic ground motion coherence

A comparison of power spectra of the pressure-isolated M-60 data collected during the period of seismic excitation and immediately afterwords proves useful. Each power spectra below, is calculated in terms of pressure, with a window length of 20 minutes.

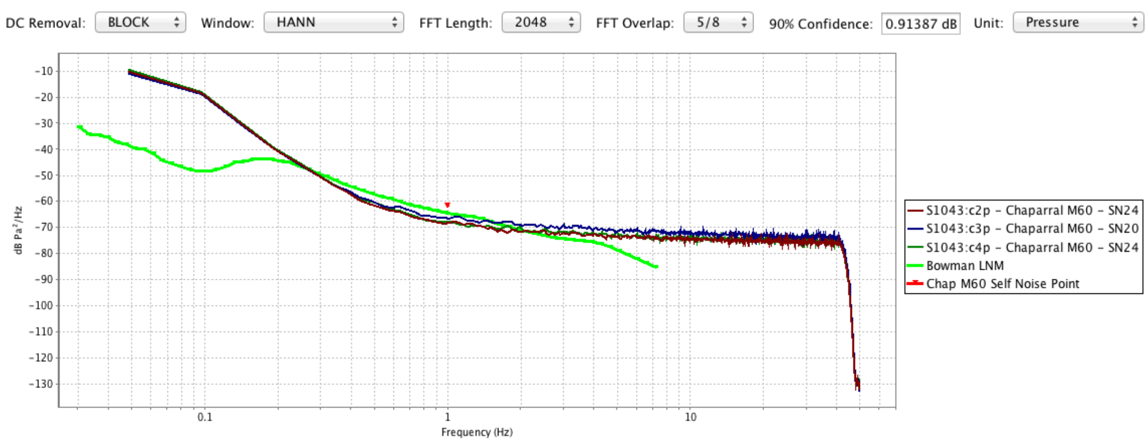

Figure 19 Pressure power spectra due to ground motion during seismic excitation

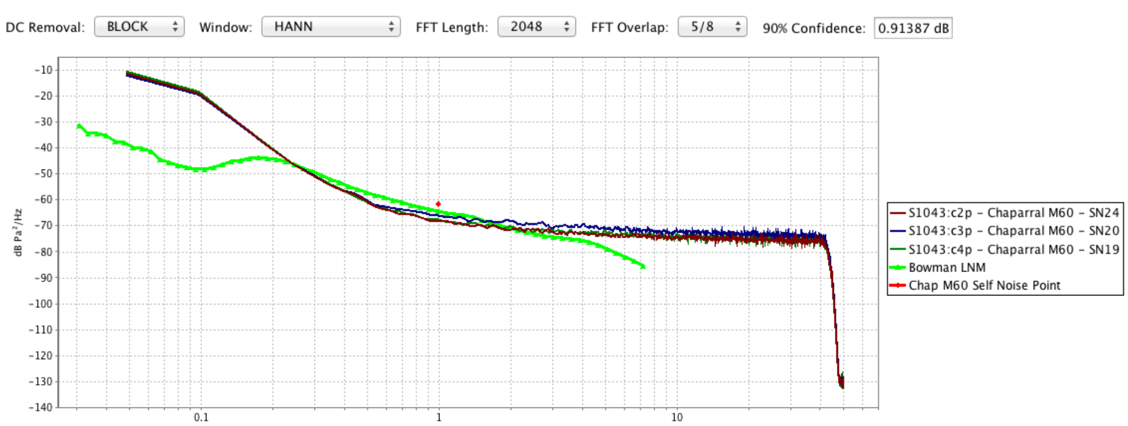

Figure 20 Pressure power spectra immediately following seismic excitation period

Comparison of the power spectra illustrated in Figure 19 and in

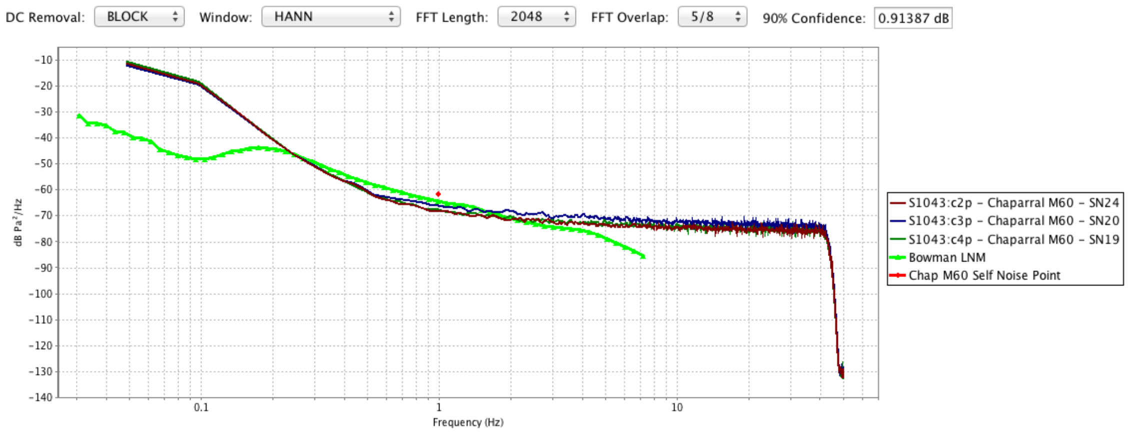

Figure 20 Pressure power spectra immediately following seismic excitation periodalso show little evidence of seismic coupling in the M-60 sensor. At 1 Hz the data immediately following the period of seismic excitation actually exhibit 0.5 db more noise.

These observations qualitatively and quantitatively imply that the M-60 has such a low seismic sensitivity that the signal due to ground motion is not visible above the sensor self-noise level.

4 EVALUATION SUMMARY

Power:
The observed power consumption of the Chaparral Physics Model 60 was between approximately 167 mW and 173 mW at 14.09 V. The stated power consumption from the sensor specifications is less than 150 mW, 12 mA @ 12.6 V.

Isolation Noise:
The Model 60 measured self-noise was below the Bowman LNM at frequencies less than 1.5 Hz. The measured sensor self-noise was consistent with the noise model provided by Chaparral Physics of -62 dB (relative to 1 Pa^2/Hz) at 1 Hz.

Dynamic Range:
The observed dynamic range of the Model 60 sensors was more than 81 dB over 0.1 – 40 Hz and at least 90 dB over 0.5 – 2 Hz. This is consistent with Chaparral Physics specification of 88 dB of dynamic range over the 0.5 – 2 Hz pass band.

Frequency Amplitude Response Verification:
The observed sensitivity at 1 Hz of the Chaparral Physics Model 60 sensors were all between 5.1% (0.44 dB) and 5.5% (0.49 dB) of the nominal sensitivity provided on the preliminary data sheet of approximately 0.4 V/Pa. All sensors were flat across the 0.7244 – 4.695 Pa amplitude range to within +/- 0.07% (0.006 dB). The variation in sensitivity observed across frequency is consistent, perhaps slightly better than, the magnitude response roll off (at the low frequency corner analyzed) provided by Chaparral Physics with the reduction in sensitivity by half at approximately 0.03 Hz.

Frequency Amplitude Phase Verification:
Broadband measurements of a white noise source indicate that both the Chaparral Physics Model 60 sensors have a response that is flat across 0.01 to 40 Hz to within 0.11 dB in magnitude and 6 degrees in phase. The evaluated M-60 sensors are generally consistent with their theoretical response model in magnitude from 0.1 Hz – 40 Hz, and in phase, from 0.3 to 3 Hz.

Dynamic Noise:
The observed self-noises of the Model 60 sensors, while exceeding the Bowman Low Noise Model at frequencies above 1.6 Hz, are below noise levels specified by Chaparral Physics and consistent with the measurement of Isolation Noise. Dynamic self-noise levels are equivalent to what was observed in the Isolation Noise test.

Seismic Sensitivity:
The Model 60 sensors have no appreciable sensitivity to ground motion induced during testing.

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APPENDIX

MB2000 Response

The MB2000 response used has the standard poles and zeros provided by CEA. The sensitivity of 0.1 V/Pa was validated by comparison of the MB2000 SN 1380 to the MB2005 SN 7009.

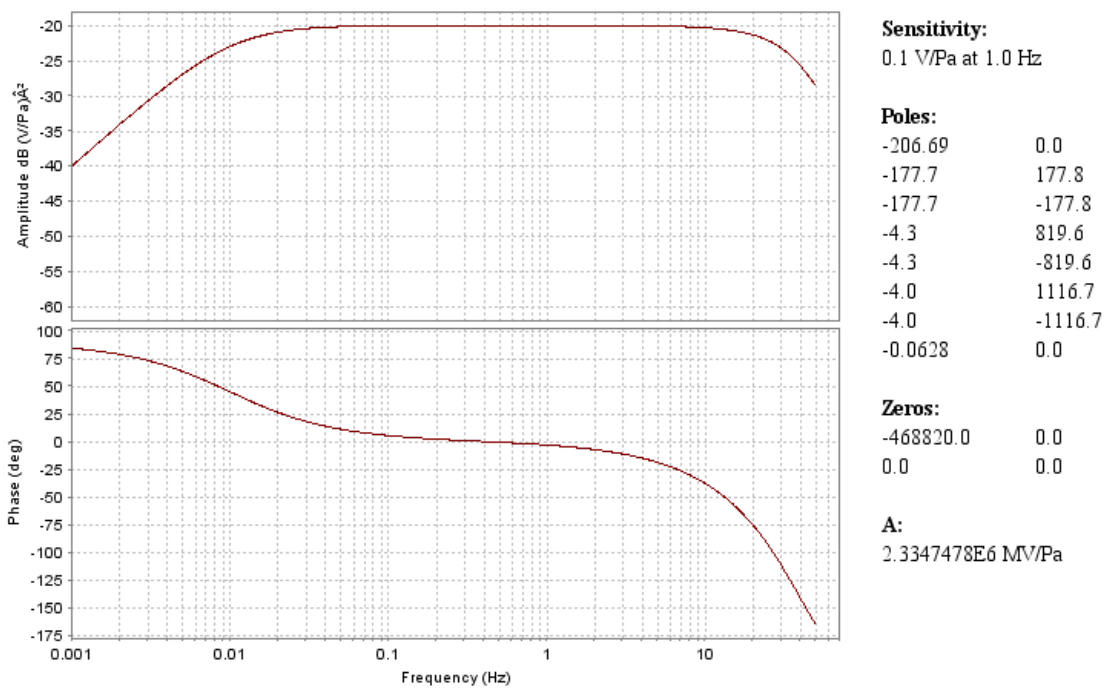


Figure 21 MB2000 Response

MB2005 Response

The MB2005 response used has the standard poles and zeros provided by CEA. The sensitivity was determined by evaluating the MB2005 SN 7009 in the Los Alamos National Laboratory traceable calibration chamber.

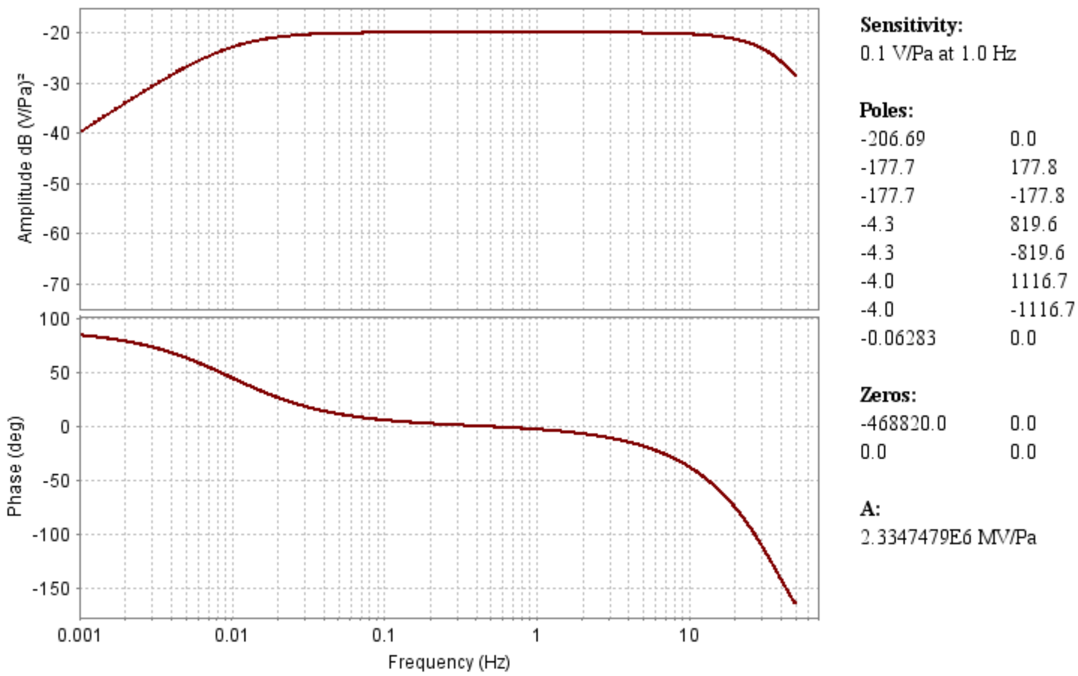
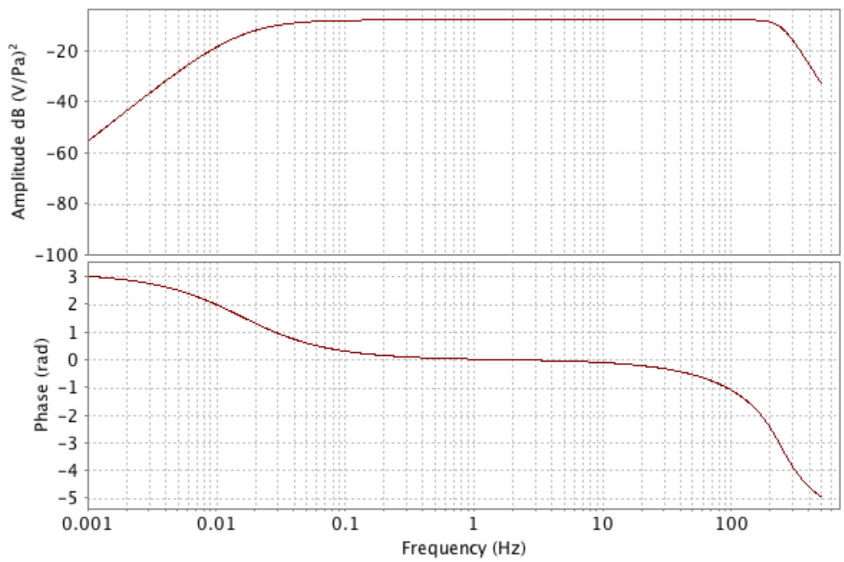


Figure 22 MB2005 Response

Chaparral Physics M-60 Response

The M-60 responses were provided to SNL by Chaparral Physics with the sensitivity, poles, and zeros below.



Sensitivity:
0.4 V/Pa at 1.0 Hz

Poles:

-1422.95	590.92
-1422.95	-590.92
-590.13	1423.55
-590.13	-1423.55
-0.112	0.0
-0.0855	0.0

Zeros:

0.0	0.0
0.0	0.0

A:
2.2556022E6 MV/Pa

Figure 23 Chaparral Physics M-60 Nominal Response

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